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Developing and evaluating the
feasibility of an active training game
for smart-phones as a tool for
promoting executive function in
children

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PhD

The University of Edinburgh

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Declaration

This is to certify that the work contained in this thesis has been composed by me and is entirely my own work. No part of this thesis has been submitted for any other degree or professional qualification.

Signed:

Abstract of The Thesis

Developing and evaluating the feasibility of an active training game for smart-phones as a tool for promoting executive function in children

by

Stuart Iain Gray

Executive function (EF) comprises a series of interrelated cognitive and self-regulatory skills which are required in nearly every facet of everyday life, particularly in novel circumstances. EF skills begin developing from birth and continue to grow well into adulthood but are most crucial for children as they are associated with academic and life success as well as mental and physical health. There is now strong evidence that these skills can be trained through targeted intervention in a diverse range of approaches, such as computer games, physical activity, and social play settings.

This thesis presents the process of the design and evaluation of an active EF-training game (BrainQuest) for smart-phones, in participation with end-users: a group of 11-12-year-old children from a local Primary School. The design process placed emphasis on creating an engaging user experience, a phenomenon which has eluded many serious games, by building upon motivational game design theory and satisfying end-user requirements. However, in the pursuit of promoting particular executive functions: working memory; inhibitory control; planning and strategizing, the design integrated aspects of a cognitive assessment while also utilizing a range of alternative approaches for training EF, including physical activity and social play.

Following an iterative design process which included many single session prototype evaluations, a mixed methods evaluation was undertaken during a 5-week study with twenty-eight 11-12-year-old school children. The study gathered exploratory qualitative and

quantitative evidence regarding the game's potential benefits which was evaluated by triangulating a range of data sources: multi-observer observations notes, interviews with children and teachers, game performance data and logs, and cognitive assessment outcomes. The analysis describes the statistical relationships between game and executive function ability, before exploring user experiences and evidence of cognitive challenge during gameplay through a series of triangulated case studies and general whole-class observations.

The analysis presents the game to be engaging and enjoyable throughout the study and, for most children, able to generate a sustainable challenge. Though there were initial difficulties in understanding the complex game rules and technology, the game became increasingly usable and learnable for the target user group and created opportunities for goal setting. It also encouraged feelings of pride and self-confidence as well as facilitating positive social interactions and requiring regulation of emotion, which are considered to be pathways to developing executive functions (Diamond, 2012). There was also promising initial evidence that the game's variable difficulty level system was able to challenge executive functions: planning and strategizing, working memory, and inhibitory control. Most notably, the game appeared to support improvements in strategizing ability by demanding increasing strategic complexity in response to evolving and increasingly difficult task demands. Supporting BrainQuest's cognitive challenge, several statistical relationships emerged between executive function ability and game performance measures. However, the game's ability to significantly improve cognitive outcomes could not yet be concluded.

Nevertheless, these findings have implications for both the future design and evaluation practices undertaken by cognitive training researchers. From a design perspective, less credence should be paid to simply gamifying cognitive assessments while greater emphasis should be placed on integration of formal game design and motivational theories. With regards to evaluation, researchers should understand the importance of establishing first whether CTGs can remain engaging over time as well as the feasibility of their challenge to cognitive functions.

In loving memory of Ellen Mayworth, I only wish you could have read it.

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Publications

1. Robertson, J., Jepson, R., Macvean, A. and Gray, S., 2016. Understanding the Importance of Context: A Qualitative Study of a Location-Based Exergame to Enhance School Childrens Physical Activity. *PloS one*, 11(8), p.e0160927.
2. Gray, S., Robertson, J. and Rajendran, G., 2015, June. BrainQuest: an active smart phone game to enhance executive function. In *Proceedings of the 14th International Conference on Interaction Design and Children* (pp. 59-68). ACM.
3. Gray, S, 2014, BrainQuest: An Executive Function Training Tool. In *Proceedings of the 14th International Conference on Interaction Design and Children*, IDC'14

Acronyms

ADT – Android Development Tools

API – Application Programming Interface

BADS-C – Behavioural Assessment of the Dysexecutive Syndrome in Children

CET – Cognitive Evaluation Theory

CTG – Cognitive Training Game

EF – Executive Function

GB – Gigabyte

GHz – Gigahertz

GPS – Global Positioning System

HTTP – Hypertext Transfer Protocol

IC – Inhibitory Control

MD – Method of Design

MET – Metabolic Equivalents

MMO – Massively Multiplayer Online

MVPA – Moderate to Vigorous Physical Activity

NFC – Near Field Communication

NHS – National Health Service

PA – Physical Activity

PATHS – Promoting Alternative Teaching Strategies

PENS – Player Experience Need of Satisfaction

PFC – Pre-Frontal Cortex

PHP – Hypertext Pre-processor

R – Requirement

RAM – Random Access Memory

RCT – Randomized Controlled Trial

SAS – Supervisory Attentional System

SDK – Software Development Kit

SDT – Self-Determination Theory

SQL – Structured Query Language

TOOLS – Tools of the Mind

UCD – User-Centred Design

XML – Extensible Mark-up Language

WHO – World Health Organisation

WM – Working Memory

1. Introduction

In recent years, health practitioners have championed the importance of physical activity (PA) for improving quality of life outcomes and combating disease attributable to sedentary behaviour. However, quality of life can also be attributed to psychological health and is increasingly associated with a set of cognitive functions, known as executive functions (EF).

The importance of both psychological and physiological wellbeing has led to research into how practitioners may be able to support at-risk groups, such as children, for whom improvements may lead to more fulfilling, happy lives. In ensuring psychological and physiological health, two computerized solutions in the field of serious games have risen to the forefront of research:

- Exergames, which couple real-world PA with video gaming, have been established as one tool to encourage long-term behavioural change towards physically active lifestyles.
- Computerized cognitive training games (CTGs), which gamify cognitive assessments with video-game aesthetics and reward systems, have been established as a method for training cognitive skills.

There is a relationship between PA and EF which suggests the integration of both genres in a single approach may be of greater overall benefit to health outcomes and produce a more potent cognitive training tool. However, research suggests that currently, both genres suffer shortcomings in sustaining the user interest needed to produce positive real-world impacts and some have argued this to be the result of inadequate design.

This thesis investigates, BrainQuest, an active training game for smartphones, designed within a Primary school context to promote EF for 11-12-year-old children. It argues that a combination of approaches to cognitive training, including PA; social play; support for self-esteem; and motivational game design theory, may be able to promote engaging training experiences and positively challenge EFs. The game was evaluated in 3 single sessions at the end of each design prototype, as well as a 5-week evaluation within a local Edinburgh Primary School which collected data regarding the user experience and the relationship between the game's design and implementation. BrainQuest was analyzed through the formation of case studies to provide a fine-grained understanding of individual user experiences and behaviour which complemented the general, broad-based quantitative and qualitative results of the entire Primary 7 class (n=28). Going beyond this, the thesis aims to

provide both design and methodological insights to be used by future researchers seeking to further this interdisciplinary field or any of the contributing fields. This thesis also explains the process of designing a game through an iterative user-centred design (UCD) process requiring a balance between user and literature requirements.

This chapter begins by defining the EF construct and outlining its importance to children before moving on to describe some of the influential training methodologies used in its improvement. Next, exergames are introduced and their potential appraised. Following this, the main research questions are then summarised in Section 1.4 (p. 6) and an outline for the thesis is presented in Section 1.5 (p. 6).

1.1 The Importance of Executive Function

Executive function(s) or (EF) is an umbrella term for a set of cognitive functions ranging in complexity, from simple core cognitive skills involving self-regulatory and working memory (WM) systems to more complex functions such as engaging in goal-directed behaviours, reasoning, problem-solving, and decision-making (Diamond, 2015; Diamond, 2013; Anderson 2010; Rabbit, 1997). We use different combinations of EFs every day of our lives to do everyday things, such driving, shopping, or cooking dinner. It is believed that EF is fundamental in novel situations where one may have to formulate a solution to a new problem. Thus, deficiencies in executive control can be detrimental to one's quality of life.

EF develops rapidly from birth and even by age one we have developed the core foundations of our executive cognition (Diamond, 2013). However, the development of function complexity and relationships are more prolonged and intermittent in nature, characterized by key stages of development for particular functions which continue to develop until around 30 years before a gradual decline into old age (De Luca, 2008). One key stage is between 9 and 12 years, with notable improvements in EFs: WM, sustained and selective attention, set-shifting, strategic planning, response inhibition, and social deception (De Luca, 2008).

Hence, EF is particularly important for children. Indeed, EF ability is associated with a variety of life quality outcomes and those with better EFs are more likely to have good mental (Diamond et al. , 2013; 2011; Fairchild et al., 2008; Baler et al., 2006) and physical health (Diamond et al. ,2013; Crescioni et al., 2011; Miller et al., 2011; Riggs et al., 2010), achieve more academically (Borella et al., 2010; Duncan et al., 2007; Gathercole et al.,

2004), earn a higher income (Diamond, 2013), enjoy better relationships (Eakin et al., 2004), and integrate into society (Broidy et al., 2003).

EF has been strongly linked to academic outcomes throughout an individual's entire school career but much of the literature has focused on the importance for children in primary schools. EF has been found to be a better predictor of school readiness than IQ (Diamond, 2007), while self-regulatory abilities are positively associated with good self-directed classroom behaviour (Ponitz et al., 2008; Saracho & Spodek, 2007; Brook & Boaz, 2005; Howse et al., 2003; Blair & Razza, 2002). Moreover, EFs are able to positively predict maths and reading abilities throughout one's academic career (Borella et al., 2010; Duncan et al., 2007; Gathercole et al., 2004) and appear to be mediated by abilities in WM and inhibitory control (IC) (Dalziel, Boyle, Mutrie, 2015; Diamond, 2013; Diamond, 2007). Some authors have also raised the importance of self-regulatory EF abilities in influencing social behaviour pertinent to the classroom (Meltzer, 2007), as well as the role of EF in learning how to learn skills (Meltzer, 2007) – such as planning, organising, checking, and reflecting upon work and time management.

Hence, EF's importance, particularly for children, has been the catalyst for the development of EF training methods, including curriculum-based programmes, computerized cognitive training, and PA programmes.

1.2 The Promise of Cognitive Training

Curricula-based programmes are one of the most well-established techniques for training EF. Programmes like Tools of the Mind (Tools), Promoting Alternative Teaching Strategies (PATHS), and Montessori curriculums have shown promise and a series of different studies have shown children engaged in such programmes to exhibit both better EF ability as well as real-world academic performance than peers engaged in mainstream curricula (Diamond & Lee, 2011). However, there are training and material costs associated with implementing such programmes. Furthermore, Diamond (2012) suggested that EF training should be undertaken throughout the entire day. Thus, there is the need for more flexible methods of EF training.

Another established technique for training cognition and EF is PA (Diamond, 2015; 2012; Daly et al., 2015; Dalziell, Boyle & Mutrie, 2015; Best, 2014; 2010; Kramer et al., 2001; Davis, et al., 2011). Benefits may begin to emerge from low to moderate intensity PA, such

as walking, which has demonstrated a beneficial effect in EFs like task switching, IC and WM (Kramer et al., 2001). However, some authors believe that higher intensity PA may be even more useful (Best, 2010). Davis et al. (2011) highlighted the potential transfer of aerobic exercise to increased mental activity in regions of the brain synonymous with executive control, as well as real-world improvements in mathematics. Yet, other research suggests PA involving a cognitive component (or cognitively engaging physical activity) like team or competitive sports may be of greatest benefit (Diamond, 2015; Best, 2010) as individuals must coordinate movements and cooperate with teammates/opponents, anticipate others behaviour, employ strategies, and adapt to changing task demands – tasks consistent with EF (Best, 2010). However, encouraging individuals to undertake PA is not always straightforward, particularly those who hold negative opinions with respect to their own physical abilities (Dishman et al., 2004).

One flexible EF training methodology which may solve accessibility problems associated with PA are CTGs. CTGs, most notably using the Cogmed game which various studies have claimed can support improvements in both general cognition and EF and even improvements in maths and reading outcomes (Spencer-Smith, Klingberg, 2015; Rapport et al., 2012; McNab et al, 2009; Holmes, et al., 2009; Klingberg et al., 2002). In recent years computerized cognitive training has also reached the mainstream and game developers have often forged close links with the neuroscience community to help in the design and evaluation of the games. Improvements in working memory and ‘fluid intelligence’, a series of high-level cognitive skills which overlap with the EF construct, are some of the most important claims of such games (Jaeggi, 2008; Hardy et al., 2015). Despite this, many authors (Simons, 2016; Melby-Lervåg, 2016; 2013; Morra & Borella, 2015; Redick et al., 2013) have given little credence to the reported improvements of CTGs because of several methodological oversights, pertaining to the design of control groups, single measures of cognitive constructs, small sample sizes, test-retest validity, and a lack of task transfer.

Adding to the shortcomings of previous research, Mishra, Anguera, and Gazzaley (2016) highlighted the lack of game design employed in many CTGs and questioned whether they would have the longevity required for any real-world impact for users. Hence, they posited a series of design recommendations for future CTGs, including providing users with: an immersive gameplay experience which encourages repeated play; performance-based challenge to keep users at the cusp of their abilities; accessibility of games to different ability levels; technologies able to capture ubiquitous user inputs, such as mobile augmented or virtual reality; incorporate other established cognitive training methodologies, such as PA.

Thus, while there is indeed a great deal of promise in CTGs, there is a need to improve their design and evaluation in order for them to be deemed a viable long-term training method. The work in this thesis is dedicated to improving cognitive training design by integrating different training methodologies, including computerized cognitive training; PA; and social play, as well as motivational game design theories.

1.3 Exergames

Exergames are a branch of serious gaming which incorporates interaction between users and video games which involve PA. Exergames were established in the mid-80s but have recently become more prominent through the introduction of console exergaming systems and mobile technology. Researchers have subsequently used and developed their own exergames to explore whether they may be able to encourage behaviour change towards more physically active lifestyles.

There currently exists an epidemic of sedentary behaviour among children in the Western world, characterized by a failure to meet PA guidelines (Wilson et al., 2015; NHS; Health Survey of England 2014) and negatively correlated with physical (Slemenda et al., 1991) and psychological health (Scully et al., 1998), cognitive development (Tompsonowski et al., 2008), as well as academic and behavioural problems (Keays & Allison, 1995). In Scotland 1 in 4 children do not meet their daily MVPA (moderate to vigorous PA) guidelines (Wilson et al., 2015) – the amount of PA they are supposed to undertake each day to maintain a healthy lifestyle. Hence, encouraging behaviour change towards more active lifestyles is vital.

Many authors believe that harnessing the motivating and enjoyable nature of video games in combination with PA, through exergames, may help children overcome the barriers they currently face towards PA (Baranowski et al., 2014; Macvean & Robertson, 2013; 2012; Park et al., 2012; Payton et al., 2011; Jegers, 2007). Most notably, many children experience a lack of enjoyment, interest, or self-efficacy towards PA (Dishman et al., 2005; 2004; Trost et al., 1997) but there are additional barriers including safety concerns (Carver et al., 2008); the sedentary-based format of school lessons (Baranowski et al., 2014; Carson et al., 2013; Donnelly et al., 2011); and a bias in extra-curricular sports opportunities towards the most physically talented children (Bocarro et al., 2008).

However, while the efficacy of the exergame concept appears sound, the extent of their effectiveness in promoting MVPA and facilitating behaviour change has been less forthcoming. For example, while it is generally accepted that exergames may be able to

facilitate at least low-moderate MVPA during play they are also associated with a novelty user engagement effect which in turn leads to a decrease in motivation to play and, therefore, remain physically active (Robertson et al., 2016; Macvean & Robertson, 2013; 2012).

Novelty effects and an inability to sustain engagement is common to other ‘serious game’ genres (Habgood, 2005) and have also been questioned with respect to CTGs (Mishra, Anguera, & Gazzaley, 2016). Hence, some serious game designers (Laine & Suk, 2015; Peng et al., 2012) have sought to remedy such novelty effects by closely aligning exergames with established motivational theories, such as Self-Determination Theory (Ryan & Deci, 2000) and the Lepper and Malone framework (1987).

Hence, the game designed and evaluated in this thesis has been developed as the first cognitive training exergame with a focus on motivational theory.

1.4 Main Research Questions

This thesis describes the design, development, and evaluation of an EF training exergame titled BrainQuest. Note, the first research question refers to a hypothesized model of EF building activities outlined in Chapter Two (Section 2.1.3.5, p. 23). The primary research questions addressed in the thesis are as follows:

RQ1. *To what extent does the game support the pathways to EF improvement identified by the Diamond (2012) model pathways: joy, social belonging, physical fitness and pride/confidence/self-efficacy?*

RQ2. *What evidence is there to suggest that the children experience EF challenge and improvement through playing BrainQuest?*

1.5 Thesis Outline

This thesis is structured into eight chapters and additional appendices.

Chapter Two presents the key EF paradigms and notable approaches towards training, providing the foundation and underpinning of the work in later chapters. Chapter Two begins by introducing the EF origins and the evolution of the concept to the present day. Next, key paradigms are presented and the important relationships between EF, emotion, and novelty are outlined. Following this, EF importance to children and its association with academic and life success is discussed. The chapter then moves on to discuss the promise and shortcomings

of various EF training methodologies, focusing upon the role of CTGs. Finally, the BADS-C testing battery and the 6E test used within this thesis are outlined.

Chapter Three considers the contribution of exergames to physical health and describes motivational design techniques applicable to improving user engagement within serious games. First, the chapter briefly describes the promise of exergames, as well as the importance of PA to health. Next, motivational theories are introduced and framed within the context of game design before presenting a review of their application to exergames and CTGs.

Chapter Four collates the design requirements and associated methods, as well as methodological lessons identified in the literature and presents a series of tables to be used as a reference point throughout the design and evaluation chapters of the thesis.

Chapter Five provides an overview of the completed BrainQuest system before relating the system to the requirements defined by the literature as well as the end-users. Following this, an overview of the software, hardware, and architecture underpinning the game is provided. Finally, the UCD process used to develop the game is described chronologically, including requirement gathering stages, consultations with experts, incremental prototype implementations, and evaluation sessions. Note, further details regarding design decisions are saved for Appendix A.

The main evaluation of BrainQuest is undertaken in Chapter Six. First, the methodological approach taken is identified, including mixed methods, case studies, and reliability measures. The chapter moves on to document the 5-week intervention involving 28 children aged 11-12 years in an Edinburgh Primary school. The evaluation methods, procedure, and analysis techniques are considered before the evaluation results are presented, including standalone sections to document the quantitative statistics, a featured case study, and qualitative evidence for the entire dataset. The chapter concludes with a brief discussion of the results and their significance to the research questions.

The main discussion of the study results, their implications for future research, and the lessons learned, is saved for Chapter Seven. The chapter opens with a discussion of the impact of findings to contributing fields and the pathways of Diamond (2012) model. Next, the challenge present within BrainQuest is considered, including maintenance of novel EF challenge, the different challenges present within the game, and alternative explanations for the findings are considered. Following this, BrainQuest's motivational design is appraised, describing aspects of the game able to engage users and the impact of the social interaction

deployed. This section also puts forward many suggestions for how BrainQuest could be improved. The PA involved in BrainQuest and the game's contribution to the exergame genre is then discussed.

Chapter Seven also discusses the employed methodology in the main evaluation, specifically, the contribution of a mixed methods approach to EF assessment and the importance of data triangulation of multiple sources. This chapter also contrasts the differences between BrainQuest and the 6E test which influenced the structure and rules of the game before finally addressing transfer observed following play. The remainder of the chapter considers the implications of the work for teachers, the logistical and technical lessons learned, and recaps upon the suggested game changes.

The thesis concludes with Chapter Eight, a summary of the primary findings and contributions which are then related back to research questions.

2. Executive Function

Executive function(s) or (EF) is an umbrella term subsuming a breadth of heterogeneous cognitive functions ranging in complexity, from simple core cognitive skills involving self-regulatory and WM systems to more complex functions such as engaging in goal-directed behaviours, reasoning, problem-solving, and decision-making (Diamond, 2015; Diamond, 2013; Anderson et al., 2010; Rabbitt, 2004). As EF covers disparate cognitive activities, definitions of its contained constructs and their boundaries, as well as their complex interrelationships, are subject to debate within the domains of cognitive psychology and neuroscience (Anderson et al., 2010). Consequently, models of EF continue to evolve fluidly with new research.

Notwithstanding, it is generally agreed that the frontal lobe portions of the brain, specifically the prefrontal cortex (PFC), play host to processes of EF, though commonly involving additional areas in a supporting role (Diamond, 2015; Anderson 2002; Baddeley & Hitch, 1974). It is executive activity within this rostral region that is characterised by the ability to consciously control of thoughts, emotions, and actions through the involvement WM and inhibitory functions – regarded the pillars of EF in high-level paradigms, such as Diamond 2013, and each subject to fine-grained definition within models like Anderson (2002), Baddeley & Hitch (1974), Norman & Shallice (1986) – which are able to work in isolation and also in combinations to form complex high order cognitive skills. The executive abilities of humans, though initially primitive, start to develop within the womb before rapidly accelerating as we progress through childhood and adolescence, plateauing as adults, and declining in old age (Anderson et al., 2010).

This chapter presents and explains the notable models, constructs, and relationships associated with EF before explaining how academics have sought to benchmark and train EF. Finally, the promise and problems of current training methods are addressed.

Throughout the chapter design requirements (yellow boxes), design methods (pink boxes), and important methodological concerns (blue boxes) which have shaped the work presented in this thesis are identified.

2.1 Executive Function in Detail

2.1.1 Executive Function Evolution

The origins of prefrontal lobe awareness and pathology can be traced as far back as the mid-nineteenth century, to the story of Phineas Gage (Harlow, 1868). Gage was a conscientious railroad foreman who tragically suffered frontal lobe trauma by way of a tampering rod passing through the front of his skull. Miraculously, however, Gage survived but following his recovery his personality underwent some drastic changes – he became “*profane*”, “*irascible*”, and “*irresponsible*” (Ardila, 2008, p. 93). Though reported with an emphasis on the behavioural effect (this was before cognitive assessment was available), it was an early example of how one’s everyday functioning and behaviour could drastically change because of frontal damage and hinted at the functionality based in this region (Ardila, 2008). Indeed, throughout the 20th Century, frontal lobe trauma was increasingly characterised by impairments in specific functions, many of which are relevant to the EF as it is understood in the present day – such as “*disturbed attention*”, “*increased distractibility*”, and inability to master new tasks or situations. (Wilson et al., 1998; Baddeley, 1986; Rylander & Frey, 1939, p. 22).

EF as a formal concept began with the work of Luria (1976; 1966) when he hypothesized the frontal lobe area of the brain was responsible for controlling and verifying activity and upon further study associated the region with programming motor behaviour, inhibiting immediate responses, abstracting, problem-solving, verbal regulation of behaviour, reorienting behaviour according to behavioural consequences, temporal integration of behaviour, personality integrity, and consciousness. Therefore, even from an early stage the diverse nature of cognitive activity was already hypothesized within the frontal region, with some of Luria’s associations becoming examples of quintessential executive functioning. Following this, during the 1970s, the work of Baddeley and Hitch (Baddeley, 1992; Baddeley & Hitch, 1974) into human memory led to the creation of the ‘Working Memory Model’ (1974), explained in Section 2.1.3.1 (p. 15), and idea of the ‘central executive’ – an attentional system with the power to delegate and coordinate informational processes to other regions of the brain, resulting in intelligent behaviour.

The central executive and other EF models (Shallice, 1982; Stuss et al., 1982; Hecaen & Albert, 1978; Luria, 1973) were unified by the involvement of attention within the ‘frontal lobe’, thus, suggested the responsibility of a single, unitary system. However, the idea of

anatomical localization in early EF models was criticized. For example, the dominant role of the frontal lobe, specifically the prefrontal cortex (PFC), in EF processes is accepted but research has highlighted the involvement of other brain regions (Stuss et al. 2002; Stuss et al., 2000; Goldman-Rakic, 1987). Consequently, EF paradigms have become fragmented over time as relationships between distinct and previously unassociated cognitive processes have been uncovered (Elliot, 2003; Piguet et al., 2002; Anderson et al., 2001; Delis et al., 2001; Hobson & Leeds, 2001; Denckla, 1996; Lafleche & Albert, 1995; Lezak, 1983) and inconsistent correlation of performance on theoretically similar tests of EF has been witnessed (Friedman et al., 2006; Salthouse, et al., 2003; Roberts et al., 2002; Parkin 1998; Burgess & Shallice, 1997; Lehto, 1996). Consequently, it has been suggested contextual and behavioural factors may influence EF (Barkley, 1997), compelling contemporary theorists to take a wider view of the concept. Thus, EF can be thought of as a series of “*separable but moderately correlated constructs*” which involving unitary and non-unitary components (Miyake, et al., 2000, p. 87).

One notable model detailing such an approach is that of Diamond (2013), who denotes core and common EF competencies that form the foundation for much more complex cognitive skills. This model is covered later (Section 2.1.3.4, p. 20) and reflects the approach and understanding of EF adopted throughout this thesis.

2.1.2 Executive Function Subcomponents

The range of EF subcomponents are exhaustive and can be grouped together in different ways depending upon the perspective of individual authors. This thesis takes a balanced view, drawing together definitions from different authors, in explaining some of the most prominent EF skills identified and most relevant to the content of this thesis.

2.1.2.1 Working Memory

Working memory (WM) involves the temporary storage and manipulation of information in one’s mind. It is thought by some, that WM can be separated into two categories – verbal and non-verbal (visuospatial) memory (Diamond, 2013). WM is used to hold in mind historical information and relate it to the present. A simple verbal example could be reciting a previously verbally spoken list in a different order, whereas a simple visuospatial example

could be imaging a previously seen object in a different colour. A more complex example involving both verbal and visuospatial could be holding in mind previously defined plans dictated by a teacher, and relating or mentally applying the most relevant plan to solve a current problem. Note, WM is distinct from short-term memory, simply because short term memory necessitates merely the holding of information in mind without manipulation (Diamond, 2013).

Furthermore, WM and IC (particularly attention) are closely interconnected – highlighted by the similarities of the independent WM (Baddeley and Hitch, 1974) and attention (Posner & Peterson, 1990) models, and emphasized by Diamond (2013). WM and IC (attention) support one another and rarely are they used independently (Diamond, 2013). E.g., one must concentrate and inhibit distraction to successfully calculate a tricky bit of arithmetic – a task in which WM is also inherent. Some authors go as far as to refute the domain-specific (verbal versus visual) representation, in favour of a domain-general understand of WM, which is essentially the product of finite capacity short-term memory stores and an attentional component used to manipulate data (Melby-Lervåg & Hulme, 2012; Kane & Engle, 2002; Engle et al., 1999). Therefore, some believe that WM capacity defines the attentional capabilities of an individual (Melby-Lervåg & Hulme, 2012).

The view adopted in this thesis that WM and inhibition are disparate functions but operate an intrinsic relationship where the use of one subcomponent commonly relies upon the involvement of the other.

2.1.2.2 Inhibitory control

Inhibitory control (IC) describes self-regulatory abilities which allow you to stop yourself from doing something (self-control and discipline), filter and focus attention (selective or focused attention), and inhibit thoughts or memories (cognitive inhibition) (Diamond, 2013; Jurado & Rosselli, 2007). With respect to self-control and discipline, inhibition is an EF associated with motor output, or praxis (Denkla, 1996) – this means that resisting a temptation is as much about motor inhibition as it is about the ‘psychological’ or cognitive aspect of IC (e.g., in the Windows Task: Russell et al., 1991).

Although attention is regarded by some authors to be a separate from inhibition (Kramer & Stephens, 2014) or to be the high-level construct of which inhibition is a sub-part (Anderson, 2002), the imbricate pattern of EF dictates that within some paradigms attention is instead

subsumed by inhibition, such as the influential Diamond (2013) model at the core of this thesis. Regardless, most authors agree attention is a fundamental EF skill and adopt similar definitions of the concept. Being able to select and sustain attention enables us to concentrate on information held in mind and suppress attention to other stimuli e.g. ignoring the background noise of other people's conversations at a cocktail party and concentrate only on one voice (Diamond, 2013). Finally, cognitive inhibition enables us to inhibit unwanted thoughts and memories and empowers us to intentionally forget information that is surplus to our requirements (Diamond, 2013).

We can also relate to the conscious/controlled vs automatic aspect of Norman and Shallice's SAS (Section 2.1.3.2, p. 17) when we consider the inhibition of a prepotent response – this is where one must refrain from undertaking actions and behaviours that would be automatic in any other circumstances (Best, 2014; Best & Miller 2010).

2.1.2.3 Cognitive Flexibility, Set Shifting

Cognitive flexibility and set-shifting, involve the ability to shift attention between alternative thoughts or actions contingent upon changes in one's environment which require new demands, rules, or priorities (Diamond, 2013; Frye, Zelazo & Palfai, 1995; Heaton, 1981). Failure to do this results in mental inflexibility – perseveration of unsuccessful or inappropriate actions, in addition to difficulties in regulating and modulating motor outputs (Hill, 2004). Cognitive flexibility is closely related to both creativity and develops within adolescence (Diamond, 2013). It enables an individual to adjust their actions, their spatial and interpersonal thoughts and perspective – e.g. reflecting upon a problem using hindsight.

5 unique methods of set shifting have been identified. All involve attending to stimuli and dynamic rules but their use depends on the type of information between which attention must be switched:

1. Location shifting – individuals are given a shifting and a non-shifting condition and must spatially locate objects attributed to each (Kramer & Stephens, 2014; Wager et al., 2004). Individuals often must switch between shifting their spatial attention between multiple locations and sustaining attention on one location (Thakral et al., 2009).
2. Attribute shifting – individuals must differentiate between object attributes e.g. colour and shape (Kramer & Stephens, 2014; Wager et al., 2004)

3. Rule switches – individuals must disregard previous responses to comply with an update of, or new, rules (Kramer & Stephens, 2014; Wager et al., 2004)
4. Object switches – individuals must switch attention between stimuli of importance and those of insignificance (Kramer & Stephens, 2014; Wager et al., 2004)
5. Task switches – individuals must alternate between two or more different tasks using the same stimuli (Kramer & Stephens, 2014; Wager et al., 2004)

2.1.2.4 Planning / Strategizing

High-level or cognitive planning (referred to as ‘strategizing’ throughout this thesis) may be defined as the ability to organize cognitive behaviour in time and space and is necessary in situations where a goal must be achieved through a series of intermediate steps each of which does not necessarily lead directly towards that goal (Owen, 1997). Cognitive planning is needed to sequence and generate solutions to problems or when novel courses of action are implemented (Owen, 1997). Hence, planning evokes goal-directed behaviour, by breaking down the steps needed to complete a goal (Kramer & Stephens, 2014) and the ability to do so may account for poor problem-solving ability (Boyle & Boyle, 2015). Research has strongly associated the ability to plan with certain frontal lobe regions, and, thus, it is regarded as a quintessential example of executive behaviour, believed to have a close relationship with WM (Owen, 1997), in addition to abstract reasoning and attention (Kramer & Stephens, 2014).

2.1.2.5 Multitasking

Multitasking can often be misinterpreted due to the varied and indistinct usage of the term. In much mainstream research, multitasking takes the meaning of ‘media multitasking’ or ‘media stacking’ which involves prioritizing information presented from multiple stimuli (Ophir et al. 2009). Perhaps the best way of summarizing this literature is the well-known (at least the English translation) Japanese proverb, Ni usagi wo ou mono wa ichi usagi wo mo ezu (One who chases after two hares won't catch even one) – thus, in trying to do two things at once, you will fail in both.

However, from a neuropsychology perspective ‘multitasking’ concerns how we interleave subordinate tasks into a superordinate task within a time limit (Rajendran et al., 2011). Thus, it really involves rapid and coordinated task switching (or set shifting) than chasing two

hares at once. One example identified by Crail and Bialstok (2006), is cooking as to complete the superordinate task or output (your delicious meal), one must time manage switching between several sub-tasks (chopping vegetables, beating eggs, boiling rice).

2.1.2.6 Fluency / Generativity

The concept of fluency, also known as generativity, is related to planning/strategizing but concerns the formation of the maximum range of feasible plans or strategies without repetition (Kramer & Stephens, 2014). Hence, we can describe fluency as the ability to generate or initiate an appropriate idea (Turner, 1999).

2.1.2.7 Self-monitoring

Self-monitoring is the internal process that involves self-examination of cognitive and emotional functioning. It is through self-examination that cognitive processes and emotional responses are adjusted in each situation, making it difficult to measure (Kramer & ML Stephens, 2014). Indeed, the regulation of emotions subsumed by self-monitoring is an area executive control often overlooked within clinical EF measurement (Ardila, 2008).

2.1.3 Key Models of Executive Function

2.1.3.1 Baddeley and Hitch – Working Memory Model (1974)

Perhaps the most influential early EF model was proposed in 1974 by Baddeley and Hitch when they realized the vital role performed by short-term memory in performing complex tasks. They noted that information held within short-term memory often must be manipulated or temporarily maintained while additional processes are undertaken e.g. during mental arithmetic. Understanding that such processes may occur with both qualitative and quantitative information, they coined the term ‘working memory’ to describe the mental gymnastics involved. In later contributions from Baddeley, the construct of WM was partitioned into the 4 following components:

1. The central executive – an attentional system (like the SAS proposed by Norman and Shallice, 1986)

2. Phonological loop – processes and stores information temporarily in a phonological or speech based format e.g. preserve spoken words in the order in which they were delivered
3. Visuospatial sketchpad – provides manipulation and temporary storage of spatial and visual information e.g. maintaining a finely detailed picture of one’s surroundings such as colour and shape of objects
4. Episodic buffer (Added in Baddeley, 2000) – temporarily stores and can integrate information coming from the visuospatial sketchpad and phonological loop

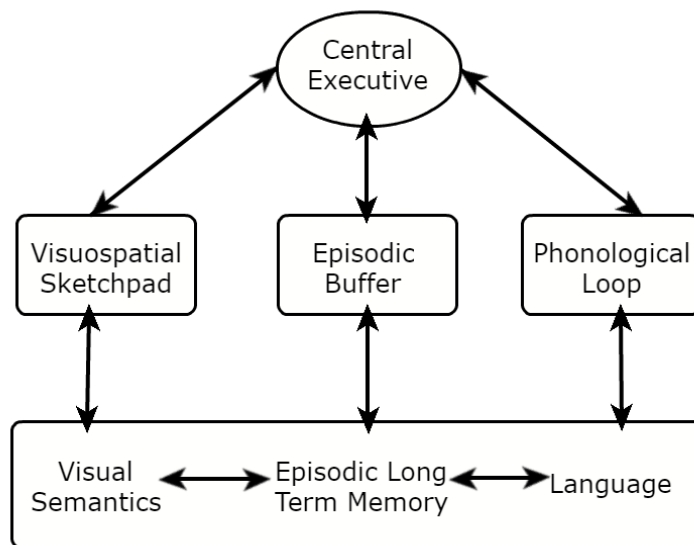


Figure 1: Baddeley (2000) Working Memory Model

At the core of the model is the idea of the central executive – an idea still reflected in contemporary EF models, which can be thought of as ‘attention’, and assumes the role of conductor within the frontal lobes, delegating relevant processes to the phonological loop and visuospatial sketchpad, and coordinating the flow of information within the brain. Robbins et al. (1996) illustrated the use and coordination of multiple WM components by showing, to a degree, two tasks can be performed at once provided they are of a different nature – the phonological loop and visuospatial sketchpad may only be able to handle one process each. This example also highlights the capacity limited nature of WM. Furthermore, the central executive can coordinate the cognitive processing of information and to integrate different data sources to perform increasingly complex cognitive behaviour, such as

reasoning, planning, and goal setting, via the episodic buffer (added to Central Executive model in 2000) and communication with long term memory.

Design Requirement:

The game should necessitate the use of WM in its challenge as it is a core EF which forms the basis of more complex skills.

Design Method:

To challenge WM, game activities involve temporary storage and manipulation of spatial, visual or auditory information.

2.1.3.2 Norman and Shallice – Supervisory Attentional System (1986)

Norman and Shallice (1986) also contemplated attentional systems, developing the Supervisory Attentional System (SAS) which drew parallels with the central executive model and was also endorsed by Baddeley (1986). In the SAS attention plays a role in understanding our world and determining our actions and behaviour. SAS references previous work regarding the distinction between resource-limited and controlled cognitive activity and automatic cognition (e.g. Shiffrin & Schneider, 1977). Echoing the theorized prerequisite of novelty in the engagement of EFs (Rabbitt, 2004), the SAS states activities which initially require a conscious and controlled response (attention), may eventually become so well practiced that they no longer require attention and become autonomous. An additional conscious element is involved in the following:

1. Tasks which involve planning or decision-making
2. Tasks which involve components of troubleshooting
3. Tasks which are ill-learned or contain novel sequences of actions
4. Tasks which are judged to be dangerous or technically difficult

5. Tasks which require the overcoming of a strong habitual response or resisting temptation

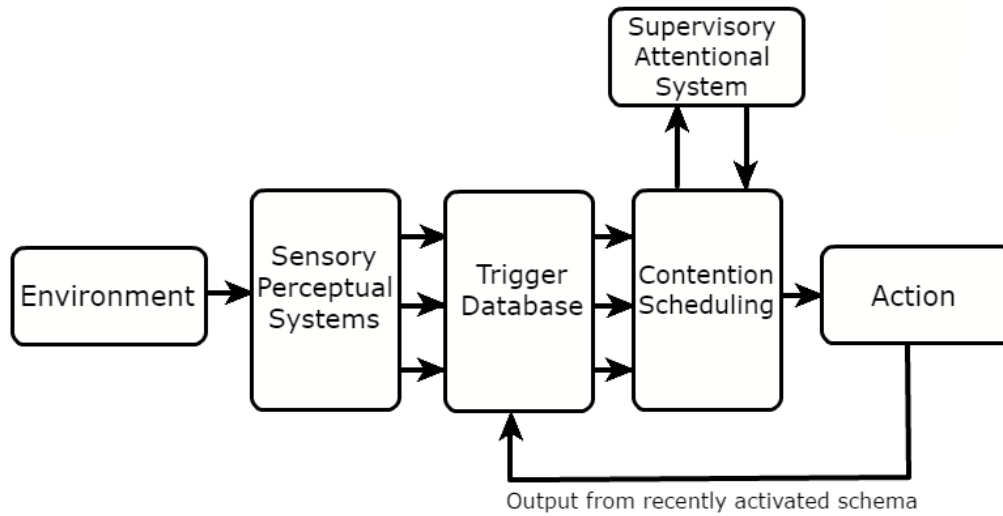


Figure 2: Norman and Shallice (1986) Supervisory Attentional System

Hence, the authors put forward a model to account for the ability to run automatic sequences but enable deliberate conscious control processes to intervene when needed. The model represents autonomous process as ‘schemas’ – a library of cognitive scripts of learned mental and physical responses associated with perceptual stimuli e.g. if it starts to rain (perceptual stimuli), put your hood up (schema). However, in situations for which there is no associated schema or several alternative schemas from which to choose, the SAS steps in, using a method called ‘contention scheduling’ to prioritize one schema over another or formulating a novel schema based on the solutions to similar problems (Anderson et al., 2010).

Design Requirement:

The game should involve (1) planning or decision making, (2) problem solving, (3) requiring a novel sequence of action, (4) challenge, (5) overcoming strong habitual response or temptation.

2.1.3.3 Anderson – Executive Control System Model (2002)

As early executive control models evolved, thinking moved away from a unitary structure and towards the decentralization of the executive component. One such model was offered by Anderson (2002) which defined four inter-correlated but dissociable components of EF (Boyle & Boyle, 2015): attentional control, information processing, cognitive flexibility, and goal setting.

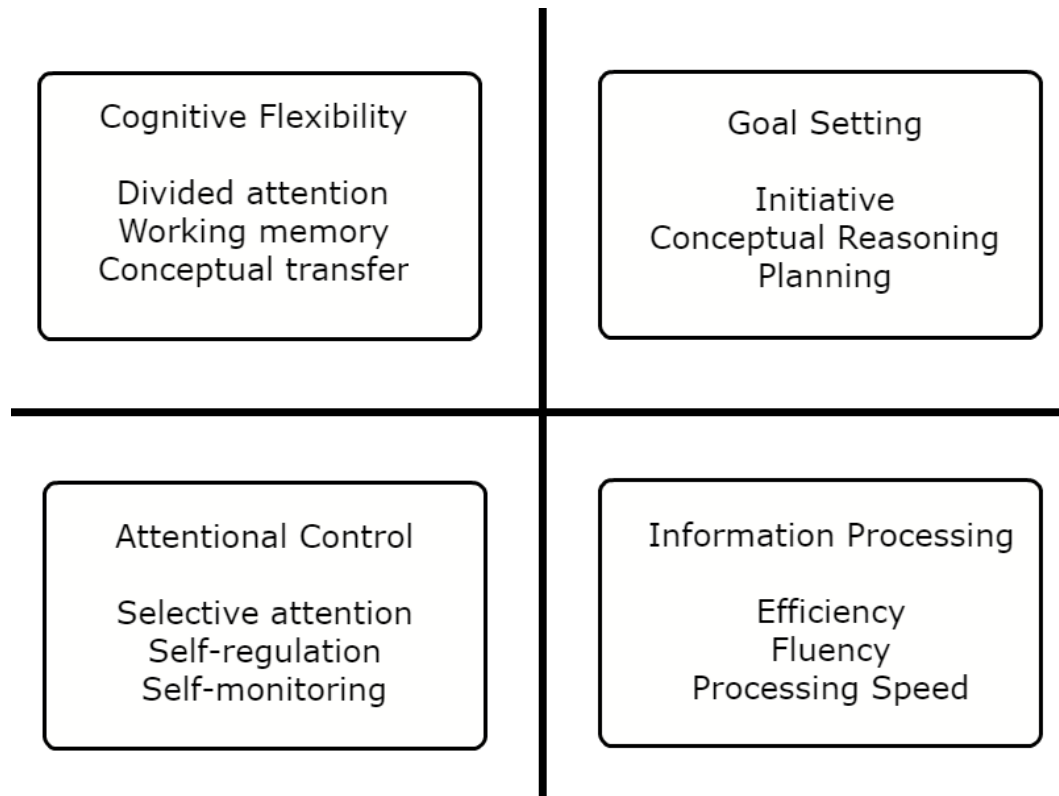


Figure 3: Anderson (2002) EF Model

1. Attentional Control Components – this collates aspects of inhibition and self-monitoring. They include selective attention (focusing on specific stimuli and focused attention over time), self-regulation and self-monitoring (initiation of actions/processes, monitoring, and termination of action/processes), inhibition (of information and pre-potent responses (Anderson, 2002).
2. Information-Processing Components – this refers to reaction speed following a stimulus (Boyle & Boyle, 2015).
3. Cognitive flexibility – Anderson (2002) produces a similar interpretation of cognitive flexibility which makes use of WM, and some attentional processes in doing so.

4. Goal-Setting Components – in other models (i.e. Section 2.1.3.4, p. 20) goal-setting is included as an aspect of planning, but in the Anderson (2002) model goal-setting is the parent type for EFs such as planning, reasoning, and coordination of strategies.

Design Method:

Making a task's goals clear can help to elicit planning, reasoning, and strategizing skills.

2.1.3.4 Diamond – Executive Function Model (2013)

Adele Diamond's research in EF since the 1980s has defined how EFs emerge and develop, the biological processes underlying the concept, and its applications beyond neuroscientific settings and into the real world – including health, PA, social behaviour, quality of life, and academic outcomes. As noted by Boyle and Boyle (2015), Diamond's view of EF is wide and expansive. Hence, her work is influential and a solid base of knowledge to build upon for the interdisciplinary research presented in this thesis where EF is evaluated through the lens of real-world outcomes.

Diamond's 2013 model of EF builds upon the present-day views of many other contributors, particularly the work of Miyake (2000; 2009), by considering a series of individualized high-level functions which draw from the same pool of underlying lower-level functions. Hence, it balances disputed schools of thought around whether EF is a unitary construct. Diamond defines EF as, “*a family of top-down mental processes needed when you have to concentrate and pay attention, when going on automatic or relying on instinct or intuition would be ill-advised, insufficient, or impossible*” (Diamond, 2013, p. 136), therefore, subscribing to the SAS idea of EF involvement only in conscious behaviour. Diamond's model proposes a hierarchical structure of EF with WM and IC modules at the fundamental level, cognitive flexibility as a product of both modules, and higher order functions, drawing from combinations of one or many of these ‘core’ skills. For example, we can assume that a higher order function, such as planning might require the use of WM, IC, and cognitive flexibility.

Diamond's representation of the core EFs appears far less fragmented than other authors. Inhibition is defined as, controlling one's attention, behaviour, thoughts, and/or emotions to override a strong internal predisposition or external lure but she assumes a wide remit which

includes inhibition of attention as well as of action and thought – which she defines as self-control; selective/focused attention; and cognitive inhibition, respectively. Accepting the disparate nature of these subcomponents (Nigg, 2000), she explains attention and motor control appear, “*to share substantially similar neural bases*” (Diamond, 2013, p. 141; Cohen et al. 2012; Best & Miller, 2010; Bunge et al. 2002). Diamond also explains IC develops a more of a prolonged pace in comparison to other EFs, and is a much harder skill for young children than adults, before rapidly declining in old age (Anderson et al., 2010; Best & Miller, 2010). Diamond draws on the Central Executive (1994) in representing WM, describing it as involving “*holding information in mind and mentally working with it*” (Diamond, 2013, p. 137), comprised of visuospatial and verbal WM, and fundamental to reasoning ability. Although Diamond regards WM a distinct construct from IC, she accepts the lock-step relationship between the different skills, and support of one another (Diamond, 2013). In addition, she accepts that selective attention and cognitive inhibition could easily be categorized within WM, such is the overlap (Diamond, 2013). Her definitions of IC, WM, and cognitive flexibility (explained in Section 2.1.3.4, p. 20) have been adopted in this thesis.

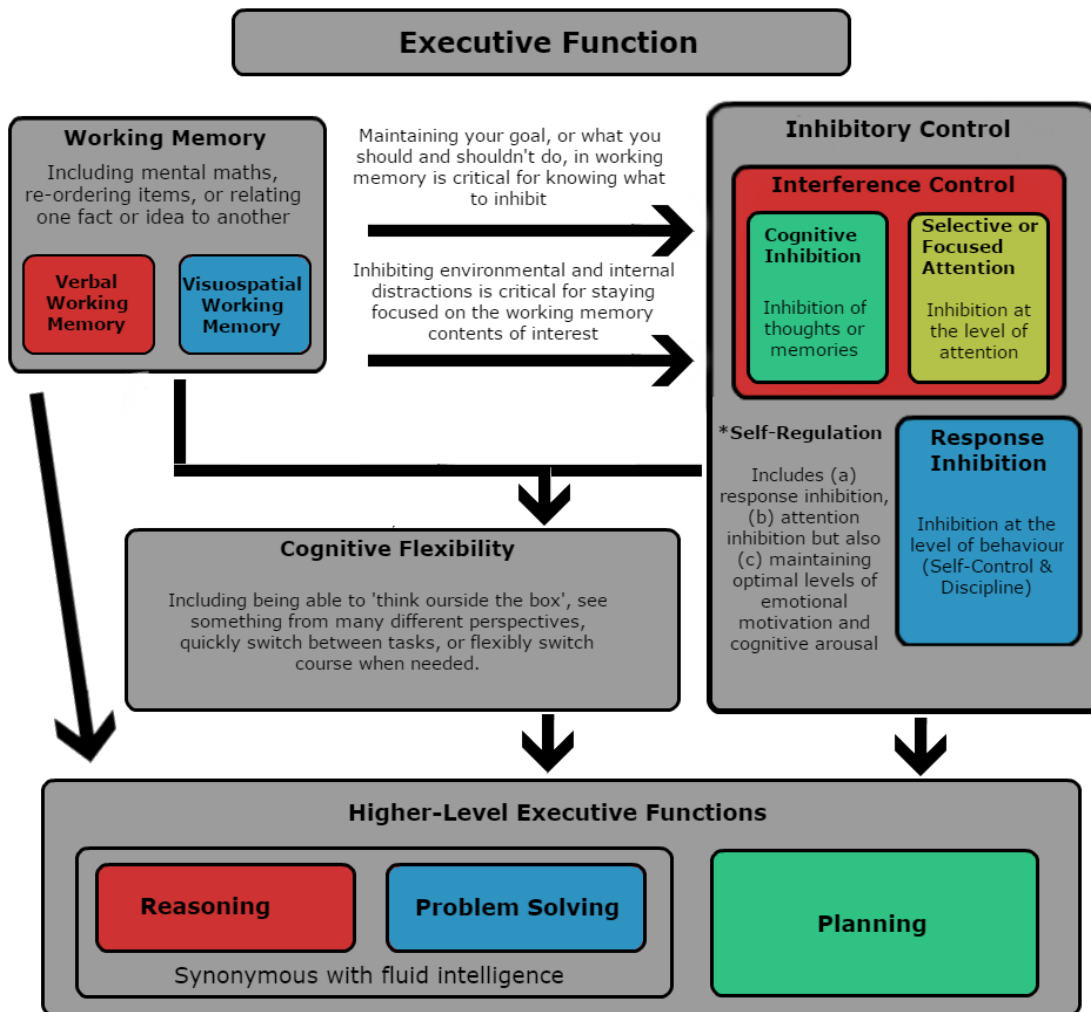


Figure 4: Diamond (2013) EF Model

Design Requirement:

The game should create situations requiring IC because they are particularly challenging for children.

2.1.3.5 Diamond – Executive Function Building Model for Interventions (2012)

Diamond has written several reviews which collate the different programs and interventions designed to benefit or train EF and discusses their impact upon their associated field. The programs and interventions have focused on the following fields:

- Computerized training
- Physical Activity
- School Curricula

Diamond (2012) evaluated contributions from each of these areas regarding their capacity for promoting children's EF and defined a series of conclusions to inform future EF training programmes:

1. Those who most need EF improvement benefit the most:

Children with the weakest EFs benefit the most from training programs and intervention and can be used to level the playing and minimize social inequalities in health and academic achievement (Flook et al. 2010, Karbach & Kray, 2009, Lakes & Hoyt 2004).

2. Generalizability of transfer effects from EF training vary:

EF training can facilitate transferal – benefiting performance in activities beyond the training intervention – but computerized training appears to be narrow (Bergman Nutley et al. 2011), thus, allowing for only near transfer e.g. training of WM may only benefit performance upon activities which have a dominant WM component and no other EFs – explored further in Section 2.3.3 (p. 36). On the other hand, programs taking a more holistic and general view of EF (training a wider range of functions), such as traditional martial arts (Lakes & Hoyt 2004) and school curricula (Raver et al. 2011, Riggs et al. 2006), have seen improvement upon simultaneous measures of EF and to untrained tasks (Karbach & Kray 2009).

3. The limit of children's EF ability should be tested by training challenges:

As children's EFs improve, training demands must increase to preserve the challenge and by extension, the child's interest in the activity (Davis et al. 2011, Diamond et al. 2007, Bergman Nutley et al. 2011, Holmes et al. 2009, Klingberg et al. 2005) – this draws parallels with theories of intrinsically motivating activity in Chapter Three (Section 3.3, p. 78). Moreover, previous training studies have shown the largest differences between control and intervention groups to be consistent with the most demanding challenges of EF – *“it is often*

only when the limits of children's EF skills are pushed that these differences emerge"
(Diamond, 2012, p. 337).

4. Repeated practice is key:

EF gains appear to depend on upon the practice time committed to such skills (Klingberg et al. 2005). In doing this Diamond advocates that EF training should be varied and embedded in different activities to maintain children's interest – something true of many activities, such as video games (Section 2.3, p. 36).

5. PA should emphasize character development and self-control:

According to Diamond, coupling aerobic activity with a cognitively engaging task is more beneficial than either approach unilaterally (Diamond, 2015; Best, 2012). E.g., exercise with an emphasis on character development or self-regulation, such as taekwondo, showed improvement upon all dimensions of IC (e.g., cognitive IC, measured on a distractible–focused continuum; discipline, measured on a quitting–persevering continuum; and emotion regulation) in comparison to a standard PE control group (Lakes & Hoyte, 2004). This is addressed in more detail during Section 2.4 (p. 57).

Design Requirements:

1. *The game should have a holistic structure, targeting many different EFs in different ways and utilizing established training techniques.*
2. *The game should include 'cognitively engaging PA' which involves the regulation of emotion, thoughts or action.*
3. *The game should encourage repeated use as it is key to making EF improvements*

Design Method:

Task demands should be incrementally increased to continue to challenge EF ability.

In addition to these principles, Diamond (2011; 2012) notes the common features deployed within existing alternative curricula which have been shown to improve EF children – Tools of the Mind, Montessori, PATHS (Riggs et al., 2006), which are covered in more detail in Section 2.2.3 (p. 38). These principles state EF training programmes should: (a) help children exercise their EFs and constantly challenge them to do so at higher levels; (b)

reduce stress in the classroom; (c) rarely embarrass a child; (d) cultivate children’s joy, pride, and self-confidence; (e) take an active and hands-on approach to learning; (f) easily accommodate children progressing at different rates; (g) emphasize character development, as well as academic development; (h), emphasize oral language; (i) engage children in teaching one another; and (j) foster social skills and bonding (Diamond, 2012; Diamond & Lee, 2011).

Following the identification of these principles, Diamond offers a model to predict the success of future programmes and interventions. This model has formed the basis to the EF training exergame developed and documented in this thesis. As such this is the model upon which our exergame is compared and evaluated against.

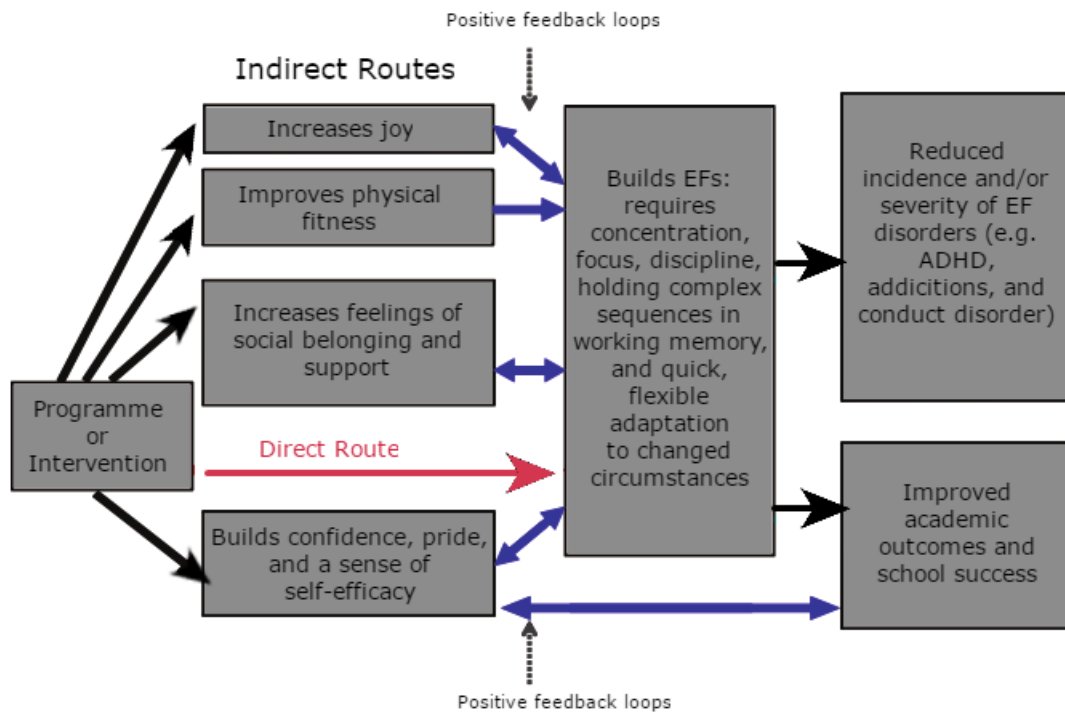


Figure 5: Diamond (2012) Ideal EF Intervention Model

Diamond states emotional, social or physical needs to be fundamental predictors of EF and PFC performance. Therefore, she hypothesizes that the most beneficial EF interventions will directly challenge EFs and support them indirectly by reducing stress, increasing joy, fostering feelings of social belonging, and improving physical fitness (Diamond, 2012).

Chapter Five (and Appendix A in further detail) explains the relationship between the model presented and game design decisions.

Design Requirements:

1. *The game should support EF by cultivating children's pride, confidence, and self-efficacy.*
2. *The game should involve social activities testing emotional regulation to promote character development.*

Design Method:

To encourage positive social interactions and challenge EFs, cooperation should be focused towards children helping or teaching each other.

2.1.4 Addressing criticisms of Executive Function

As stated, early unitary conceptualizations e.g. the SAS and Central Executive faced criticism for representing EF as a central command or homunculus for complex cognitive skills (Parkin, 1998). While no doubt valid, evolving EF paradigms have addressed this argument by the compartmentalization of a single unitary system into several subsystems (Shallice et al., 1996). Although dominated by the PFC, exercising EF likely involves networking with other regions of the brain in the coordination of lower-level cognitive processes. This principle is taken into consideration within the design of various EF assessment batteries, which are comprised of several subtests each seeking to capture several overlapping skills, rather than just a through a unitary test.

Another general criticism is the idea of EF as some form of homunculus within the brain to be infinitely broken apart into sub-functions and sub-homunculi (Zelazo & Muller, 2002). While it may be true that the activities encapsulated within executive control systems can be hard to measure and definitions can at times be somewhat convoluted, it may only be by breaking down recognized constructs, we truly understand how the components fit together. Moreover, models of EF proposing both unitary and distinct functions, by authors such as Miyake (2009; 2000), Anderson et al. (2010; 2000), and Diamond (2013), may have put an

end to infinite fractioning and emphasised the need to better understand the relationships between existing functions.

2.1.5 Executive Function and Novelty

EF is most commonly used in novel situations where one cannot rely on a pre-learned automatic response (Anderson et al., 2010; Rabbit, 2004). Hence, many tests of EF necessitate a degree of novelty, which is almost certainly diminished or even lost following repeated exposure to the same circumstances (Anderson et al., 2010), thereby creating test-retest challenges with respect to EF assessment – such as those of the BADS-C, outlined in Section 2.5.2 (p. 62). So how might it be possible to train EF over long periods using repeated measures? The answer may lie in understanding how responses to situations requiring EF become learned and autonomous over time.

Burgess (1997) believes that novel tasks challenge EF most effectively when first attempted by an individual before becoming progressively less challenging at each subsequent encounter, though the same task may nevertheless become a novel challenge of EF in a different context with different demands. This comes from the mental processes one uses to fine-tune a novel task becoming increasingly efficient and readily usable at each attempt, and this results in a shift in the response – from being self-regulatory (conscious or controlled) to being automatic (Anderson et al., 2010; Rabbit, 2004) e.g. mediated by the SAS. Such theories are supported by neuroimaging studies which have shown that as task practice increases, activity in the PFC and other EF associated areas decrease, suggesting liberation from executive control (Luu, Tucker, & Stripling, 2007; Chein & Schneider, 2005). However, the automaticity of a previously learned task may be disrupted and once again require conscious behaviour, if the task demands are changed significantly (Jurado & Rosselli, 2007; Rabbit, 2004).

This theory applies itself well to a driving analogy, such as learning to drive routes so often that they become automatic (the feeling of driving home from work, being on ‘autopilot’, without having to ‘think’ about the route). In contrast, drivers may be less experienced at driving on unfamiliar roads or surface types after learning to drive in the city. So, the change in task demands may invoke an executive system to intervene – automatic actions may now require self-regulation and other EF skills to adapt to the situation.

Therefore, it seems reasonable to hypothesize the maintenance of task novelty, and therefore the challenge to EF, might be possible by significantly updating task demands to keep the task at the cusp of one's ability.

Design Method:

To preserve novelty challenge, change task demands to disrupt pre-learned solutions and effect re-planning of actions.

2.1.6 Open-ended vs Constrained Tasks

Tasks of EF may also be classed as being 'constrained' or 'open-ended' (White, Burgess & Hill, 2009). Constrained tasks give individuals clear structure and rules to follow and often isolate individual EFs but do not often reflect real life – regarded as lacking ecological validity (Kenworthy et al., 2008; Burgess et al., 2006). Notwithstanding, constrained tasks can consistently measure some of the lower order EFs, such as WM and inhibition.

Examples include the rule shift cards task of the BADS-C (Emslie et al., 2003) and BADS (Evans et al., 1997), the Dimension Change Card Sort Test (Frye et al., 1995), or Wisconsin Card Sorting Task (Heaton, 1981).

On the contrary, open-ended tasks, are less constrained and permit an individual to devise their own solution to a problem or challenge – e.g. the Six Elements Test (6E) (Shallice & Burgess, 1991). Many tasks of this nature tap into combinations of high order EFs, such as planning, reasoning, generativity, and are most sensitive if they hold verisimilitude to real-world activities – we can say open-ended tasks are more ecologically valid (White, Burgess & Hill, 2009). The 6E test was found to be one of the most ecologically valid tests available to clinicians (Burgess et al., 2006). However, open-ended tasks are much more susceptible to poor test-retest reliability in comparison to constrained tasks because of the increased novelty involved (Rabbitt, 2004; Emslie et al., 2003).

2.1.7 Task Impurity

Somewhat related to open vs constrained task is the issue of task impurity. Regardless of ecological validity, some consider the notion that any test of EF can be 'pure' – that a test of

a certain function reflects only the ability of that function in isolation – to be fanciful (Hughes & Graham, 2002). The complexity of standard EF tasks ensures that attempts to isolate the performance individual functions may, in fact, represent the pooled outcome of several specific cognitive processes which may be executive or non-executive (Hughes & Graham, 2002).

For example, when we seek to assess multi-tasking (task switching) performance, we are likely to control for baseline processing speed ability which is a basic non-executive aspect of cognition. Equally if we consider Diamond's 2013 model of EF (Section 2.1.3.4, p. 20) in attempting to isolate a high-order EF such as planning, it is likely to involve elements of less complex EF skills (WM, cognitive flexibility, and IC).

Task impurity is not only an EF-specific problem and other abstract cognitive constructs also encounter these assessment difficulties. E.g., the concept of fluid intelligence (Redick, 2013) – the ability to reason and to solve new problems independently of previously acquired knowledge, overlaps with many complex cognitive skills and includes many EFs (Jaeggi et al., 2008).

In the analysis of cognitive tests, experimenters may have to control for a seemingly endless list of additional cognitive factors (Redick, 2013). Therefore, some authors suggest attempting to correlate the same skills using multiple assessments which differ in terms of context or content (Simons, 2016).

2.1.8 Hot and Cool Cognition

Recently, some authors have dichotomized EF into two broad categories – 'hot' and 'cool' (De Luca & Leventer, 2008; Kerr & Zelazo, 2004). Cool EF is emotionally neutral and elicited by abstract decontextualized problems, used in situations requiring a purely cognitive response such as in planning, exercising motor control to inhibit or regulate certain movements, and decision making based purely upon logic (De Luca & Leventer, 2008; Kerr & Zelazo, 2004). Meanwhile, hot EF is elicited in contexts which are affective, involve emotion, motivation, or the consideration of social factors, and are no longer purely cognitive. Consequently, hot EF most often concerns IC of thoughts and actions (De Luca & Leventer, 2008; Kerr & Zelazo, 2004). It has also been argued that cool EFs correlate with measures of general intelligence, whereas the same cannot be said for hot aspects (De Luca & Leventer, 2008; Kerr & Zelazo, 2004). Nonetheless, both hot and cool EFs may work in

cooperation within real-world situations (De Luca & Leventer, 2008; Kerr & Zelazo, 2004). It raises the question of how representative of real-world EF ability most EF assessments might be given their cool nature and absence of social or moral influences. Hence, inconsistencies between test and real-world performance have been noted (Anderson, 2002; Eslinger & Damasio, 1985).

While, both cool and hot EF may make use of similar subcomponents of EF such as WM and IC, a solid body of neuroimaging research has suggested that hot and cool EF involve different neural circuits, and are believed to develop distinctly, at a different pace which may be influenced by different factors (Kerr & Zelazo, 2004). Thus, one may have better hot EF than cool EF ability and therefore successful decision making may be very contextual and can vary dramatically.

The inclusion of both hot and cool EF is important to consider when designing any EF training programme to be applicable to real-world functioning. Hot EF is tacitly acknowledged in Diamond's 2012 model of EF interventions (Section 2.1.3.5, p. 23) where the author advocates training to elicit and control emotions and behaviour. For example, some of the indirect pathways have the characteristics of emotional involvement – fostering feelings of social belonging, joy, pride/confidence/self-efficacy.

Design Requirements:

- 1. The game should train for real-world relevance by challenging both (emotionally affective) hot and (logical) cool EF.*
- 2. The game should create situations involving hot EF by using rewards, penalties, social implications or personal feelings.*

2.1.9 Development of Executive Function

By one year of age we have already developed, albeit at an elementary level, the most fundamental components of EF before the networked relationships between these functions evolve and increase in complexity throughout our childhood and adolescence (Diamond, 2013). However, this maturation does not happen all at once. Several authors have proposed humans to have many different developmental stages, involving different aspects of cognition which progress at different speeds (Ardila, 2013).

De Luca et al. (2008) produced a structured interpretation of EF development, by fractioning development into 5 stages: Infancy (up to 2 years old); Preschool and Early Childhood (3-7 years old); Preadolescence (8-12 years old); Adolescence (13-19 years old); and Adulthood (20+ years old), and describing each stage with respect to age and the associated anatomical brain development, cold EF development, and hot EF development occurring simultaneously. Relevant to the work in this thesis are the pre-adolescent developmental changes occurring from ages 8-12. With respect to cold EFs, Klimkeit et al. (2004) observed development in sustained attention, selective attention, set shifting, response inhibition and impulsive responding in between ages 8 and 10 years. Moreover, between ages 9 and 12 further development in WM capacity and efficiency (Brocki & Bohlin, 2004), less sensitivity to interference (e.g. confusing old and new information or memories) (Leon-Carrion et al, 2004), and improvements in strategic planning and fluency (Luciana & Nelson, 2002; Korkman et al, 2001). There are also changes in hot EF, such as regulating emotions as children begin to understand social rules (De Luca, 2008; Baron-Cohen et al, 1999). IC is a “disproportionally difficult” task for children (Diamond, 2013, p. 141).

Design Requirement:

The game should target ages 8-12 – a critical age range for inhibitory, WM, and strategic EF skills as well as social skills.

2.2 Executive Function, Quality of Life and Education

2.2.1 Importance of EF to Quality of Life

Although the complex relationships and structural paradigms of EF remain under iterative refinement, current representations portray a concept both definable and measurable and permissible to study beyond the laboratory in the real world. It is increasingly acknowledged that EF development may be influenced by more than just genetics, physical trauma, or quality of education (Diamond, 2013). Family and other social factors, as well as one’s environment can also be influential.

As described in Table 1, EF is associated with a range of serious quality of life outcomes, where those with good EF ability are more likely to have good mental and physical health,

achieve more academically, earn a higher income, enjoy better relationships, integrate into society, and enjoy greater life happiness. Consequently, the importance of EF is relevant to all walks of life and is of greatest importance to young children where EF abilities can predict future life success. This section explores some of the ways in which researchers have sought to try and improve EF, particularly in children, to combat the potentially grievous implications of EF weaknesses.

Aspect of Life	Association with EF	Refs
Mental Health	Weak EFs are associated with: Addictions Depression Attention Deficit Hyperactivity Disorder (ADHD) Obsessive Compulsive Disorder (OCD) Conduct Disorder Schizophrenia	Diamond et al. ,2013,2011, 2005; Fairchild et al., 2008; Penad'es et al. 2007; Taylor-Tavares et al. 2007; Lui & Tannock 2007; Baler et al., 2006; Barch 2005
Physical Health	Weak EFs are associated with: Obesity and overeating Substance abuse Poor treatment adherence	Diamond et al. ,2013; Crescioni et al., 2011; Miller et al., 2011; Riggs et al., 2010
Quality of Life	Strong EFs are associated with a good quality of life	Brown et al., 2010; Davis et al., 2010
School Readiness	EFs are more important for school readiness than are IQ or entry-level reading or math	Morrison et al., 2010; Blair & Razza, 2007
School Success	EFs predict both math and reading competence throughout the school years	Borella et al., 2010; Duncan et al., 2007; Gathercole et al., 2004

Job Success	Weak EFs lead to poor productivity and difficulty finding and keeping a job	Bailey, 2007
Marital Harmony	A partner with weak EFs can be more difficult to get along with, less dependable, and/or more likely to act on impulse	Eakin et al., 2004
Public Safety	EFs lead to social problems (including crime, reckless behaviour, violence, and emotional outbursts)	Broidy et al., 2003

Table 1: EF & Life Outcomes – Diamond, 2013

2.2.2 EF and Education

Within education, EF has been linked strongly to academic success across all developmental stages, from preschool to high school. However, previous literature has been weighted towards the significance of EF for young children, with EF a better predictor of school readiness than IQ (Diamond, 2007) and self-regulatory control positively associated with positive self-directed classroom behaviour (Ponitz et al., 2008; Saracho & Spodek, 2007; Brook & Boaz, 2005; Howse, et al., 2003; Blair, 2002), while EF deficiencies seem detrimental to academic achievement (Dalziel et al., 2015; Vitaro et al., 2005; Green & Francis, 1988).

EF has also been associated with fundamental skills required throughout a child’s academic career, such as maths and reading abilities which appear strongly influenced by WM and IC (Dalziel, Boyle, Mutrie, 2015; Booth, 2014, 2009; Diamond, 2013, 2007). For example, a skill linked closely to IC, namely phonological awareness (which enables us to blend and fraction components of sound and syllables) has been shown highly transferable to both reading and writing (Dalziel, Boyle, Mutrie, 2015; Blair & Razza, 2007). Furthermore, Rhodes, et al. (2016) demonstrated the association between visuospatial WM ability and performance in Chemistry.

Despite the association between core EFs, WM and IC, and academic outcomes, only a few studies yielding equivocal results have sought to consider the importance of more

sophisticated EFs. Two studies reported a relationship between academic performance (maths and reading ability) and higher-order EFs (using the Tower Task) (Bull et al., 2008; 2001). Another study associated higher-order EFs and structured report writing ability in children aged 8-9 after controlling for the involvement of individual core EFs (Altemeier et al., 2006). Furthermore, Naglieri et al. (2004; 1997) found a moderate correlation between the CAS Planning Scale (a task involving 3 EFs) and academic achievement. Despite this, a link between high order EFs and academic ability has eluded other researchers (Cohen, et al., 1995). Consequently, this has led some to investigate whether EF is domain specific to certain subjects or skills and for which ages it is most importance (Best et al., 2011).

Best et al. (2011) built upon the work of Naglieri et al. (2004) by comparing the performance on an academic test (Woodcock–Johnson Tests of Achievement, WJ-R), comprising 9 assessments of reading and mathematics skills, with performance on 3 EF-based CAS subtests with children aged between 5 and 18 years (n=1395). They found significant correlations ($p < 0.01$) between complex EFs and all WJ-R subtests across all ages and domains after correcting for multiple tests (Bonferroni correction). The strength of each correlation was influenced by the age of the children and the subtest but was commonly assessed as moderate to moderate-large. Hence, EF is pertinent to more than one core academic skill but there was variability of correlation between EF and skills within each domain. E.g., within mathematics, EF was most closely related to problem-solving questions. Thus, the authors state that the EF training could be beneficial to academic disciplines “*where strategy creation and implementation is needed*” (Best et al., 2011, p. 335).

The importance of EF within educational contexts also extends to tacit (or learning to learn skills) and behavioural skills required within and beyond the classroom. For example, individuals may be capable of conceptualizing learning content but struggle to exhibit knowledge due to EF deficits concerning planning, setting goals, prioritizing, initiating tasks, organizing materials and information, time management, reflecting upon work, and switching between different activities (Meltzer, 2007). Moreover, these children may face social learning challenges as difficulties in emotional and behavioural regulation may lead to failed peer interactions and ostracisation from the school community (Meltzer, 2007). Issues such as these can cause children with EF disadvantages to fall behind year upon year and have been associated with high dropout rates (Diamond et al., 2007).

2.2.3 Curriculum-based EF Training Methodologies

The promise of EF training in education has been echoed by Diamond who reports on different curricula designed to encourage the development of executive skills – e.g. Tools, PATHS, and Montessori. One example, Tools of the Mind (Tools), is a full curriculum for preschool and nursery aged children which emphasizes the importance of social play in the development of EF (Diamond & Lee, 2011). Indeed, social skills are linked closely with EF ability within and beyond education, and concern the regulation of behaviours required within learning (Vitiello, 2009).

In Tools, EF training is interwoven into academic activities and enable children to take part in role playing games where they must exercise at least the 3 core as well as higher order executive skills (Diamond & Lee, 2011), e.g. inhibiting breaking character, remembering other people's roles, flexible improvisation. Accompanying the role-playing exercises are scaffolding visual cues to help support EF (e.g. supporting IC by drawing a child an ear to remind them to listen), and incrementally these scaffolds are removed as EF is perceived to improve, keeping children at the cusp of their abilities. Children undertaking the Tools programme have been found to outperform others enrolled in a high-quality traditional curriculum on several measures of EF where both curriculums covered the same content but Tools delivered in the settings of play whereas the traditional curriculum was instruction centred (Diamond & Lee, 2011).

An alternative method which mitigates the costs and time requirements of full curricula change are add-on curricula programs like PATHS (Promoting Alternative Teaching Strategies) (Diamond & Lee, 2011) which is now incorporated into the curriculum of 110 (PATHS, 2017) UK primary schools. PATHS trains teachers in strategies to help facilitate the EF development of their pupils (aged 3-12) in competencies such as self-control, recognizing and managing feelings, and interpersonal problem solving (Diamond & Lee, 2011). Teachers are encouraged to create opportunities for the children to exercise EF skills in different contexts throughout the school day (Diamond & Lee, 2011). In one study, following a year of PATHS incorporated education, 7- to 9-year-olds showed better IC and cognitive flexibility than control children (Diamond & Lee, 2011). In another, PATHS helped two groups of children, aged 5-8 and 9-12 respectively, be more aware of their emotional states, better understand social conflicts, provide more competent responses to peer problems (Diamond & Lee, 2011).

Despite these promising programmes, many teachers still receive little instruction on how to promote EF, leaving students with underlying EF deficits disadvantaged academically. Consequently, we need to find additional strategies for promoting EF development in schools. However, as Diamond (2012) states, EF training is most effective when it is undertaken throughout the entire day and EF training should not just cease beyond the school gates. The remainder of the chapter outlines additional EF training approaches which can be used both within and beyond educational settings.

2.3 Executive Function, Videogames, and Cognitive Training

2.3.1 Overview

This section begins by presenting evidence of a relationship between video gaming and cognition (including EF) before introducing cognitive training games (CTGs) – a genre of game specifically designed to train cognition. The work presented in this thesis, including the game described and evaluated in later chapters, is particularly relevant to the field of CTGs. Thus, a critical review of CTGs is provided which gives an overview of notable games and their research highlights before addressing the shortcomings of their work and methodological barriers to quality evaluation.

2.3.2 Action Video Games

There is evidence that EF and general cognition can be successfully trained through commercial and academic computer tools and games. Even computer games designed solely for entertainment purposes have indicated cognitive benefits, like action video games – a popular genre that features fast moving objects, often transiently visible, and can present several objects requiring scheduled monitoring (Green et al., 2012). Green and Seitz (2015) note action video games improving both low-level cognition (perceptual and processing skills) as well EF associated abilities, such as attention and fluid intelligence – a term used to describe a range of high-level cognitive skills, including many EFs. It is hypothesized that processing and perceptual improvements, like temporal processing (responding quickly to stimuli); contrast sensitivity (discerning colour differentiations); and visual activity

(discerning features), may be a result of repeatedly filtering fluid and information rich images common in action video games (Green and Seitz, 2015).

Likewise, fundamental EFs like attention and WM may also benefit. Attention may be demanded while switching between situations requiring intense focus and others exacting selective attention or suppression of stimuli (Green & Seitz, 2015). However, given the close relationship between attention and WM, situations requiring one construct may often involve the other (Diamond, 2013). E.g., WM and attention may be used together in many circumstances during action video game play – mentally manipulating objects, organizing and rapidly switching between tasks, anticipating and planning for game environment changes and intermittently updating projections (Green and Seitz, 2015; Strobach et al., 2012; Feng, 2007). These circumstances are consistent with complex EF involvement and, consequently, improved multitasking (task switching) abilities have been found following AVG play in several studies (Green et al., 2012; Strobach et al., 2012; Colzato et al., 2010). Task switching is often measured by the ‘switch cost’ - *“reaction times are typically faster on a given task if the previous trial was the same task rather than a different one, with the difference in reaction time between these two situations being referred to as the switch cost”* (Green et al., 2012, p. 984).

A series of 4 experiments undertaken by Green et al. (2012) showed action video game players to perform significantly better on tests of task-switching (multitasking) ability after accounting for baseline differences in reaction time. Furthermore, the abilities generalized:

- N=18: From a test eliciting manual responses onto arbitrary game controller buttons (the same controller as the action video game) to vocal responses describing switching activities ($t(1,16) = 3.85, p < .001, \text{Cohen's } d = 1.94$)
- N=28: From perceptual tasks (like different colours and shapes) to cognitive tasks (like odd and even numbers) ($t(1,22) = 2.350, p = 0.028, \text{Cohen's } d = 1.002$)
- N=32: Between goal (e.g. attend to colour and shape) and motor switching (e.g. the physical responses undertaken) ($F(1,24) = 4.2, p = 0.05$). Therefore, indicating potential transfer between different task contexts.

Nevertheless, the use of action video games as a vehicle for training has been less successful. In the final experiment reported by Green et al. (2012), following 50 hours of play with action video games (training, $n=19$) compared to an active control group playing video games of an alternative genre (control = 17), the training group recorded significantly greater reductions in switch cost ($t(1,33) = 2.39, p = .02, \text{Cohen's } d = 0.83$). However, after

adjusting for baseline differences in reaction time, this result was no longer significant ($t(1,33) = 1.67, p = .052$ one-tailed, Cohen's $d = 0.58$), implying action video games were only able to positively impact basic cognitive skills rather than task-switching ability, a complex EF.

In summary, though there appears to be a relationship between cognition and action video games, the extent of skill complexity (i.e. basic cognitive vs EFs) and the mechanisms of transfer remain relatively unclear, such as the length of time and activities required to make improvements. Action video games, as with most entertainment games, have not been designed with the intention of fostering cognitive skills (Green & Seitz, 2015). Some believe awareness and integration of neuroscientific principles may profit the cognitive potential of video games and this has led to the creation of 'cognitive training games', a branch of 'serious gaming' with the sole purpose of improving cognition.

Design Requirement:

The game should require switching between sustention, selection, and inhibition of attention – present in action video games and associated with EF challenge.

Design Method:

To create a dynamic EF challenge for user: switch between tasks; anticipate actions of in-game characters and objects; and update plans.

2.3.3 Cognitive Training Games

2.3.3.1 Introduction

In recent years, there has been an explosion where academic studies exploring the effects of cognitive training have met commercial ventures seeking to enable improvement (and monetization) of players' cognitive skills in their own homes and recreational settings through computerized tools. This has led to many academic neuroscientists marketing their own research tools while game producers have enlisted their help to create 'cognitive training games', colloquially known as 'brain training games', such as Cogmed, Nintendo

Brain Age, Lumosity, Posit Science BrainHQ, WMPPro. Recently CTGs have gained serious traction with \$715 million annual sales in the digital brain health software recorded in 2013 and predicted to surge to \$3.38 billion by 2020 (Simons et al., 2016; Worland, 2014).

There is now a rapidly growing literature base regarding the effects of CTGs but there are huge variations in the quality of individual studies and the inclusion criteria of meta-analyses which has led to an absence of consensus. Consequently, CTGs are a subject of hot debate, trapped in a cycle of polarised sensationalism played out in the press and contradictory meta-analyses. Many ‘brain training games’ courting headlines with sensational claims have been savagely criticised. However, though the exceptions raised are undoubtedly valid, often the failings of one game or study are unfairly generalized to all cognitive training studies. Moreover, some researchers have been guilty of overstating their findings but some reviewers have been equally cynical – the issue of transfer is a quintessential example discussed throughout this chapter. Thus, there is a tendency to dismiss or even ignore the potential of positive but modest outcomes. Nevertheless, aggressive scrutiny is the price to be paid for excessive claims and the commercialization of infant research without validating effectiveness. In many respects, the current feasibility of CTGs is a question of standards (Simons, 2016). This thesis aims to take a measured view, presenting some notable case studies to illustrate methodological issues.

2.3.3.2 Notable Cognitive Training Games

This subsection provides a brief overview of notable CTGs and their associated studies.

2.3.3.2.1 Cogmed: The Most Studied Cognitive Training Game

Cogmed, a CTG developed within academia before migrating into commercial channels through healthcare authorities and schools, has undergone evaluation in over 80 academic studies and featured in many meta-reviews. Cogmed is the most studied CTG and has WM games for all ages which focus on recalling sequences and mental manipulation of information (complex WM span tasks – Section 2.3.3.4.3, p. 50) with an incremental increase in difficulty. Cogmed makes the following claims:

1. Sustained improvements in WM from childhood to adulthood (Rapport et al., 2012; Klingberg, 2002)
2. Sustained improvements in both objective and subjective measures of attention (Spencer-Smith & Klingberg, 2015)

3. Cogmed Training has been associated with changes in functional brain activity – seen as changes in neurochemistry (McNab, et al., 2009)
4. Improvements have been seen in reading and maths outcomes for underperforming children following Cogmed training (Holmes et al., 2009)

A meta-analysis (Spencer-Smith & Klingberg, 2015), co-authored by one of Cogmed's founders, collated the results of 12 Cogmed studies, evaluating pre- to post-test changes in WM (through cognitive assessment tests) and attention in daily life (by self, parent, and teacher-reported data and attention assessments) in a mixture of healthy, ADHD diagnosed, and WM impaired child, adolescent, and adult participants (n = 486). The results of the relevant 7 WM studies reported on two different measures – visuospatial WM and verbal WM, reporting significant and moderate (SMD = 0.67, 95% CI 0.31, 1.02, p = .0002) and significant and small (SMD = 0.40, 95% CI 0.18, 0.62, p = .0004) effect sizes respectively. All 12 studies included measures of attention in daily life and reported a significant and small pooled effect size – comparing Cogmed to control group measuring 'inattention in daily life' (SMD=-0.47, 95% CI-0.65, -0.29 p<0.00001).

2.3.3.2.2 Lumosity: Biggest Commercial Cognitive Training Game

Lumosity is one of the most aggressively marketed CTGs and claims a user base of 70 million people. Its WM-based training games are gamified and built from well-known cognitive assessments, such as the Dual N-Back test and the Flanker Task and Lumosity cites 55 research publications to support its claims (Simons, 2016). Research investigating Lumosity's benefits purport improvements on reading tests, WM and fluid intelligence tests, and MRI-measured change in cognitive function. However, the research has been criticized for falling foul of many common methodological limitations, reporting biases, and omissions – described throughout this chapter.

Lumosity, like many of its competitors, markets its games in an equivocal manner. The game's makers, Lumos Labs, emphasize the neuroscientific expertise of team members; cite general evidence for neural plasticity as a key justification for their game's potential; and exaggerate the value of gamifying cognitive assessments for training purposes (Simons, 2016). Though they do present an extensive amount of research regarding their game's effectiveness, there are some serious shortcomings which weigh heavily on its reliability (Simons, 2016).

Such issues have led to claims of false advertising and in 2015 Lumos Labs faced a high-profile legal challenge brought by the Federal Trade Commission for misleading consumers, resulting in a \$2m fine (reduced from \$50million) (Simons, 2016). Despite the criticism and legal wrangling, the game's creators have admirably remained undeterred. They have shown conviction in their beliefs regarding the value of CTGs or, at the very least, sought better press to salvage Lumosity's reputation. Hence, the most recent studies have shown greater promise and, to some extent, further methodological rigour which reflects the realization of previous limitations.

A recent randomized active-controlled trial ($n = 4725$) sought to establish the impact of Lumosity on general cognitive abilities over a wide age range between 18 and 80 (mean = 39) (Hardy et al., 2015). Participants were separated into a treatment group who played Lumosity and an active control group who did crossword puzzles, with all participants instructed to undertake their activity for a minimum of 15 minutes per day, 5 days a week, for 10 weeks. A neuropsychological assessment battery comprising 7 different tests of high (including EFs: WM, cognitive flexibility, reasoning, problem-solving, response inhibition, visual attention) and low-level cognitive skills, as well as participant reported surveys of in-game performance and emotion, were undertaken at pre-and post-test.

The results presented a significant increase from pre-to post-test on battery performance for both groups but the training group improved twice as much with significant between groups gains on 5 tests ($t(4712) = 8.73$, $p < 10^{-15}$, Cohen's $d = 0.255$, 95% CI = [0.198, 0.312]) but reported different within group change effect sizes in each condition – treatment group pre-post ($d = 0.467$), control ($d = 0.212$). Moreover, participants in the treatment group reported improved outcomes in cognitive and emotional status survey scores compared to the control ($p < 10^{-15}$, Cohen's $d = 0.249$, 95% CI = [0.191, 0.306]).

2.3.3.2.3 Dual N-Back: The Catalyst for CTGs

A strong influence on many CTGs, including Lumosity, and cited over 1200 times, is the work of Jaeggi et al. (2008), where 70 healthy young adults (mean age = 25.6, SD = 3.3) completed a benchmark of fluid intelligence using reasoning ability assessments (Raven's Progressive Matrices or Bochum Matrices Test [BOMAT]) before being separated into training and control groups. The training group practiced a computerized WM task called 'Dual N-Back' (further explained in Section 2.3.3.4.3, p. 50) before a post-test assessment of a different version of the pre-test.

Both training and control groups were separated into 4 sub-groups and the 4 training subgroups all trained for approximately 25 minutes per day but for a different number of days – 8, 12, 17, or 19 days – after which they received post testing. Meanwhile, the 4 control groups remained inactive without any alternative activity but also post-tested after 8, 12, 17, or 19 days. The results of this study indicated significant gains from pre-to post-test ($p = <0.05$; Cohen's $d = 0.65$) in fluid intelligence for the training group and increasing training frequency resulted in even greater improvements ($p = 0.001$; Partial $\eta^2 = 0.48$). Superficially the results appeared impressive and portrayed moderate to large effect sizes, hence, its influence on the training activities of various CTGs.

2.3.3.2.4 Neuroracer: Integrating Gameplay and Cognitive Training

Neuroracer, developed by Dr. Adam Gazzaley at the Cognitive Neuroscience Research Lab at UCSF, is a research-exclusive CTG incorporating a user experience similar to a racing video game – a 3D animated game environment and is controlled using a PlayStation controller (Anguera et al., 2013). The game was developed after identifying many of the game design shortcomings of previous CTGs and the Neuroracer team believed that a better game design could revolutionize the genre and be more likely to yield better results – *“cognitive control processes, which can be enhanced by immersion in an adaptive, high-interference environment”* (Anguera et al., 2013, p. 99). Instead of simply gamifying a cognitive task, the universal status quo for CTGs, in Neuroracer the player must drive a car along a road course to set a time, adjusting their speed and direction in order to keep the car from crashing off the road (Anguera et al., 2013). Furthermore, the user is also required to respond to a series of intermittently displayed signs which appear during gameplay. The game is designed to challenge multitasking, IC and WM skills by requiring the player to respond in different ways to signs appearing intermittently while maintaining control of the car (Anguera et al., 2013). E.g. some signs must be ignored but others must be shot down.

Neuroracer's revolutionary design has been warmly received by mainstream media and academics alike. It has been used mostly with older adults, one group who may particularly benefit from cognitive training given the decline in cognitive ability seen with age. In a study (Anguera et al., 2013) involving 46 older adults (aged 60-85 years, mean = 67.1, SD = 4.2), participants were separated into 3 groups - a multitasking training group (MTT) playing Neuroracer in the simultaneous sign and drive conditions; a single task active control group (STT) playing an individual sign or drive condition of Neuroracer but never multitasking;

and a no-contact control group (NCC). The participants undertook pre-and post-test performance benchmarking on the training task itself, on a testing battery of 13 different cognitive tests, and an EEG during gameplay (measuring brain activity), as well as a 6 month follow up training task performance benchmark.

Following training for 1 hour days, 3 times a week for 4 weeks, the results suggested that the MTT group had significantly reduced their switch cost (task switching ability) from pre (-64% cost) to post (-16% cost) and remaining low (-21.9 cost) at the 6-month follow-up, denoting long-term improvements in multitasking ability. The MTT group switching cost had also reduced to a level below that of a group of 20-year-old participants from the first experiment (-36.7 cost) but they had played only a single session of Neuroracer.

Furthermore, there were also significant pre- to post-test improvements on the cognitive testing battery measures of WM (Delayed-recognition task with and without distraction) and sustained attention (Test of Variables of Attention – TOVA). Analysis of EEG data revealed only the MTT led to significant neural changes, specifically – enhanced midline frontal theta power and long-range coherence – which is associated with cognitive control and correlated with game performance multitasking measures and TOVA performance.

2.3.3.3 Validating Research

With notable CTGs and studies established, some of the key methodological flaws prevalent, in the examples provided and the general literature base, are outlined.

2.3.3.3.1 Difficulties with Experimental Designs

Experimental designs dominate CTG study methodologies because of the inability of non-experimental methodologies (such as correlational, skilled vs novice, longitudinal, and non-control group designs) to concretely attribute performance change to the training intervention by accounting for external influences (Melby-Lervåg et al., 2016; Simons, 2016).

Notwithstanding, it is a misconception to believe all experimental designs are of greater benefit in ascertaining the feasibility of CTGs, especially with regards to initial exploratory studies. In fact, experimental designs short of the gold standard – a double blind, placebo controlled, randomized, trial – can generate misleading results detrimental to our understanding of training potential, as well as limiting evidence (Melby-Lervåg et al., 2016;

Simons, 2016). Thus, non-experimental designs may be suitable for initial or exploratory work regarding novel cognitive training approaches (Simons, 2016) – described later in this section.

The use of ‘passive’ control conditions, particularly the use of ‘no contact’ control groups, are a common criticism of cognitive training studies (Baniqued, 2014; Melby-Lervåg & Hulme, 2013; Redick, 2013; Shipstead et al., 2012) – this was a shortcoming of 7 studies in the Cogmed meta-analysis and the dual n-back study by Jaeggi et al. (2008). Passive control conditions can account for test-retest effects – changes from pre-test to post-test benchmarking caused by training/learning effects, natural developmental changes, or environmental change. However, researchers often have no comprehension of control activities or lifestyle factors which may positively or negatively affect the performance of control participants depending on the activities undertaken. It is also plausible for the training group to be presented psychological advantages. For example, there may be an expectancy by the training group to improve because of (1) observational effects, such as a desire to impress experimenters (i.e. a Hawthorne effect); (2) positive preconceptions regarding the effectiveness of CTGs increased confidence of post-test improvement (i.e. a Placebo effect); (3) they were engaged by the training condition and were additionally motivated to perform well in the post-test (i.e. motivational-expectancy) (Simons, 2016; Morra and Borella, 2015; Redick, 2013; Shipstead et al., 2012). Hence, providing an ‘active’ control group is crucial (Simons, 2016; Morra and Borella, 2015; Redick, 2013; Shipstead et al., 2012) and recently cognitive training studies are beginning to take heed (i.e. Hardy et al., 2015).

However, the simple inclusion of an active control condition is not enough; the control activity is arguably as important. The activities undertaken should be like those of cognitive training groups to be perceived by participants as a viable placebo (Mankin, 2016; Simons, 2016; Melby-Lervåg et al., 2016; Melby-Lervåg & Hulme, 2013; Shipstead, 2012; Rosnow & Rosenthal, 1997). In fact, the only difference between groups should be the isolated cognitive skill(s) itself, meaning that all other game structures should ideally remain as identical as possible, particularly with respect to user engagement i.e. level of challenge or fun (Simons, 2016; Melby-Lervåg & Hulme, 2013). This is also of importance to subjective self-reported measures of performance as much as objective assessment (Redick, 2013). Nevertheless, this practice is difficult to implement and unsurprisingly rare within cognitive training studies (Simons, 2016) which commonly fail to suitably match active control and training activities.

The Neuroracer study (Anguera et al., 2013) included the perfect control activity by applying the same game activities between treatment and control groups, with the only difference being between single and multiple tasks. Hence, isolating multitasking ability. Contrarily, in the Lumosity RCT (Hardy, 2015) the active control condition was a crossword puzzle which was potentially a cognitively engaging activity but bore little resemblance to the cognitive training programme. Furthermore, unlike the Lumosity games, the crossword puzzles had no adaptive difficulty level which may have meant the activity was too hard for some and too easy for others, therefore, affecting user engagement and influencing the post-test benchmarking. Hence, controls are likely to have been aware of their role in the study and may not have been as engaged as the training group, creating a psychological difference between the groups.

Methodological Concerns:

- 1. Caution should be taken with experimental designs short of the gold standard as they can pose complex methodological challenges with the potential to negatively impact the quality of findings.*
- 2. Non-experimental designs may be suitable for initial or exploratory work regarding novel cognitive training approaches but are unable to provide concrete conclusions regarding cognitive improvements.*

2.3.3.3.2 Sample Sizes and p-Values

A fundamental criticism of CTG studies, which applies to the Neuroracer (Anguera et al., 2013) and Dual N-Back (Jaeggi et al., 2008) studies, is the prevalence of small sample sizes. E.g., in Jaeggi's study, divided 70 participants over 4 treatment and 4 control conditions – a small number in each group. Small sample sizes, contributing to a lack of study power, can create misleading effect sizes inflations and make statistically significant results appear more publishable in the absence of a true effect (Melby-lervåg, et al., 2016; Robertson & Kaptein, 2016; Button et al., 2013). This can create a bias towards incorrectly concluding the effectiveness of a treatment (Melby-lervåg et al., 2016) and impact study replicability (Button et al., 2013).

Though the Dual N-Back work of Jaeggi et al. (2008) has been influential on CTG research, it typifies the problems caused by a lack of study power by failing to replicate. Redick

(2013) attempted to replicate transfer of the Dual N-Back to fluid intelligence with 73 18-30-year-olds, separating participants into treatment, active and passive control groups and undertaking pre, middle, and post-test on a range of cognitive assessments – including fluid intelligence, multitasking, WM. The findings of this study were damning. Though there were performance improvements on the Dual N-Back treatment task and the active control task (a visual search) performance as well as self-reported improvements in various aspects of cognition, there was a dearth of any objective improvements upon the cognitive tests.

A second issue is the unhealthy focus on providing ‘significant’ evidence based on p-values of $<.05$ in CTG studies (Melby-lergå, Redick, Hume, 2016; Simons, 2016). The Neuroracer study (Anguera et al., 2013) only reports ‘Yes or No’ as to whether p was significant at the level .05 rather than the specific p-values. As with any null-hypothesis significance testing, a ‘significant’ p-value on an outcome measure does not confirm the effectiveness of a treatment. Instead, it quantifies the probability of obtaining the observed effect given a null-hypothesis. Hence, p-values neither confirm the existence or absence of a treatment effect and researchers should justify their findings using additional statistics or measures.

Methodological Concern:

Small sample sizes contribute to a lack of successful replication within experimental designs.

2.3.3.3.3 Correlating Multiple Measures

Undertaking multiple measures of the same cognitive construct is important because cognitive assessments are not ‘process pure’, particularly skills involving complex cognition like EFs where there are also contextual factors and contributing processes (both executive and non-executive). Thus, capturing the targeted cognitive skill is unlikely to be free from the noise of other phenomena so it is crucial to include multiple correlated measures of the target skill to isolate skill performance and validate findings (Makin, 2016; Redick, 2013).

Positively, both the example studies provided included multiple measures of the same cognitive construct. The Cogmed meta-analysis pooled the outcome measures and results from several small studies (Spencer-Smith & Klinberg, 2015), while the Lumosity RCT incorporated a range of different outcome measures which overlapped to necessitate the involvement of WM (Hardy et al., 2015). However, employing multiple measures alone is

not enough, something characteristic of many brain training studies (Simons, 2016). First, multiple significance tests necessitate statistical corrections made to alpha values (Robertson & Kaptein, 2016; Simons, 2016).

Multiple measures are also the root of a second issue prevalent in cognitive training studies – selective reporting of measures. E.g., assuming an alpha value of $p < .05$ for 20 distinct tests, we can also assume a false-positive rate of 5%. Therefore, we can predict the likelihood of at least one statistically significant result (i.e. 5% of 20 = 1). An unscrupulous technique common to the evidence base provided CTGs is to, conveniently, report only significant outcomes and neither the existence nor number of the additional outcomes undertaken – Jaeggi et al. (2008) is one such example of this and it was unclear as to whether the Neuro racer study (which reported 3 significant outcome measures from 11 tests) adjusted appropriately.

Furthermore, reporting different outcome measures from a single study across different publications is also common, thereby, giving the impression of a larger body of supporting evidence (Simons, 2016). Hence, it is unclear just how many ‘statistically significant’ results reported are merely fluke. Simons (2016) suggests CTG studies should be compelled to register the details of outcome measures and predicted skill transfer before data is collected to avoid researchers blanketing cognitive tests to cherry pick significant results.

Methodological Concerns:

- 1. EFs can be hard to isolate in assessment because they are not process pure and may overlap with each other and non-executive processes.*
- 2. Multiple measures of the same construct are required to validate isolated function improvement.*

2.3.3.3.4 Test-retest Reliability & Novelty

Test-retest issues are another concern. Positively, the Lumosity RCT (Hardy, 2015) used reliable assessments and reported their reliable values ($r > 0.70$) which are not always stated in cognitive training studies. However, in the RCT and Neuro racer study (Anguera et al., 2013), both training and control groups achieved significant increases from pre-to post-test and this cannot be overlooked. There may be natural explanations for such phenomena –

regression to the mean, developmental, motivational, or environmental influences – which can be controlled for by deploying an appropriate experimental design. However, it undoubtedly questions the credence payable to repeated cognitive assessment regardless of quoted reliability values, particularly regarding executive abilities.

As stated by Rabbit (2004), every subsequent exposure to a set of circumstances diminishes task novelty, critical to the accurate assessment of EF and associated skills like fluid intelligence. Hence, it is worth noting ‘untrained’ tasks do not necessarily mean novel if performed at both pre-and post-test. Further, if a test is highly reliable then novelty is less of an influence on performance. Therefore, such tests must overlook some higher order cognitive skills (such as planning or problem-solving EFs) otherwise required in novel contexts – see Constrained vs Open-ended Tasks (Section 2.1.6, p. 28).

Equally, if hypothetically, a test requires higher-order EF skills, a reduction in the novelty could conceivably impact or even change the cognitive skills and processes used to perform successive attempts at the task. This raises the question, is the cognitive test measuring the same skills at post-test as at pre-test? Unimpeachable test-retest reliability regarding EF is regarded fictitious by some (Burgess, 1997; Denckla, 1996) who believe progressive experience to similar conditions changes one’s response from initially requiring executive control to formulate a conscious and novel response, to one which automatically deploys learned processes (Anderson et al., 2010; Rabbit, 2004). Thus, assessments of EFs are often only consistent in their inconsistency (Waber et al., 2006; Anderson et al., 2002; Vriezen & Pigott, 2002). Hence, alternative or complementary methods of evaluation need to be considered when attempting to assess changes in high-level cognitive skills.

Methodological Concern:

Repeated cognitive assessment may be incompatible with measuring novel cognitive skills over time.

2.3.3.4 Transfer

2.3.3.4.1 Focus on Working Memory

CTGs predominantly focus on improving WM (Diamond, 2013; Klingberg et al., 2005) and there are several theoretical advantages of doing so. First, there are many cognitive tests of

WM which are relatively pure, reliable and repeatable in comparison to the measurement of other functions (Müller et al., 2012), making it a hypothetically easy skill to isolate and model through gamification. Most importantly, however, as portrayed in Diamond's (2013) model, WM is a core component of cognition and a root EF which forms the basis for higher order complex skills (Klingberg, 2010). CTG designers subscribe to the idea WM mediates attentional abilities, in keeping with the idea of a 'central executive' component. They often cite examples of how individuals with better WM ability (Melby-Lervåg & Hulme, 2012) have shown better performance on tasks thought to involve IC of action and attention (Melby-Lervåg & Hulme, 2012; Kane & Engle, 2003; Conway et al., 2001).

Furthermore, with regards to higher order cognition, latent variables of fluid intelligence and WM share 50% of their variance (Redick, 2013). Hence, the belief that WM is in the driving seat of complex cognition underpins the theoretical justification for transfer from WM challenge to improvement fluid intelligence and real-world functioning. However, if the variance accounts for 50%, at best, this makes WM only half of the story (Redick, 2013) and an additional 50% must be attributable to separable cognitive skills. At worst, correlation does not predict causation and some authors have suggested the relationship between WM and fluid intelligence to be more complex than first thought (Melby-Lervåg et al., 2016). Thus, current efforts to use CTGs to train high complexity cognitive functions may be limited by a WM focus and could be more effective.

2.3.3.4.2 Definitions of Transfer

Task transfer is the catalyst for greatest cognitive training debate within scientific communities. There are two predominant definitions of transfer which can be differentiated by 'context' (where the skill is being performed) and 'content' (what skill is being performed) (Simons, 2016; Shipstead et al., 2012). 'Near transfer' considers post-training performance on an untrained task involving the same skills as the training activity in a similar context (i.e. WM training leads to improvements on a WM test) (Simons, 2016; Shipstead et al., 2012). By comparison, 'far transfer' considers post-training performance on untrained tasks in a different context and/or different or more complex content (i.e. WM training leads to improvements on a fluid intelligence test) (Simons, 2016; Shipstead et al., 2012). However, in practice, whether something is near or far transfer can be somewhat subjective and require a judgement call within these rules (Simons, 2016), such as when the context is similar but the content is different. For example, does training to cook plain rice

make you more likely to cook better risotto than a non-rice trained individual? Many believe that the more specified the context or content of training, the lesser likelihood of transfer (Simons, 2016).

2.3.3.4.3 Evidence of Transfer: Dual N-Back & Complex Span Tasks

To challenge WM, three dominating approaches have been taken by CTGs, n-back tasks, complex span tasks, and gamification of cognitive assessments (Melby-Lervåg et al., 2016):

- **n-back & Dual n-back:** *“In the n-back task, a person must maintain active representations of the previous n items and their serial order, encode the current item, compare it with the first of the memory list, make a decision, respond, drop the first item from the memory list, and update the list by including the last item and rearranging the order, so to continue with the next item—and all these operations must be performed under a certain time pressure”* (Morra & Borella, 2015, p. 2).

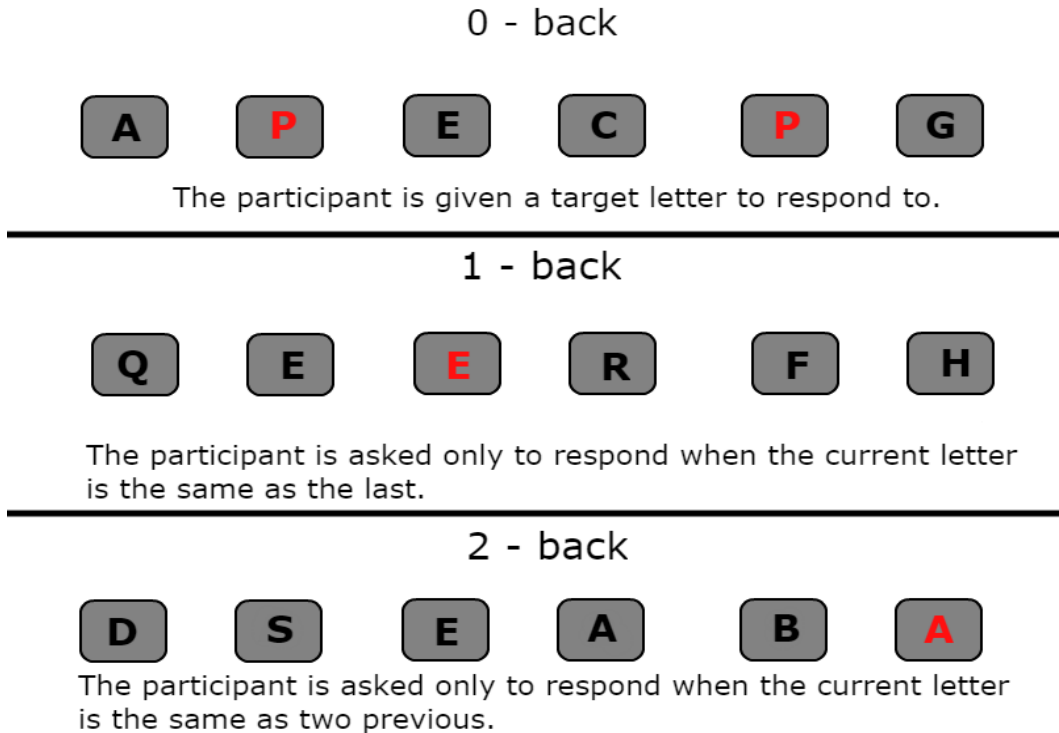


Figure 6: N-back Task Example

The example shown in Figure 6 shows a series of n-back tasks. When n is 0 (0-back), participants are given a target letter to respond to. When n is 1 (1-back), participants must only respond when the current letter is the same as the last. When n is 2 (2-back),

participants must only respond when the current letter is the same as the letter before last. This n continues to increase in line with the theoretical difficulty.

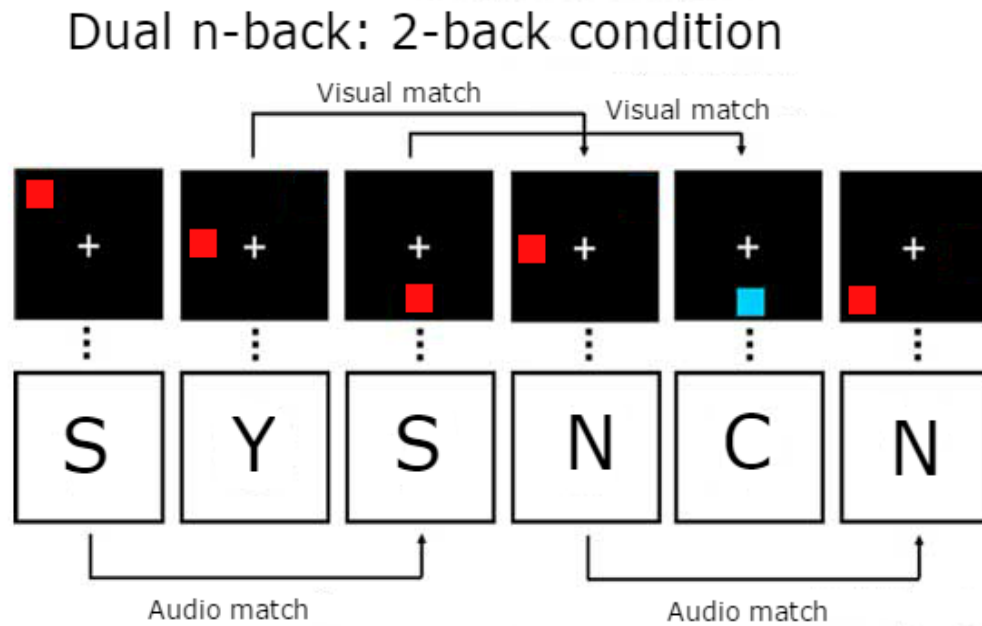


Figure 7: Dual N-back Example

Sometimes, such as in the ‘Dual n-back’ (Jaeggi, 2008) in Figure 7, there are multiple streams of information to track. The participant might be presented with simultaneous visuospatial and phonological data and be required to follow n-back rules for both conditions.

Improvement in n-back performance is theorized to reflect improvements in the speed or efficiency in the operations described, in the task control processes, or in use of WM storage and attentional resources (Morra & Borella, 2015). The n-back task is strongly correlated with fluid intelligence, even more so than WM (Redick, 2013).

- **Complex span:** *“To perform a complex span task, a person must encode one or more items of the processing task, perform the prescribed operations, encode an item of the memory task, keep the memory item(s) activated, and start over again with a cycle of the processing task, until recall of memory items is required”* (Morra & Borella, 2015, p. 2).

The example in Figure 8 shows the difference between simple and complex span tasks. In the simple span task, the participant must remember the items presented sequentially before recreating the sequence in order. In the complex span task, the participant must do the same thing, however, in between each item to be encoded into memory, they must perform an additional distractor process.

Like the n-back, improvements in complex span tasks are posited to reflect speed and efficiency improvements in the operations and processes involved. Tasks may be made more difficult by increasing the number of items to remember (Shiptstead et al., 2012)

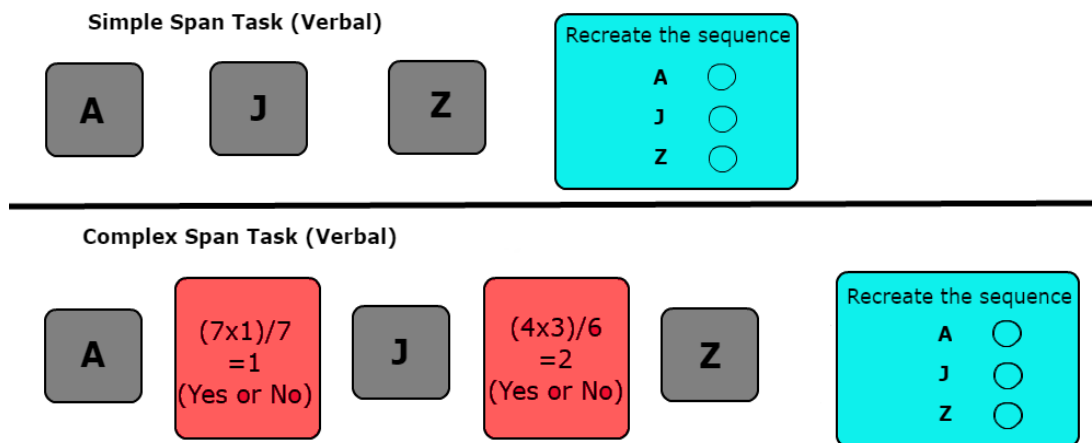


Figure 8: Simple vs Complex Span Tasks

- **Gamification:** involves adding game components to cognitive training assessments allowing a user to theoretically challenge and practice the same skills present in the test but perhaps in a slightly different context or content. Again, these often target WM skills (Simons, 2016).

These techniques are predicated on the idea of WM, being ‘a muscle’ which can be made bigger by repetitive use in decontextualized environments, thereby, providing near transfer improvements to other WM tasks and far transfer to benefit more complex cognitive skills – a notion questioned by some (Simons, 2016; Morra & Borella, 2015). However, though both Dual N-Back and complex span task performance correlate strongly with fluid intelligence, there is no evidence to suggest practicing one leads to benefits in the other.

It is generally accepted that CTGs using the techniques outlined can facilitate near transfer. However, some have questioned the value of near transfer itself. Are observed improvements on outcome measures attributable to gains in underlying WM skills or merely increased

speed and efficiency in very specific mental processes and solution strategies (Morra & Borrella, 2015; Hambrick, 2014)? In the Lumosity RCT, though the outcome measures noted improvements in tests covering a disparate range of cognitive skills, the multiple games included in Lumosity were gamified versions of many of the outcome measures themselves (Simons, 2016) – this is indisputably near transfer but it is unclear whether it would be of any benefit to contextually different WM tasks. Hence, though achieving near transfer is an important step, the end goal of CTGs is to enable the far transfer applicable to different contexts and content. At present, there is little (if any) evidence to suggest far transfer to fluid intelligence, high-level EF, or real-world functioning is currently possible (Redick, 2013; Morrison & Chein, 2011; Shipstead et al., 2012, 2010; Conway & Getz, 2010).

Design Requirement:

The game should challenge WM beyond incremental and contextually specific refinement of specific processes.

Methodological Concern:

Games based on a cognitive assessment must include additional outcome measures to ensure performance changes go beyond 'training to task'.

2.3.3.5 The Future of Cognitive Training Games

2.3.3.5.1 Reassessing Transfer

Instead of dismissing the theory that WM training may be able to provide far transfer, some authors have called for CTG designers to attempt to garner a greater understanding of transfer complexities, rather than simple utilization of the training methods described (Melby-Lervåg et al., 2016). Unsworth et al. (2014) suggested WM involve 3 distinct processes in mediating fluid intelligence:

- The number of items that can be held in primary (short-term) memory
- The ability to search strategically among items in secondary (long-term) memory
- The ability to control attention according to goals

Hence, current training strategies using n-back and complex spans are likely unable to deliver all 3 (Melby-Lervåg et al., 2016). Morra & Borrella (2015) acknowledge the possibility current CTGs train speed and efficiency in implementing specified, contextually specific mental processes and solution strategies. This assumption highlights the lack of novelty involved in the challenge of CTGs – as we know, novelty is a pre-requisite of both executive skills and fluid intelligence, therefore, it's inclusion in training is fundamental. Consequently, future training games may benefit from disrupting successful problem-solving strategies and instead require the generation of new strategies rather than incremental refinement of successful solutions.

Emotion is mostly overlooked by CTGs, which may account for transfer limitations. CTGs focus on training cool skills in decontextualized environments with individuals. Yet hot cognition also impacts real-world abilities because emotion influences our actions, involving different brain regions to cool cognition (De Luca & Leventer, 2008; Kerr & Zelazo, 2004). Thus, without the presence of external influences, such as social factors, in CTGs there may be a contextual disparity in the way we use cognitive skills in comparison to the real world. This also has methodological implications for assessing the effectiveness of cognitive training – evaluation must take account of hot cognition.

To positively impact real-world cognitive functioning, CTGs need fundamental redesign (Melby-Lervåg et al., 2016; Mishra et al., 2016; Moreau & Conway, 2014). Understanding how envisaged training designs map to the skills challenged during gameplay and the mechanisms of transfer is of utmost importance. However, some believe that CTGs should go beyond the isolation and decontextualized fixation on WM. E.g., Mishra, Anguera, and Gazzaley (2016, p. 216) state, *“it is becoming clear that the current, unimodal approach of training an isolated cognitive function or even a set of cognitive functions will not achieve these goals”*. Instead, training programs should be presented in more naturalistic settings, requiring complexity, novelty, diversity, and activities involving motor demands (Moreau & Conway, 2014). But how is this possible? Modelling cognitive training on activities with stronger evidence linking them to cognitive gains, such as PA (Hambrick, 2014), is one option. This echoes early ‘learning transfer’ pioneer Edward Thorndike who believed *“the most common and surest source of general improvement of a capacity is to train it in many particular connections”* (Simons, 2016; Thorndike, 1906, p. 248). Hence, we should consider training in contexts relevant to real-world activities to help bridge the transfer gap – a skill itself (Simons, 2016).

Design Requirements:

1. *The game should train complex EFs directly and including WM rather than simply training of WM in isolation.*
2. *The game should train cognitive skills in a way which is applicable to different contexts and more likely to foster far transfer.*
3. *The game should train cognitive skills used in diverse and novel situations.*

Design Method:

To challenge WM in a way which may benefit complex EFs: create situations requiring the user to store and manipulate information in both short and long term memory as well as controlling attention according to an overriding goal.

Methodological Concerns:

1. *There is a need to understand the skills being challenged in CTGs over time before the mechanisms of transfer can be fully understood.*
2. *Cognitive tests utilized in cognitive training studies rarely coordinate hot EF measures of emotion, which are a factor upon their ecological validity.*

2.3.3.5.2 Importance of Motivation and Gameplay

Limitations in experimental designs, assessment validity, lack of transfer, emphasis on WM, and subsequent reporting bias have made it hard to comprehensively understand the potential of CTGs. However, there is an additional factor affecting the quality of CTGs and their applicability to improving real-world outcomes, motivation. Recent studies suggest creating intrinsically motivating experiences which are engaging and encourage sustained practice (Morra & Borrella, 2015; Jaeggi et al., 2014; Diamond, 2013;) may be fundamental to CTGs and their EF building effectiveness.

Currently, there is a lack of user engagement and motivation to play CTGs (Mishra, Anguera, and Gazzaley, 2016) stemming from the limitations of most designs – CTGs are

often designed by neuroscientists with no formal game design background or are simply gamified versions of cognitive tests (Mishra, Anguera, and Gazzaley, 2016). While compiling this review of CTGs, there was a conspicuous lack of studies reporting the long-term playability of CTGs nor user experiences. Consequently, irrespective of methodological problems, it may be impossible to gauge the potential of training without first making them interesting or fun to encourage learning and repeated practice.

Though the Neuroracer (Anguera, 2013) study suffered from several methodological problems, the design underpinning the game was revolutionary and consistent with formal game design theory integration of gameplay and motivational qualities. The game was more akin to entertainment games and perhaps more likely to foster a genuine enjoyment of training – absent or undetermined in previous CTGs. Unfortunately, the described study produced very limited conclusions with regards to how participants enjoyed the game, making it hard to understand whether they could successfully implement their theory. This is something which future game designs should seek to assess. However, in a separate publication a series of design recommendations are proposed by Gazzaley for future CTGs – these are discussed in Chapter Three (Section 3.4.4, p. 103).

Design Requirement:

The game should integrate game design theory and motivational qualities rather than simply gamification to increase user engagement.

2.3.3.6 Conclusions

In summary, CTGs appear to lie somewhere along the middle ground between being the next frontier in personal improvement and being just another video game. Though they may hold promise, their research and design must be improved or given fresh perspective to achieve their potential. This is critical given the sheer numbers of consumers spending their time and money on CTGs and the increasing interest from parents, children, and academic bodies as a method to improve educational outcomes. As such, it is important for the future of education that the evolution of cognitive training tools and games draw a greater and more positive consensus from experts.

Regardless of whether current strategies can benefit cognition, the confusion concerning transfer is symptomatic of a lack of understanding as to whether cognitive skills are truly tested during repeated gameplay. Thus, we know very little of how a participant's experience changes during training and the events precipitating objective performance change. This means that a wealth of rich data concerning the beneficial and unsuccessful aspects of training may be lost in most studies. Incorporation of qualitative analysis may provide a reliable window to study the process of change as well as offering observable means to understand hot EF beyond self-reporting questionnaires of behaviour.

2.4 Executive Function and Physical Activity

2.4.1 Cognitively Engaging Physical Activity

The important contribution of PA to health and lifestyle outcomes is discussed in Chapter Three (Section 3.2, p. 71) but this section examines the relationship between PA and cognition. Many researchers credit PA with benefiting mental well-being and cognitive functioning. PA has been shown to benefit cognitive performance in both children (Hillman et al., 2008) and elderly adults (Colcombe and Kramer, 2003). Unlike the durational and intensity prerequisites of PA in addressing physiological wellbeing, even a modest cumulative daily 30 min of aerobic exercise may benefit cognition e.g. Tuckman & Hinkle (1986) reported increased creativity and the ability to generate solutions to questions.

The benefits of PA may also be instantaneous and affect higher order cognitive skills including EFs. Best (2011) noted EF assessment performance increases following a single exercise session and even greater benefits following multiple sessions, while similar results were seen by Caterino & Polak (1999). A meta-analysis of 18 fitness cognitive training interventions concluded that fitness programs encompassing aerobic exercise enhance executive control and visuospatial ability in healthy but sedentary elderly adults (Colcombe & Kramer, 2003). Davis et al (2011) reported increases in PFC activity with obese youths following aerobic exercise as well as the transfer of cognitive benefits to everyday life with significant improvements in mathematics.

Low to moderate intensity PA (e.g. walking) has shown beneficial effects in measures of task switching, IC, and WM (Smiley-Oyen et al., 2008; Colcombe et al., 2004; Kramer et al., 2001; Blumenthal et al., 1991; Dustman et al., 1984). Playing sports and exercising at higher

intensities may accelerate these EF improvements due to increased cognitive demands (Best, 2012; Hillman et al., 2008). Research also suggests elite sportspeople have better EF ability than normal populations (Verburgh et al., 2014; Vestberg et al., 2012). Moreover, the relationship between PA and EF appears bi-directional with those with higher levels of EF are more likely to undertake PA regularly (Daly et al., 2014; Hall et al., 2008).

Though a volume of research has established a relationship between PA and EF, the underlying mechanisms are less well documented. However, Best (2010) identified 3 pathways by which aerobic exercise may affect EF:

1. Aerobic exercise induces physiological changes in the brain.
2. The cognitive demands inherent in the structure of goal-directed and engaging exercise.
3. Cognitive engagement is required to execute complex motor movements.

Aerobic exercise appears to increase the volume of grey matter and cognitive activity in the prefrontal cortex, as measured by MRI testing (Weinstein et al., 2012; Davis et al., 2011; Colcombe et al., 2006). Despite this, some remain sceptical as to whether it is the aerobic component of exercise alone responsible for such change, leading to alternative and complimentary theories (Diamond, 2015).

One theory is cognitively-engaging PA. Best (2010) cites the ways in which children approach team sports as being one example where PA and EF are simultaneously required. Children often partake group activities or sports that require complex cognition, elicited by cooperation with teammates, the anticipation of teammates and opponent's behaviour, employment strategies, and adapting to ever-changing task demands (Best, 2010). Such activities may be governed by underlying EF processes focusing on developing plans, modifying them where necessary, and monitoring their success. For example, Decety et al., (2004) found competitive social activities result in medial prefrontal cortex activity. Hence, such environments necessitate the performance and practice of higher order cognitive skills collectively rather than by isolating WM – the training method common to CTGs.

Diamond (2015) also champions cognitively engaging exercise and questions the strength of the link between simple, solitary, repetitive PA (i.e. running) and EF. Echoing Green & Bavelier (2008), Diamond broaches the methodological limitations of EF-associated PA research and highlights control group problems and the lack of evidence to support the generalization of findings across different age groups (i.e. results for the elderly may not generalize to children). Instead, Diamond advocates activities which couple PA with thought

and praises the success of interventions which have involved taekwondo and yoga, and team sports. Diamond also states the importance of increasing PA durations, citing studies like Davis et al., 2011 where EF benefits were seen in a group who had undertaken 43 hours of aerobic team sports, but not in a group undertaking the same activities but for a lesser amount of time (22 hours). Finally, Diamond prescribes PA which helps individuals to find joy, build self-confidence, and is social, in addition to being cognitively engaging – thereby assimilating both direct and indirect pathways to improve cognition (Section 2.1.3.5, p. 23).

The execution of complex motor movements may be another potential factor of association between EF and PA. Complex motor movements share a neural link with EFs through the prefrontal cortex and the cerebellum areas of the brain, actively involved in both skills (Diamond, 2000). Chang et al., 2013 found motor-coordinative exercise to be beneficial for the EF ability of kindergarten children regardless of intensity. An everyday example of motor-coordinative exercise involves walking and looking at a phone screen simultaneously – one must coordinate whole body movement with the contents of the screen and environmental obstacles, therefore, exercising visual-motor control (Agostini et al 2015). Diamond (2000; 2009) believes that much like cognition, motor control runs on both conscious and automatic modes and at times certain movements we make will require an element of cognitive engagement. Best (2010) explains that learning to walk as a child appears to be a cognitively engaging task but as one improves and eventually masters the skill, it becomes automatic. Finally, in animals, such as nonhuman primates, the execution of complex motor movements appears to promote neural growth in different areas of the brain to a greater degree than repetitive motor movements (Best 2010).

Design Requirements:

- 1. The game should incorporate PA component to accelerate EF improvements by coupling motor and cognitive engaging demands.*
- 2. The game should promote higher intensity PA (MVPA) to accelerate EF improvements.*

Design Methods:

1. *To facilitate 'cognitively engaging PA', activities can involve complex motor control, such visual motor control while coordinating phone screen activities and real-world movements.*
2. *To facilitate 'cognitively engaging PA', integrate complex EF skills, such as strategizing to overcome ever-changing task demands.*
3. *To facilitate 'cognitively engaging PA', activities can make use of direct cooperation or competition with others.*

2.4.2 Executive Function and Exergames

There holds promise in improving EF through PA and computerised training and the work of Best sought to bring these research strands together by evaluating cognitively engaging PA through exergaming. Exergames are a genre of video game which involves PA as part of the user interaction – the concept and its effectiveness are covered in greater detail in Chapter Three. Hence, they have been mooted as a method of cognitively engaging PA.

In a 2x2 design comparison of commercial exergames and commercial sedentary games, where each game type had a high cognitive engagement condition and a low engagement condition, children (aged 6-10) displayed significantly greater EF ability on the ANT-C testing battery following exergame play (Best, 2012). However, only the PA component of the game rather than the cognitive demands of the game tasks was culpable for the effect (Best, 2012) which, therefore, contrasted with the prediction that the cognitive engagement would most strongly influence cognitive change. Best posits the lack of social interaction (common to other cognitively engaging activities like team sports) involved in the training games as a possible factor to explain the results. Alternatively, other potential influences are the motor complexity differences between the study games and traditional cognitively engaging activities – e.g. running on the spot on gamepads rather than real-world running.

Best (2013) proposes a theoretical model of the mechanisms provided by future exergames to benefit physiological and cognitive development. In the model, exergaming leads to cognitive training, motor skills training and increased PA, all of which lead to improved EF. Increased PA leads to improved fitness, which in turn improves EF. Improved EF can also increase PA through enabling young people to ignore immediate gratification to pursue longer term fitness goals.

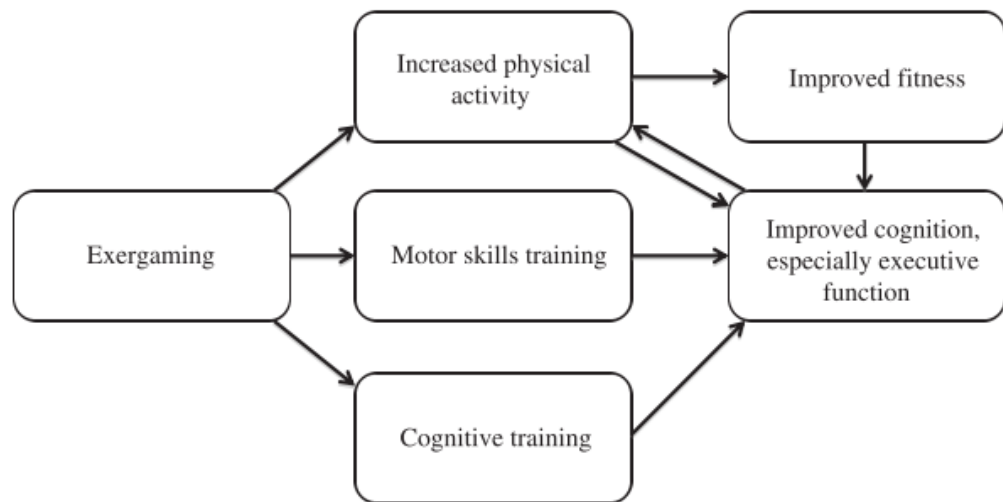


Figure 9: Best (2013) Theory of Exergame Cognitive Benefit

A few similar studies have also considered the relationship between EF and exergames, producing auspicious outcomes. In a small study (n=24) significantly greater focus and concentration (IC) were shown after using an exergame in comparison to a sedentary equivalent, following attention and maths assessments (Gao et al., 2012). Moreover, the exergames were perceived as being more fun than the sedentary equivalent – a mouse-controlled version of the same game. Another study, (Flynn et al., 2014) in the naturalistic setting of a summer camp, found playing Wii Fit games regularly over a 6-week period improved EF test scores and the number of sessions predicted test gains.

Staiano et al. (2012) evaluated the EF impact of exergame training and sought to understand the benefits of cooperative and competitive social interaction. In a 3 x 2 design study with African American students in a high school (n=54, 31 females, 23 males) aged 15-19 years, participants undertook on average 10.6 sessions playing Nintendo Wii EA Sports Active in either a competitive or cooperative condition, or in a control group continued their typical in-school leisure activities. EF was benchmarked before and after training using 2 subtests

(Design Fluency and Trail making tests) from the D-KEFS testing battery. Only the competitive training group produced significant pre-test to post-test improvements – 7 times greater control group and twice the cooperative exergame group. Hence, this highlights the importance of including a competitive component to the design of any EF training exergame programme.

In summary, though only limited research has sought to explore the relationship between EF and exergaming but a few studies have shown encouraging results. Research suggests exergames be more effective than sedentary video games in facilitating cognitive improvements, yet it is unclear how the effectiveness of exergames compare to more traditional forms of ‘cognitively engaging PA’, such as team sports. Furthermore, additional research may be required to compare exergames with a wider range of video game genres, especially those associated with cognition such as CTGs and action video games.

It appears to maximize the short-term benefits of exergames to EF they should take design cues and build on traditional cognitively engaging PA, such as the social nature of activities and complex motor movements involved. Notwithstanding, as discussed in Chapter Three, the potential motivational and measurement benefits of exergames may help to overcome the traditional barriers individuals face to PA and create more engaging experiences for users – a current shortcoming in CTGs. Furthermore, unlike sedentary forms of gaming, such as action video games, exergames may be able to contribute to physical health outcomes which are, in turn, associated with their own positive associations with cognition. The process of creating an exergame which meets these recommendations is explored in this thesis.

2.5 Executive Function Assessment

2.5.1 The Difficulties of Executive Function Assessment

The review of CTGs and the methodologies of their study raised several difficulties concerning the assessment of cognition, particularly high-level cognition like EFs. This section summarises such difficulties concerning EF measurement:

- The importance of novelty and the difficulty in maintaining it is outlined in Section 2.1.5 (p. 27) (Anderson et al., 2010; Rabbit, 2004; Burgess, 1997; Denckla, 1996). Novelty is key to complex EFs making use of both WM and IC, such as problem-

solving, which makes it a challenge of ecologically valid tests attempting to be verisimilar to tests of real-world functioning.

- The dominant EF assessment approach involves creating task-based tests which are sensitive to identifying capacities, processes, and abilities in those with frontal lobe impairments. Performing these tasks involves multiple EFs, an ecologically valid approach which can make an assessment more sensitive to uncovering frontal lobe deficits. However, such tests may highlight obvious inabilities, rather than provide a fine-grained picture of the performance of able individuals (Miyake et al., 2000).
- EF assessments lag behind the advances made in EF modelling and neurological imaging (Royall et al., 2002). As stated, high-level cognitive skills (including many EFs) are not ‘process pure’ (Hughes & Graham, 2002; Burgess, 1997) and there is difficulty in isolating EFs for assessment due to their interconnected nature and reliance upon non-executive aspects of cognition – necessitating control for many specific processes (Burgess, 1997).
- EF assessments are usually very well structured and controlled and coordinated by an examiner, and this may diminish the requirement of exercising key EFs (like goal setting, structuring, and decision making) – hence, the examiner is effectively replacing the frontal lobes (Lezak, 1983).
- Tasks which are ‘constrained’ as opposed to ‘open-ended’ (Section 2.1.6, p. 28) are most reliable and, therefore, unaffected by repeated testing but they lack ecological validity and performance may not represent an accurate picture of a person’s everyday functioning (White et al., 2009). To solve problems of ecological validity, some authors have mooted basing future tests around real life scenarios under experimental conditions (Rajendran et al., 2011).

2.5.2 BADS-C

2.5.2.1 Overview

Behavioural Assessment of the Dysexecutive Syndrome in Children (BADS-C) is a modified version of the adult BADS testing battery, developed by Burgess (1997), but is geared towards children. Both BADS and BADS-C draw from key models of EF, specifically the Central Executive (1974) and the SAS (1982). BADS-C consists of 6 subtests and an

optional questionnaire which examine different complex EFs including cognitive flexibility and perseveration, novel problem solving, sequencing, using feedback, planning, impulsivity, and following instructions.

	Flexibility and Perseveration	Novel Problem Solving	Sequencing	Using Feedback	Planning	Impulsivity	Following Instructions
Playing Cards	*						
Water Test	*	*	*	*			
Key Search Test		*		*	*	*	
Zoo Map 1		*	*	*	*	*	
Zoo Map 2	*			*		*	*
6E	*			*	*		

Table 2: EF Skills and Subtests from BADS-C Manual

BADS-C was chosen as an assessment tool and a design influence within this thesis due to its incorporation of open-ended tasks (though not exclusively), transcending a broad spectrum of both low and high-level EFs, thereby allowing for a near complete representation of EF ability (Emslie, 2003). Its designers also acknowledge the interconnected nature of EF and the same skills are overlap in different BADS-C subtests – thus, it is more representative of real-world functioning. Unlike many of the other tests noted, in addition to the standardized scoring system, BADS-C facilitates the recording and structuring of qualitative data, particularly with respect to planning and strategizing, providing a richer picture of individual performances by establishing **how** each test was implemented rather than a simple outcome score (Emslie, 2003).

BADS-C is also somewhat unique as almost all EF assessment is geared towards adults where Dysexecutive behaviour may be more easily distinguished from normal behaviour – unlike children and adolescents, where behaviours (like impulsivity, poor self-control, erratic carelessness, poor initiation, and inflexibility) may equally be present in healthy individuals (Emslie, 2003; Lezak, 1995). This is important as EF testing in children must consider

limited skills with respect to onset, rate, and level of mastery. BADS-C provides normative data for children aged between 8 years and 15 years and 11 months and allows for the scaling of scores according to age to allow for standardized scoring of performance, in addition to a standardized administration procedure – unlike many singular EF tests e.g. Stroop Test, Towers of London, Towers of Hanoi. Therefore, the acknowledgment of such issues the BADS-C design makes it more sensitive and appropriate for children’s EF measurement than many other assessments.

Methodological Concerns:

- 1. EF assessments vary in terms of their age appropriateness.*
- 2. Testing batteries can capture a wide spectrum of EF skills, many of which overlap.*
- 3. EF assessments may be more sensitive to abnormal or dysexecutive behaviour rather than differences in healthy individuals.*

2.5.2.2 Reliability

In the inter-rater reliability of BADS-C, scoring of 25 control subjects (aged 8-14 years) from the normative dataset (n=265) yielded a very high inter-rater reliability ranging between 0.53 and 1.00, with absolute agreement on 6 of 14 measures, and (the perseveration measure of the Water Test excluded 0.53) produced an inter-rater correlation between 0.91 and 1.00. However, characteristic of any true EF testing which considers the importance of novelty, test-retest reliability from 6-12-month follow-up testing produced mixed results.

Consider Table 3. There was a tendency for the 25 controls to slightly improve on their second attempt at the BADS-C but only two tests, the 6E and Playing Cards, produced a statistically significant increase in mean scores. Despite this, the 6E test produced a significant and moderate correlation between pre-and post-test performance, indicating that the ranking of individual performance was similar during both attempts.

Mean scores on the Key Search, Zoo Map 1 and Zoo Map 2 tests increased slightly but not significantly. The Key Search and Zoo Map 1 also recorded significant high and moderate correlations between pre-and post-test performance, respectively – suggesting these tests to be the most stable within the BADS-C battery.

For the Water Test, the researchers reported all children to be at the ceiling on their second attempt, while the agreement shows that 76% of participants achieved the same score from

pre-post. Thus, 76% of participants must have already scored at the ceiling on their first attempt.

The number of participants who underwent re-testing was small and the authors did not state any multiple comparison measures, making it hard to extrapolate statistics with total confidence. However, in general, the test-retest reliability of BADS-C appears to vary between subtests, with the Key Search and Zoo Map 1 appearing to be the most reliable in terms of stable mean scores and correlation. The 6E test appears moderately reliable in terms of correlation but significant mean improvements suggest the presence of some practice effects. The lowest reliability concerns Zoo Map 2 and the Playing Cards, while the Water Test remains a bit of an unknown entity as ceiling performances limited analysis. However, the Water Test is a particularly novel problem, which is likely to impact additional attempts and, subsequently, retest reliability (Emslie et al., 2003).

	Time 1 mean scaled score (SD)	Time 2 mean scaled score (SD)	p*	Correlation	p	% agreement
Playing Cards	8.76 (2.89)	11.16 (1.18)	0.004	-0.238	0.252	32
Water Test	Correlation and t cannot be calculated as all children were marked at ceiling at time two					76
Key Search	11.00 (2.87)	11.68 (3.01)	0.071	0.814	<0.001	56
Zoo Map 1	10.72 (3.31)	11.32 (2.91)	0.304	0.585	0.002	52
Zoo Map 2	9.92 (3.34)	10.56 (2.72)	0.389	0.289	0.161	72
6E	10.28 (2.64)	11.8 (1.94)	0.006	0.436	0.030	36
<i>* differences in mean between first and second time test, using paired t-tests</i>						

Table 3: BADS-C Test-retest Reliability (Emslie et al., 2003, p.23)

2.5.2.3 Modified 6 Elements Test (6E)

A full description of all 6 BADS-C subtests is given in Appendix C but this subsection concerns the 6E test – crucial to the game described in this thesis.

This is a test of planning, task scheduling, cognitive flexibility and performance monitoring which requires both attention and use of WM. Children are given three different colour-coded tasks to do: a green task (simple arithmetic), a blue task (picture naming), and a red task (sorting). Each of these tasks has two parts, part 1 and part 2, so there are two piles of cards for the green task and two piles for the blue task. Both parts of each task type are graded in difficulty to be suitable for children from age 8 years upwards. The third task, the red task, consists of two boxes of objects, one containing multi-coloured and multi-shaped beads, and the other a mixture of nuts, bolts, and washers. Children should schedule their time to attempt something from all six parts over a five-minute period with restrictions on the order in which parts can be attempted. A key requirement of this test involved generating strategies (Emslie et al., 2003).

Below is an overview of the 6E task structure:

1. Each task contains two parts (A and B), where only one may be undertaken at a time. Furthermore, once one task type is completed, the same task may not be re-chosen until the user has completed a further task of a different type, e.g. If Task 1A is chosen and then completed, then the user may not choose any part of Task 1 until a part of Task 2 or Task 3 are completed.
2. Within the 5-minute time limit, the user must make sure that they have attempted all 6 subtasks while following Rule 1.

The task and subtasks involved in the 6E test are named, structured and described below:

1. How many? – in these tasks the user must perform some sums written on a series of cards before writing the answer down on paper
 - a. How many? Part 1
 - b. How many? Part 2
2. What is it? – in these tasks the user must write down on paper which object that they see on each card
 - a. What is it? Part 1
 - b. What is it? Part 2

3. Sort it – in these tasks the user must sort items into their box lids, according to a picture drawn on the inside of each box lid:
 - a. Sort it Part 1
 - b. Sort it Part 2

Note: though the undertaking of both parts (A and B) of each task are identical, the content is different e.g. in ‘Sort it Part 1’, the user sorts bolts, while in ‘Sort it Part 2’, the user sorts beads.

In the scoring system for the 6E test, the user earns 2 points per unique task attempted (e.g. 4 different tasks = 8 points) with a maximum of 12 points available. The user loses a mark for every unique task type in which they break the rules (e.g. ‘What is it? Part 1’, followed by ‘What is it? Part 2’ = -1 points) with a maximum of 3 penalty points. Finally, the user can earn extra points for using a discernible strategy, such as task ordering or time management strategies, while they may also lose an extra point for persistent rule breaking.

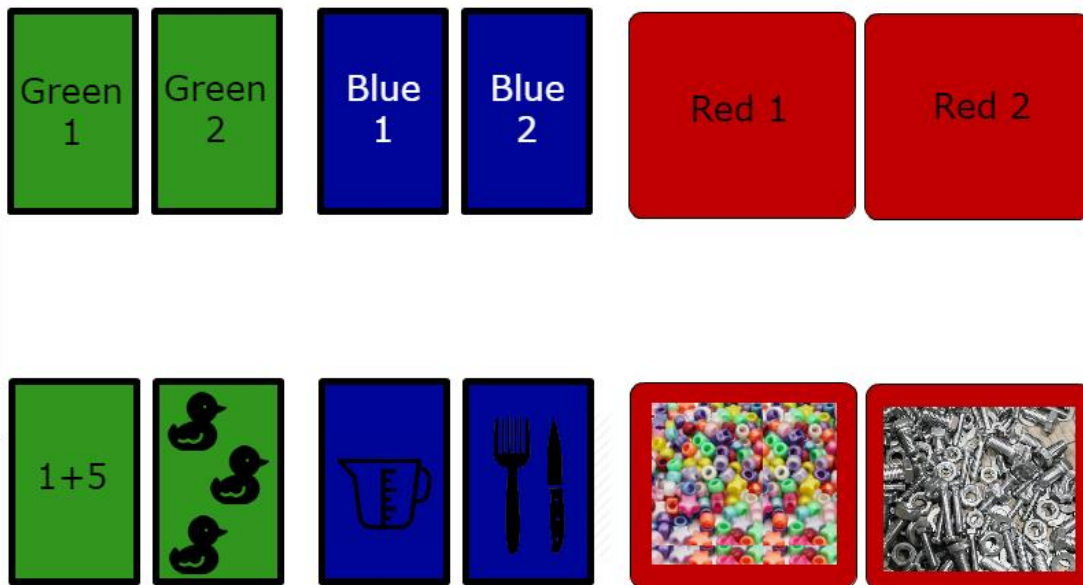


Figure 10: 6E Test (Example)

2.6 Summary

This chapter began by introducing and defining EF, including important paradigms, subcomponents, impact on quality of life outcomes, and training methodologies. Most importantly, the work of Adele Diamond and her 2012 model of EF building pathways for

training interventions was introduced – research which underpins much of the work presented in this thesis.

Following this, the chapter presented a critical review of CTGs, the closest field to the work presented in this thesis and a promising vehicle for training cognition (including EF) in a convenient and enjoyable manner. Though CTGs hold promise, there is currently a lack of quality research with many ‘ground-breaking’ studies suffering from severe methodological shortcomings. Furthermore, the widespread CTG design practice of gamifying cognitive tests or isolating and training WM has been criticized for being too contextually removed from the real-world to merit any ecologically valid outcomes. Thus, some of these concerns are addressed in Chapters 3 and 5.

Towards the end of the chapter, a link was established between PA and EF which highlighted the potential of cognitively engaging PA in promoting EF. It appears the cognitive benefits of PA may be enhanced by coupling the deployment motor control with cognitive skills – e.g. strategizing while playing sports. Throughout the chapter, game design requirements, methods and methodological concerns were identified from the literature to inform the design and evaluation of BrainQuest, the exergame described and evaluated later in this thesis – these principles are reviewed in Chapter Four.

3. Game Design

As discussed in the previous chapter, authors have raised concern at the lack of game design literature at the core of CTGs. This has led some to advocate closer design consistency with motivational game design theory, shown to positively influence user engagement and maintain game longevity – often hard within serious games. Furthermore, the work of Best (2015, 2014, 2012, 2011, 2010) suggests incorporating cognitively engaging PA by using exergames to accelerate cognitive and EF improvements as well as provide physiological benefits to users.

This chapter explores the emergence and difficulties associated with developing engaging games with a serious purpose before examining the effectiveness of exergame promotion and sustention of PA. Following this, motivational theories, paradigms, and techniques used by game designers to harness user engagement are established and discussed. Finally, some recent techniques to integrate game design theory and CTGs are presented and critiqued.

3.1 Defining Serious Games and Exergames

‘Serious games’ are games designed not merely to offer the user fun or escapism but to deliver a serious outcome (Ma et al., 2014; Djaouti et al., 2011a; 2011b). However, they are not a new phenomenon. In fact, the first computer games were also serious games, designed to showcase the sophistication of the era’s cutting edge research in technology (Djaouti et al., 2011a; 2011b). Today, serious games encompass fields such as health, education, politics, and advertising, leading to a range of domain-specific definitions (Djaouti et al., 2011a; 2011b). Furthermore, even entertainment games can be used for serious purposes. Thus, in this thesis, the adopted definition of a serious game is “*any piece of software that merges a non-entertaining purpose (serious) with a video game structure (game)*” (Djaouti, 2011a, p. 2). This thesis focuses on two subsets of serious games for health: exergames and CTGs.

Modern exergames can be defined as video games which incorporate PA in the user interaction and can be deployed on several different platforms, most commonly console-based motion-tracking (Nintendo Wii, Xbox Kinect, Sony EyeToy) and mobile, pervasive (Pokémon Go!, Zombies Run, Ingress). Mobile, pervasive exergames have recently courted global headlines with Pokémon Go! breaking app store records and being downloaded over

500 million times (Pearce, 2016). Despite this initial popularity, it remains unclear as to whether mobile exergames can bolster long-term play and subsequently positive changes for health. Thus, this chapter explores how motivational design literature may be of benefit to both cognitive training and exergames.

3.2 Exergames Overview

3.2.1 Children and Physical Activity

PA is “*any bodily movement produced by skeletal muscles that requires energy expenditure*” (WHO, 2015) categorized in terms of light, moderate, and vigorous intensities and measured in metabolic equivalents (METs). Light intensity PA includes walking, doing housework or fishing and may clock between 1.5-3 METs; moderate intensity includes walking briskly, jogging or stair climbing, clocking between 3-6 METs; and vigorous intensity includes both aerobic and anaerobic exercise, like playing football, Tig/Tag or lifting weights, and may clock greater than 6 METs (WHO, 2015). Research suggests moderate to vigorous (MVPA) may yield the greatest health benefits – including cardioprotective benefits and cardiorespiratory fitness (WHO, 2015). Hence, in guidelines adopted by the governments of developed nations, the WHO recommend:

- Children and adolescents (aged 5–17) should accumulate a daily total of 60 minutes or more MVPA and, though most PA should be aerobic, vigorous intensity activities should be incorporated at least 3 times per week. (WHO, 2015)
- Adults should undertake a cumulative 150 minutes of MVPA per week. (WHO, 2015)

However, in many countries, particularly in the Western world, there are worrying failures to meet daily PA guidelines by certain groups of the population, increasingly associated soaring rates of obesity – itself correlated with serious illnesses like heart disease, diabetes, cardiovascular illness and cancer (Lee et al., 2012). Failure to achieve sufficient levels of PA (less than 150 minutes of MVPA per week) is in the top ten leading behavioural risks for global mortality (WHO, 2015; 2009). Though there are groups within society which are unable to undertake PA for physiological reasons, such as the elderly or infirm, the inability

to meet PA targets extends even to healthy populations, particularly children (NHS, 2016; NHS; Health Survey of England 2014; Griffiths, 2013;).

PA is incredibly important to children's physiological and psychological wellbeing and development (Tomporowski et al., 2008; Scully et al., 1998; Keays & Allison, 1995; Slemenda et al., 1991). It is positively correlated with happiness, self-esteem, academic performance, and can predict adult PA levels (Singh et al., 2012, Rasciute et al., 2010; Telama et al. 2005; Telama et al., 1997). However, several barriers to PA may account for an uptake in sedentary lifestyles and failure to meet targets for concerning numbers of children:

- Increased screen time watching television and playing video games, particularly during the adolescent years. Note, screen time is also correlated with unhealthy eating habits, arguably exacerbating health worries (Cliff et al., 2016).
- There are barriers within the structure of education, for example, most schools subscribe to a format prolonged periods of sitting during lessons, totalling many hours of sedentary activity throughout the day (Carson et al., 2013; Donnelly et al., 2011). Furthermore, extra-curricular sports options can be limited and there is a tendency to advocate sporting activities to only those with high ability levels (Bocarro et al., 2008).
- Ecological determinants, such as the limited and the associated costs of access to recreational facilities (Davison et al., 2006). In many areas, safety concerns are also a barrier to outdoor PA and may also limit opportunities for physically active commutes e.g. walking to school (Carver et al., 2008).
- Psychological considerations also apply. E.g., those with positive attitudes towards PA and competence / self-efficacy with respect to ability levels, are more likely to undertake it (Dishman et al., 2005; 2004; Trost et al., 1997). Hence, the need to promote intrinsically motivating PA experiences has been posited by some authors (Laine & Suk, 2015; Dishman et al., 2005; 2004).
- Other factors may also include time constraints, weather and parental interest in PA.

Consequently, recent studies of PA participation have produced troubling results. A British Heart Foundation review found only 21% of boys and 16% of girls aged between 5-15 in England met PA recommendations (NHS, 2014), with similar results reported from studies across the Western world. There have been relative exceptions to these trends in some studies like the 'Scottish Health Survey' (Wilson et al., 2015) which found 75% of children achieved PA targets.

However, at best such studies fail to highlight the serious reality of what appears to be superficially optimistic results. Consider 75% meeting these targets means that roughly 1 in 4 children do not achieve enough PA. At worst, such studies often grossly misrepresent the true statistics. The WHO's European 'Health Behaviour in School-aged Children' study produced grossly different statistics. In Scotland, less than 30% of children between the ages 11 and 15 met PA guidelines, with teenagers enduring even further decreases (15 year olds: 11% girls, 14% boys; 13 year olds: 13% girls, 19% boys; 11 year olds: 21% girls, 29% boys) (Inchley & Currie, 2013). Meanwhile, the European average was less than 30% for the same age range, again decreasing as children entered their teens (15 year olds: 11% girls, 21% boys; 13 year olds: 15% girls, 25% boys; 11 year olds: 21% girls, 30% boys) (Inchley & Currie, 2013).

Design Method:

To promote moderate to vigorous intensity PA (MVPA), activities should elicit aerobic and anaerobic exercise.

3.2.2 Exergames: Fitness for Purpose

With the barriers to PA facing children and the serious implications of sedentary lifestyles now clear, researchers wish to establish methods for breaking down barriers and helping children to meet their MVPA targets. Although researchers have attempted to do this through non-technology based PA programs and interventions, enforcing their participation is resource intensive and questions remain over their long-term feasibility (Payton et al., 2011). Many individuals, particularly children, choose to take part in activities because they are deemed to be fun or enjoyable and, thereby, compelling (Payton et al., 2011). Such experiences can be generated by playing video games and, therefore, exergames have been studied in relation to promoting MVPA while fostering engaging PA experience. Notwithstanding, the goal is not only to promote PA but promote behaviour change towards healthier lifestyles.

Exergames suitability for promoting children's activity is highlighted by the following trends and statistics:

- The Pew Internet & American Life Project's survey revealed that among young people, ages 12 – 17, 97% of respondents play video games (Thomas, 2015)
- A 2015 UK Ofcom reported listed the following (Ofcom, 2015):
 - 40% of children aged 5-15-year-olds own a tablet while 35% own a smartphone
 - 75% have access to a mobile device either at home or school
 - Tablet use is increasing
 - Following televisions (99%), games consoles (fixed or portable) are the second most common type of media device in 5-15-year-old children's bedrooms (37%)
 - 86% of 5-15-year-olds have a network enabled device and internet access at home

To establish exergame potential, researchers have designed and evaluated their own interest-tailored exergames but also evaluated the commercial exergames compatible with mainstream media devices and wider audiences – see Peng, Crouse, and Lin (2012).

Although, literature has established the ability of commercial exergames to promote light to moderate PA, in many cases the intensities or durations recorded were not enough to address MVPA targets. Therefore, there is debate regarding exergames' potential real-world benefit.

A systematic review of 13 exergame interventions and 28 laboratory studies (Peng, Crouse, and Lin 2012) found exergame energy expenditure to be highly variable and dependent upon their design but reported a general promotion of light to moderate (2-5 METs) PA during gameplay. These results echoed an earlier review by Biddis et al. (2010) and in both, the studies reviewed made use of commercial home exergame titles like Dance, Dance Revolution, and Cateye GameBike, in addition to Wii and Sony EyeToy exergames. Biddis et al. (2010) highlighted the need for full body movement in exergames and noted the involvement of the lower limbs provided the most exerting experiences, at levels able to significantly contribute towards MVPA targets if maintained for longer durations.

Irrespective of such limited outcomes, many researchers remain philosophical and believe future results may be positively influenced by improving exergame designs and embracing ubiquitous gaming platforms (Laine, 2015; Peng, Crouse, and Lin 2012). Peng, Crouse, and Lin (2012) concede that developments in mobile exergaming (not included in either review) may lead to more consistently exerting or intense PA experiences, such as 'pervasive exergames' which integrate physical and social aspects of the real world (Kasapakis, 2016) and make use of wearable or mobile technology.

One example was the Monster and Gold exergame, a research-developed pervasive exergame, able to produce relatively consistent levels of moderate intensity PA for the study's 14 participants – around 70% of game time. Recent studies evaluating console-based exergames have also shown positive potential. E.g., 36% of 34 pre-pubertal children (20 boys, 14 girls; 10.8 ± 1.0 years old) achieved a mean energy expenditure of >6 METs (vigorous) while completing two 15-minute 'Kinect Adventures!' games on the Xbox Kinect (McNarry and Mackintosh (2016)). These studies present the potential of exergames as a vehicle for addressing MVPA targets and identify some predictors of energy expenditure (i.e. gender, fitness, and age). However, the small participant numbers limit the weight of such findings and highlight the need for further research to ascertain, confidently, the extent of MVPA possible during exergame play over time.

Despite recent successes, evidence for behaviour change towards physically active lifestyles remains inconclusive (Biddis & Irwin, 2010). Novelty effects associated with exergaming may be a key factor. Remember the Nintendo Wii's record-breaking early sales but failure to maintain mainstream interest which led to falls in use and long-term sales. However, novelty has also been observed in academic exergames. One three month study using the Wii Fit exergame with 21 participants from 8 households, showed decreases in average use from 22 minutes per day during the first 6 weeks, to only 4 minutes per day for the remaining 6 weeks (Owens et al., 2011). Furthermore, there was no discernible change in performance between pre- and post- fitness testing which emphasises the implications of novelty on real-world outcomes.

By considering exergaming limitations in energy expenditure, behavioural change, and novelty, some researchers have placed impetus on creating intrinsically motivating experiences (Laine & Suk, 2015). Evolving exergaming to mobile and pervasive platforms may be one method. Jegers (2007) reported the inclusion of real-world environments in exergames may allow for greater social interaction and immersion, characteristic of intrinsic motivation.

'iFitQuest' (Robertson et al., 2016; Macvean and Robertson, 2013; 2012), a location-based, pervasive exergame for smartphones, attempted to evoke feelings of self-efficacy and competence through user-centred design (UCD) – game development in partnership with their target users. The process sought to understand the interests and needs of users while providing variable challenge, goal setting and opportunities for social interaction and competition. Unlike many studies, the research team opted not only to gather PA data but also to understand user experiences to inform future design. In an initial 7-week pilot study

(Macvean and Robertson, 2013) involving 12 P7 (aged 11-12) primary school pupils, accelerometry data revealed the ability to promote light, moderate, and vigorous PA – and 8 participants reported wanting to replay the game following the study. This study was followed up by a 5-week RCT (Robertson et al., 2016) involving 215 P7 children from 10 Scottish Primary schools, where children played iFitQuest for approximately 60 minutes per week and unearthed different motivations for play. Some participants valued earning points and only picked games likely to maximize scores, some valued mastery and attempted all mini games equally, and others played for social reasons like impressing peers with their achievements. Hence, these studies showed the need to support both commonly shared and individualistic player motivations.

Design Requirement:

The game should be mobile to take advantage of the greater social interaction and engagement associated with pervasive over console exergames.

Methodological Concerns:

- 1. A UCD process involving end-users can be useful in encouraging enjoyment and engagement*
- 2. Understanding the process of change as well as evaluation outcomes may help to develop more engaging user experiences*
- 3. Given the novelty effects on user engagement synonymous with serious games, studies need to evaluate impact longitudinally.*

Designing exergames which support social interaction can positively influence motivation to play (Payton et al., 2011; Park et al., 2012). One study explored the differences in exergame adherence using single and multiplayer game modes with 27 children (aged 9-12 years) over a 12-week period and found significantly lower dropout rates (15%) in the multiplayer group in comparison to the single player group (64%) (Paw et al., 2008). Similar results were seen in an independent small study (n=14) comparing the single and multiplayer modes of two different exergames on different platforms and concluded “*playing AVGs with a friend in multiplayer mode significantly increases heart rate and energy expenditure above that reached during single player mode*” (C. O’Donovan et al., 2012, p. 288).

Design Requirement:

The game should involve social play to sustain engagement and longevity, as well as PA intensity.

Echoing the need for creating intrinsically motivating games is Payton et al. (2011), who stated the potential of exergames to make PA more attractive and rewarding for players. Payton et al. (2011) suggest breaking down the adherence barriers, common to PA interventions, by providing ‘continual challenge’ tailored to a player’s physical abilities and providing opportunities for social interaction (another factor associated with sustained PA) – such as play which integrates both competition and collaboration. Similar findings affirming the need for social integration within exergames have been presented by Mueller and Aquamaniles (2008) using their exertion interface, and Trout and Zamora (2008) who successfully integrated the Dance, Dance Revolution game within a P.E. class.

Several authors have advocated the use of exergames within structured environments, such as schools (Baranowski et al., 2014; Roberstson & Macvean, 2013; Eiriksdottir et al., 2011). Baranowski et al. (2014, p. 73) state, “*children spend up to a third of their weekdays at school, making this an important setting to promote physical activity*”, and reference the positive impact on children’s PA when exergames have been used in PE classes. However, Baranowski also highlights other opportunities to use exergames within school settings, like break times and after school clubs. In addition, some have recommended assimilating aspects of school contexts into the design of exergames, specifically modelling game activities and patterns of play around the game mechanics of popular playground games as a vehicle for providing both motivating and exerting experiences (Misund, 2009; Jegers, 2007; Ratel, 2004). The advantages of mimicking playground game patterns of play may also apply to intensities. Ratel et al. (2004) found an interval training approach to PA, consisting of low to moderate PA interspersed by periods of vigorous PA to be very appropriate for children because it mimics patterns of exercise within many traditional playground games (Ratel et al., 2004).

Finally, there is strong support for a Self-Determination Theory approach (Baranowski, 2014; Peng, Lin, Pfeiffer, 2012) – a theory of intrinsic motivation covered in Section 3.3.2 (p. 79) which encapsulates many of the recommendations presented in this chapter.

Design Methods:

1. *To promote user engagement and physical exertion, model game activities and patterns of play around the mechanics of playground games.*
2. *To mimic PA experiences common to children in playground games, exercise should follow a pattern of intermittent high-intensity (i.e. sprinting) interspersed with lower intensity periods of PA (i.e. walking or jogging).*

Methodological Concern:

A structured school environment may be an appropriate venue for exergame interventions, given the time spent there during weekdays.

3.3 Developing Engaging Game Design

Game design as a discipline of academic discussion is still in its youth, emerging in the early 80s as psychologists and game developers alike sought to understand the arcade and home gaming phenomenon sweeping the globe (Wolf et al., 2003). Since then, there has been no shortage of literature and research, attempting to capture both enthralling and underwhelming characteristics of games designs, yet there is no silver bullet nor unified methodology for designing universally successful video games (Schell, 2014). Perhaps this is a utopian ideal given the heterogeneity in gaming genres, content, player interests, and purposes and is perhaps why game design remains to some extent a subjective art form. Instead, what exists is a great breadth and depth of some distinct and related design principles, theories and models (Schell, 2014).

The literature presented to this point has highlighted a lack of longitudinal evidence to support the ability of exergames and CTGs in retaining user engagement over time. In the pursuit of user engagement, serious games should consider greater congruence with motivational theories of play, which underpin the attraction and longevity of many

entertainment games while balancing the context specific design requirements required to achieve the serious high levels goals of the game (Habgood, 2011; 2005). This section describes key motivational theories, principles, and techniques involved in driving user motivation for game play.

3.3.1 Intrinsic vs Extrinsic Motivation

People have different motives for undertaking any activity, such as to earn a reward, to challenge themselves against others, to avoid punishment, to achieve a personal goal or simply because it is enjoyable. However, some theorists have attempted to dichotomize motivation into two distinct categories – intrinsic or extrinsic motivation. Intrinsic motivation is defined as “*the doing of an activity for its inherent satisfactions rather than from some separable consequence,*” e.g. for fun or challenge rather than to achieve a reward or avoid punishment (Ryan & Deci, 2000, p. 70). Meanwhile, extrinsic motivation is undertaken “*in order to achieve a separable consequence*” and external rewards or consequences are commonplace (Ryan & Deci, 2000, p. 71). However, there can be exceptions to these rules – e.g. an activity which is initially extrinsically motivated but becomes enjoyable and increasingly valued over time, resembling intrinsic motivation. This interplay between intrinsic and extrinsic motivation is studied in more detail through Self-Determination Theory (SDT).

3.3.2 Self-Determination Theory (1985)

Due to generalizability of motivation across every aspect of our lives, Self-Determination Theory (SDT) has been used in many fields of research, including PA promotion and, more recently, video games (Ng, 2012; Teixeira, 2012; Peng, 2012; Rigby & Ryan, 2011; Silva, 2010). Hence, many of the examples given in this subsection are as applicable to encouraging PA as to encouraging video game play.

Influenced by the study and debate of intrinsic and extrinsic motivation, Ryan and Deci (Deci & Ryan, 1985a; 1985b; Ryan & Deci, 2000; Ryan et al. 2006) noted the positive, persistent and powerful characteristics of human beings, who at their best are “*agentic and inspired, striving to learn; extend themselves; master new skills, and apply their talents responsibly*” (Ryan & Deci, 2000, p. 68). However, regardless of social and cultural

demographics, the same people could also exhibit characteristics to the contrary, instead appearing “*apathetic, alienated and irresponsible*” when subjected to certain contexts (Ryan & Deci, 2000, p. 68). Coupling traditional empirical methods with organismic metatheory, Ryan and Deci proposed ‘Self-Determination Theory’ (SDT) as a means of highlighting “*the social-contextual conditions that facilitate versus forestall the natural processes of self-motivation and healthy psychological development*” (Ryan & Deci, 2000, p. 68). In other words, what motivates our decision making and behaviour irrespective of external influence.

SDT presents a vivid picture of motivation to classify the grey areas between intrinsic and extrinsic motivation, left often unaddressed in previous motivational theories. The authors believe intrinsic motivation to be the driving force behind the pursuit of challenge, novelty, learning, subject or skill mastery, as well as cognitive and social development. They point towards many everyday examples, such as recreational sportspeople engaging in their chosen sport without necessitating extra-game rewards or approval in exchange for their participation, and may even pay to play themselves.

Ryan and Deci (2000) present motivation as a continuum (Figure 11) with 3 distinct motivational categories:

1. Amotivation
2. Extrinsic motivation
3. Intrinsic motivation

Each category comprises different regulatory states – in other words, to the extent of personal value one holds towards an activity and the underlying motives for doing it. For example, as individuals move towards the intrinsically motivated end of the scale, their behaviour becomes increasingly self-determined and less influenced by external pressures.

Consider the regulatory facets of extrinsic motivation:

- External Regulation - motivation occurs to gain extrinsic reward or avoid extrinsic punishment
- Introjected Regulation - motivation occurs to gain approval from others or to increase self-esteem or lessen guilt
- Identified Regulation - motivation occurs as an individual is consciously aware of the activity’s value
- Integrated Regulation - motivation occurs as the activity is fully congruent with an individual’s other values

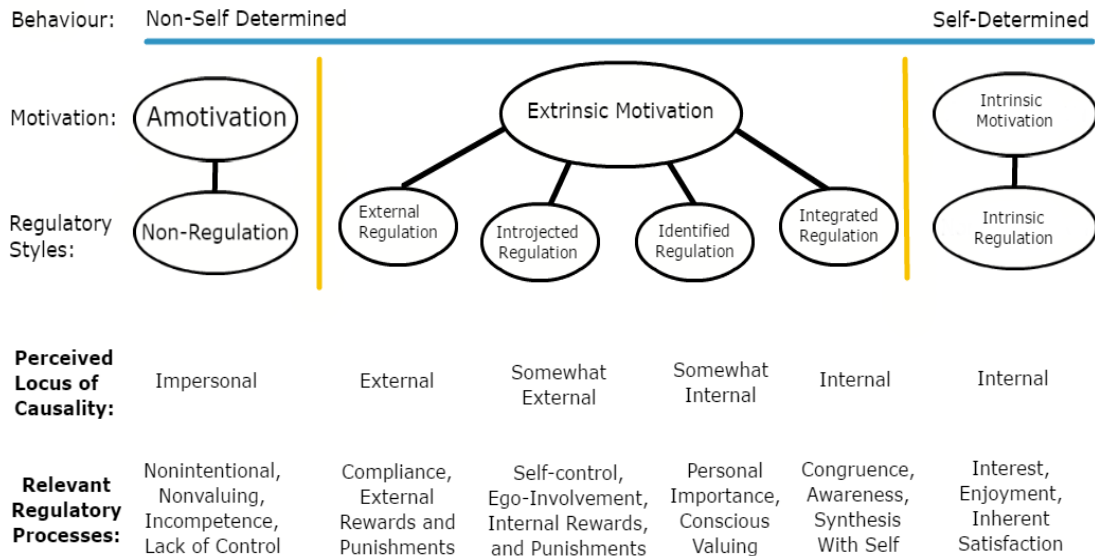


Figure 11: Ryan & Deci (1985) Self Determination Theory Continuum

SDT recognizes the subtle variations of extrinsic motivation e.g. “students who do their homework because they personally grasp its value for their chosen career are extrinsically motivated, as are those who do the work only because they are adhering to their parents’ control” Ryan and Deci (2000, p. 71). In this example, both motives typify an extrinsic value but in the first scenario there is a greater sense of autonomy (nobody is coercing them) and an understanding of the value of the activity – hence, placed as identified regulation on the continuum. In general, external and introjected regulation are classed as controlled motivation, while identified and integrated regulation are classed as autonomous motivation and share many of the same qualities as intrinsic motivation. However, it is not necessary to progress along the continuum in order of external regulation to integrated regulation, instead, an individual can move directly between different facets.

Ryan and Deci believe that to progress along the continuum, the activity must contain intrinsically interesting properties which satisfy some specific mental needs (Ryan & Deci, 2000; Ryan et al. 2006). In SDT, these needs appear as a sub-theory called Cognitive Evaluation Theory (CET) which comprises:

- Competence: a need for challenge and feelings of effectance (Ryan et al., 2006)
- Autonomy: a need for control or willingness of choice during an activity (Ryan et al., 2006)
- Relatedness: a need to connect with other people (Ryan et al., 2006)

Design Requirement:

The game should facilitate competence, autonomy, and relatedness to positively influence an individual's motivation and adherence.

3.3.3 Glued to Games: Player Experience Need of Satisfaction Model (2011)

SDT pioneer, Richard M. Ryan, explored the applicability of SDT to game design contexts in which he reported many motivational properties deployed within video games which subscribe to the theory. In Ryan's co-authored book, 'Glued to Games' (Rigby & Ryan, 2011), he states there to be a lack of rigorous evaluation regarding the psychology underpinning the popularity of video games. Ryan acknowledges the need to redefine ambiguous phenomena used to describe game motives, such as 'fun', and replace such terms with better-formed definitions and concrete methods for maintaining user engagement. This is presented as the Player Experience Need of Satisfaction Model (PENS) which applies SDT, particularly Cognitive Evaluation Theory (CET), to video game contexts (Rigby & Ryan, 2011).

Video games tap into our innate need to achieve skill mastery and are a platform for the associated feelings of pride, confidence, and self-efficacy (competence) (Rigby & Ryan, 2011). However, to continue the long-term enjoyment of any activity, we must routinely test our skills by attempting ever greater and more complex challenges (Schell, 2014; Rigby & Ryan, 2011). While many successful video games can facilitate the improvement of skills, albeit often contextually specific skills, they can support a user's thirst for challenge through variable difficulty. The level of challenge experienced should be at an optimal level which is perceived difficult but is achievable. Regardless of whether the user succeeds or fails, feelings of competency may still be fostered through positive feedback (Schell, 2014; Rigby & Ryan, 2011). To do this in video games it may be necessary to include positive and meaningful feedback which indicates progress and empowers the user to feel a goal may be goal completed with practice (Rigby & Ryan, 2011). Ryan also argues the importance of intuitive controls which are easy to learn and allow players to concentrate efforts upon play rather than game mechanics (Rigby & Ryan, 2011).

The theory of competence draws parallels with other attempts to understand motivation, such as Bandura's idea of 'self-efficacy' – commonly associated with intrinsic motivation and described as the “*judgements of how well one can execute courses of action required to deal with prospective situations*” and deals with “*how people feel, think, motivate themselves and behave*” (Bandura, 1982, p. 122). Self-efficacy is a variable and internal measure of task competency which can be influenced by many factors, such as past performances and external social issues (Rigby & Ryan, 2011). The importance of designing for self-efficacy within exergames has been previously discussed in the iFitQuest studies (Robertson et al., 2016; Macvean and Robertson, 2013; 2012).

Design Requirements:

- 1. The game should implement challenge at the cusp of ability or else the user may disengage.*
- 2. The game should avoid creating feelings of inconceivable challenge which may damage self-efficacy.*
- 3. The game's controls should be easy to learn and not distract from the experience.*

Design Method:

The user should be supported through the use of positive and meaningful feedback.

Autonomy is the freedom to make choices based on one's volition, to exercise control to pursue interests or values, and the empowerment of self-expression (Rigby & Ryan, 2011; Deci, 1985). Nevertheless, creating opportunities for choice allow us to exert control more frequently. Games can satisfy the need for autonomy by empowering players to make choices over strategies or solutions to challenges or between different activities (Rigby & Ryan, 2011). Autonomy can also be exercised by control over one's identity. Many games allow the creation and customization of personal avatars upon which users may impose valued characteristics or ideas. However, in instances where there are no customizable characters, a player may represent their identity through their style of play (Rigby & Ryan, 2011). E.g., the decisions they make during play – strategies and tactics, goals undertaken or choices made.

The PENS model (Rigby & Ryan, 2011) emphasises the role of in-game rewards in fostering autonomy but states such components should be informational rather than controlling. E.g. a controlling reward might tell a user *“to earn a prize, you must do XYZ”*, whereas an informational reward might explain the instructions before surprising the user with a prize following a successful attempt. Hence, game designs should provide flexibility over movements and strategies, choice over tasks and goals, and rewards structured to provide feedback rather than to control behaviour (Rigby & Ryan, 2011). Failure to provide choice, control or freedom can decrease feelings of autonomy and the intrinsic motivation to continue game play.

Design Method:

To promote feelings of autonomy, include opportunities for self-expression, personal tactics and strategies, and goals within the gameplay experience.

The PENS model (Rigby & Ryan, 2011; 2006) cites the increasing popularity and prevalence of social games, such as those focused towards network-connected gameplay, in highlighting the importance of ‘relatedness’. Relatedness is characterised by the way *“humans inherently seek to be connected with others and feel that they are interacting in meaningful ways,”* (Rigby & Ryan, 2011, p. 65-69) e.g. seeking friendship and attention or to simply avoid loneliness and isolation. In games relatedness is usually satisfied by experiencing companionship which is supported both cognitively and empathically through the pursuit of common goals, providing opportunities to receive attention, and seeing the impact of one’s actions upon other players (Rigby & Ryan, 2011). Relatedness in video games can help positively impact or sponsor new relationships by giving players things to do together and provide individuals with reason to communicate (Rigby & Ryan, 2011).

Relatedness may be felt most strongly through cooperative play which can extend feelings of competence in situations where it is possible to achieve with the help of another, what would otherwise be impossible alone (Rigby & Ryan, 2011). In overcoming shared challenges, communication and a sense of mattering to one another is experienced and may explain the success and longevity of massively multiplayer online (MMO) games, such as World of Warcraft, where some players routinely are motivated to play for more than 14 hours a day (Schell, 2014). Such experiences of intense consumption in gameplay, which the authors define as ‘presence’, is related to the theory of ‘flow’ in which a user experiences extreme

engagement, blurring the boundaries of time – see Section 3.3.5.4 (p. 96) (Schell, 2014; Csikszentmihalyi, 1990).

While cooperation is regarded as an intrinsically motivating attribute of gaming, competition is more divisive (Song, 2013; Adachi, 2011; Rigby & Ryan, 2011; Vallerend, 1986). Though recognizing that competition, or ‘destructive competition’, can result in negative consequences and feelings, Rigby & Ryan (2011, p.78-79) argue that this occurs only in situations when opponents are *“trying to tear us down people through taunts, cheating, and mean-spirited play.”* Conversely, when good-natured or ‘constructive competition’ occurs it can foster both relatedness and competence. E.g., through challenging oneself against other people, it provides an opportunity to test and increase one’s skills, to learn from more gifted opponents or to exhibit one’s talents – each, in turn, increasing competence. Moreover, as each player is contributing to the feelings of competence of the other, it can support *“meaningful and supportive connections that are the hallmark of relatedness”* Rigby & Ryan (2011, p.78-79).

Design Methods:

1. *To encourage feelings of relatedness, social play should strengthen companionship by (1) pursuit of a common goal, (2) chances to receive attention from others, and (3) impacting other people.*
2. *To encourage feelings of competence, constructive competition can be used to enable one to test new skills, learn from opponents or exhibit one’s talents.*

3.3.4 Lepper & Malone Framework (1987), Leblanc’s Taxonomy (2004)

3.3.4.1 Design Parallels

During the 80s, Lepper and Malone introduced a framework of intrinsic motivations for learning, using computer games as an appropriate medium for evaluating their theories (Lepper & Malone, 1987; Malone & Lepper, 1987). One problem, and perhaps even a stereotype, of many serious games, such as educational games (Habgood & Ainsworth, 2011) and CTGs, is the *“chocolate-covered broccoli”* (Habgood & Ainsworth 2011, p. 5;

Bruckman 1999) approach to design. In other words, rather than integrating serious learning content, many designers use *“the gaming element of the product as a separate reward or sugar-coating”* (Habgood & Ainsworth, 2011, p.5). Malone and Lepper (1987) posited the importance of ubiquitous learning content within gameplay, utilizing techniques which closely couple serious and gaming content.

Design Method:

To promote user engagement, keep gameplay at the core of the game and at the centre of the user experience rather than being used as a reward or distraction.

Though one of the earliest attempts to understand the psychological draw of video games and inform future game design, Lepper and Malone’s work still influences many contemporary game designers and many of their principles remain commonplace with game design books and literature (Egenfeldt-Nielsen, 2016; Hamari, 2016; Laine et al, 2015; Habgood 2011, 2005). There are many parallels between the Lepper and Malone framework and SDT and with other popular contemporary game design models, such as the Le Blanc Taxonomy (Schell, 2014; Hunicke et al., 2004) which advocates designers *“move away from words like ‘fun’ and ‘gameplay’ towards a more directed vocabulary”* to describe motivational phenomena (Hunicke et al., 2004, p. 2).

Shared principles outlined by Lepper and Malone, Le Blanc, the PENS model and other authors which are important to the work presented in this thesis are summarized in the following subsections.

3.3.4.2 Challenge

Challenge is considered in Le Blanc’s taxonomy (Schell, 2014; Hunicke et al., 2004), the PENS model (Rigby & Ryan, 2011), and the Lepper and Malone (Malone & Lepper, 1987) framework as one of the core pleasures of gameplay. The following methods are important in ensuring effective challenge:

- **Variable Difficulty Level:** Malone and Lepper (1987) propose 3 ways in which difficulty can be manipulated to provide challenge:
 - (A) Determined automatically according to how well the player does

- **(B)** Chosen by the player (perhaps the ego-involving labels like ‘Cadet’, ‘Captain’, ‘Commander’ in Star Wars)
 - **(C)** Determined by opponent skill (chess, Chase, etc.)
- **Self Esteem:** *“Challenge is captivating because it engages a person's self-esteem. Success in an instructional environment, like success in any challenging activity, can make people feel better about themselves. The opposite side of this principle is, however, that failure in a challenging activity can lower a person's self-esteem and, if it is severe enough, decrease the person's interest in the instructional activity”* (Malone, 1981, p. 360). To maintain self-esteem Malone and Lepper (1987) advocate a variable difficulty level where learners can work at an ability appropriate level, while Schell (2014) and Costikyan (2005) state challenge must be ‘tuned’ to avoid being either too easy or too hard and users should be uncertain whether they will accomplish the challenge.
- **Performance Feedback:** Performance feedback is required to support continued challenge and according to Malone and Lepper (1987, p. 232) *“learning from the activity and sustained motivation depends on performance feedback”*. The authors suggest feedback can foster intrinsic motivation when it is:
 - **(A)** Frequent
 - **(B)** Clear
 - **(C)** Constructive (i.e. providing useful information concerning the direction and nature of one’s errors)
 - **(D)** Encouraging

Design Methods:

1. *To provide challenge, difficulty can be determined by (A) automatically according to how well the player does, (B) chosen by the learner or (C) determined by the opponent's skill.*
2. *To promote feelings of competence, (1) Include a type of variable difficulty level (2) Support self-esteem through appropriate but achievable challenge.*
3. *To promote feelings of competence, include frequent, clear, constructive and encouraging feedback.*

3.3.4.3 Fantasy

Fantasy features in the works of Le Blanc's taxonomy (Hunicke et al., 2004), Costikyan (2005), and Schell (2014) who note the importance of immersing oneself in imaginary worlds, scenarios, and characters, and reinforcing fantasy through vocabulary, fonts, and images in games. However, Lepper and Malone define fantasy in greater detail:

- **Intrinsic & Extrinsic Fantasy:** Malone and Lepper (1987), Habgood (2005) state intrinsic fantasies are more interesting and instructional than extrinsic fantasies and, thus, more suitable for creating engaging learning contexts. Extrinsic fantasies are analogous to the chocolate covered broccoli approach in which the fun of learning is increased by integrating the existing curriculum with a *"fantasy goal or to avoid a fantasy catastrophe"* depending on a player's answers to questions (Malone, 1981, p. 360). In such cases, *"the fantasy depends on the use of the skill but not vice versa"* (Malone, 1981, p. 360). In intrinsic fantasies, not only does the fantasy depend on the skill, but the skill also depends on the fantasy. This allows learning challenges and constructive feedback to be presented through fantasy gameplay e.g. *"the Adventure game in which a vast underground cavern system is explored in response to the players' commands can be considered an intrinsic fantasy for the skills of reading (the cave descriptions) and writing (the commands)"* (Malone, 1981, p. 361).
- **Emotional Aspects:** Malone and Lepper (1987) state that game fantasy is powerful because of its ability to satisfy the emotional needs of players. Though it can be difficult to know individual fantasy preferences, those which elicit an emotionally-involved response, such as war, destruction, and competition are likely to be popular with a broader set of individuals. Similarly, the Leblanc's taxonomy (Costikyan, 2005; Hunicke et al., 2004) lauds the use of fantasy narrative as a means of creating a series of dramatic events which can provoke an emotional response from users.

Design Method:

To promote user engagement and elicit emotional regulation, fantasy should (1) be intrinsic and fully integrated into gameplay and (2) harness popular interests.

3.3.4.4 Curiosity / Sensation

Le Blanc's taxonomy (Hunicke et al., 2004) advises the inclusion of rich aesthetics in games, including graphics and sounds, to capture user interest. Furthermore, sensory pleasure can extend even further to game controls, such as in a game like Dance, Dance Revolution where the controls induce physical feedback in the form of physical movement. However, sensory pleasure *"cannot make a bad game into a good one, but it can often make a good game into a better one"* (Schell, 2014). Discoverable content, like levels; characters; and content, is another means of harnessing user curiosity. Similarly, Malone and Lepper suggest the use of sensory curiosity.

- **Sensory Curiosity:** *"Sensory curiosity involves the attention-attracting value of variations and changes in the light, sound, or other sensory stimuli of an environment...Computers provide even more possibilities for graphics, animation, music and other captivating audio and visual effects which can be used (1) as decoration, (2) to enhance fantasy, (3) as a reward, and perhaps most importantly (4) as a representation system that may be more effective than words or numbers"* Malone and Lepper (1987, p. 235).

Design Method:

To promote user engagement, sensory curiosity can be created through graphics, animations, music and be used to decorate, enhance fantasy, to reward, or to describe.

3.3.4.5 Control (Autonomy)

In Leblanc's taxonomy (Hunicke et al., 2004; Costikyan, 2005), opportunities to control one's choices and express one's self can empower users – like the concept of autonomy from the PENS model (Rigby & Ryan, 2011). Malone and Lepper suggest two ways of creating autonomy:

- **Contingency:** *"The first characteristic of an empowering environment is that one's outcomes are, indeed, dependent upon one's responses. In almost any learning environment, there will be differential feedback as a function of the learner's success or*

failure on particular problems, providing some element of control for learners who have the ability to succeed at the task” Malone and Lepper (1987, p. 238).

- **Choice:** *“The provision of choice among alternatives requires special emphasis. Not only has the provision of choice been shown to enhance intrinsic motivation per se, it has also proved a significant variable in a variety of motivational paradigms” Malone and Lepper (1987, p. 238).*

Design Method:

To promote feelings of autonomy, allow the user to be (1) in control of their environment and outcomes should be dependent on the user’s choices, and (2) have a range of choices to choose from.

3.3.4.6 Interpersonal

Echoing the concept of relatedness from the PENS model (Rigby & Ryan, 2011), Leblanc’s Taxonomy (Hunicke et al., 2004) encourages cooperation with other players by information sharing or supplying conditions that are more difficult to achieve alone to create community and friendship, while Costikyan (2005, p. 28) reports *that “shared intense experiences breed a sense of fellowship.”* Malone and Lepper try to identify meaningful ways of interacting socially in games including the interplay between competition and cooperation:

- **Interpersonal Factors – Competition & Cooperation:** *“Often, cooperation has been assumed to be good and competition has been assumed to be bad. However, both can provide powerful motivations for learning and...in ways, that have beneficial effects”* (Malone and Lepper, 1987, p. 242-243). Competition and cooperation can both be distinguished by tasks which are independent (exogenous or extrinsic) – e.g. a game in which players would compete with score, taking turns on alternate rounds – and those which are dependent (endogenous or intrinsic) – e.g. a game where the actions of one player may have a direct effect on the outcomes of another and vice versa. It is believed that endogenous cooperation and competition may have more positive effects upon motivation than their exogenous counterparts, as it provides an individual with a sense of control – outcomes will be directly predicted by one’s performance which has direct consequences for an opponent or teammate (Malone and Lepper, 1987).

Design Method:

To encourage positive social interactions, competition and cooperation should both be included in designs but must be endogenous and direct rather than turn based.

3.3.5 Game Balance

3.3.5.1 Balance Overview

Balance is essential to successful game design and its role within a game is far reaching (Schell, 2014). This subsection introduces many important design methods which influenced the development of the BrainQuest in Chapter Five and Appendix A. Designers often must capture the middle ground between different mechanics and sometimes between different schools of thought.

3.3.5.2 Balancing Motivation

Many of the previously presented theories have emphasised the importance of intrinsic over extrinsic motivation to maintain engagement and game longevity. However, as noted by Schell (2014), although “*some are quick to vilify extrinsic motivation as being ‘cheap’ game design, savvy designers know that one motivation can grow another.*” Consider, the non-binary nature of SDT which stipulates the fluidity of motivation – what may begin as being extrinsically motivated may become more intrinsically motivating over time (Ryan and Deci, 2000). Hence, extrinsic factors may provide an initial reason to engage in gameplay and can be used as a hook or subsequent gateway to an intrinsically motivating experience.

Design Requirement:

The game should include both intrinsic and extrinsic motivators.

3.3.5.2.1 Leaderboards

Leaderboards are defined as extrinsic game motivation, specifically exogenous competition, as they encourage competition between game players beyond the scope of direct gameplay. Hence, many authors have questioned their suitability for sustaining motivation towards an activity (Butler, 2013; Hecker, 2010; Nicholls, 1984) and competition in general (Song et al., 2013). Leaderboards which evoke ego-involved motivations and can have negative implications on performance depending on the background of the player (Butler, 2013; Nicholls, 1984) - individuals with high perceived ability are likely to worry about failure, leading them to undertake easy tasks in which they are assured of success rather than risk failure by challenging themselves (Nicholls, 1984). This is potentially counterproductive to maintaining the challenge at the cusp of ability, something key to preserving user engagement and development in serious games.

Despite this, such detrimental effects have been disputed and other authors have presented social and motivational benefits to the contrary. In an empirical analysis of common gamification elements with 300 participants in a non-game context, Mekler et al. (2013) found the use of leaderboards have no negative effect on intrinsic motivation and, in fact, led to enhanced activity performance. However, it should be noted that Mekler's study was not longitudinal and the reported results may be subject to change with time. Notwithstanding, other authors have justified the inclusion of leaderboards as they may be interpreted as a form of performance feedback (Kim et al., 2015) and a means of goal-setting by the user – gaming psychology literature stipulates that having a goal is always better than not having a goal (Zagal et al., 2005; Locke & Latham, 2002). Leaderboards have also been shown to encourage social interactions (social comparison) between players (Weiser et al., 2015; Kim et al., 2015; Schell, 2014), and may lead to increased user engagement. Hence, while leaderboards may be a positive, yet exogenous game design aspect, caution needs to be taken to avoid negative consequences for less competitive users.

Design Methods:

- 1. To foster social interaction, leaderboards can be used.*
- 2. To promote user engagement, leaderboards can be used as a form of goal setting.*
- 3. To promote feelings of competence, leaderboards should be opt-out for those of a non-competitive nature.*

3.3.5.2.2 Rewards

Like leaderboards, reward systems may also be detrimental to intrinsic motivation (Vansteenkiste et al., 2010; Kohn, 1993). However, others (Hidi 2016; Schell, 2014; Denis & Jouvlot, 2005) believe there to be an auxiliary role for rewards in creating positive gameplay experiences. Furthermore, extrinsic rewards can be viewed differently depending on academic school, e.g. within the field of neuropsychology rewards are generally considered to be positive reinforces that result in learning (Hidi, 2016). Even Lepper (1998) acknowledges the usefulness of extrinsic rewards, at least in the short term, e.g. when an individual lacks the initial motivation to undertake an activity. Hence, effective game design considers both intrinsic and extrinsic rewards for play (Dondlinger, 2007).

Trophies can be used as additional performance feedback or sub-goals for the users. Earning a trophy is a direct response to one's actions, enhancing the contingency component (Malone & Lepper, 1987) of the game. The trophy sub-goal also gives the user increased choice as not only do they have the short-term goal of earning points but they also have a long-term goal of collecting all or specific trophies. Hamari & Eranti (2011) describes achievements as goals beyond the scope of individual game sessions, while Jakobsson (2011) sees achievements as quests in a system where players collect virtual rewards which are separated from the rest of the game and are almost games within themselves (Hamari & Eranti, 2011).

The way in which trophies are presented may also be of importance. Hidi (2016) proposes that rewards which are intermittent in nature and are earned rather than presented as a token gesture may lead to sustained motivation because of increased competence from the positive feedback. Furthermore, Hamari & Eranti (2011) praise the use of historical rewards, such as a collection of aesthetic in-game belongings or achievements, as a catalyst for building a social system of reputation and competition – like games such as 'Team Fortress 2' (Hamari & Eranti, 2011) where users may compare achievements with friends. This last point illustrates how rewards may sometimes present themselves implicitly – granting individuals a feeling of status, which is particularly important to competitive players (Schell, 2014).

3.3.5.2.3 Bartle's Taxonomy

Whether a design decision evokes intrinsic or extrinsic motivation may also depend on individual personalities. What is "fun" for some, may not be for others. E.g., some

individuals flourish under and have an intrinsic enjoyment of competition, while others seek to avoid competition wherever possible. Furthermore, players' goals may change over time as one's confidence and ability develops. Thus, good game design provides opportunities for different player types (Schell, 2014).

In 1996 Professor Richard Bartle, proposed a taxonomy for 4 different types of video game players with different goals from single and multi-player games (Bartle, 1996):

- Achievers – these players “*give themselves game-related goals, and vigorously set out to achieve them*” (Bartle 1996, p.3). These players appreciate challenge and seek to accomplish all that the game can offer e.g. collecting rewards. The achiever may enjoy sharing achievements with others and topping public ranking systems e.g. leaderboards (Bartle 2005, 2003, 1996).
- Explorers – these players tend to travel and discover areas game maps and features (Andreasen & Downey, 2001). Explorers prefer trying to understand the stories, places and people in the game to create a rich, memorable experience. These players enjoy storytelling with other players (Bartle 2005, 2003, 1996).
- Socializers – these players “*use the game's communicative facilities and apply the role-playing that these engender, as a context in which to converse with their fellow players*” (Bartle 1996, p.4). They are motivated by connecting with others and are more likely to seek out multiplayer games or popular mainstream games. Socializers seek to fill up in-game friend lists, use messaging services to make new connections, and join in-game clubs and gangs – engaging in cooperation (Bartle 2005, 2003, 1996).
- Killers – these players “*wish to dominate other players through bullying or through politicking*” (Bartle 2005, p.2), preferring to fight real players than computer controlled derivatives. Killers revel in playing a villainous role and are very competitive adversaries. Note, they are often experienced players who have come from their humble beginnings as achievers, who now become their prey (Bartle 2005, 2003, 1996).

Design Methods:

1. *To foster social interaction and competition, historical game rewards, such as trophies, can be used.*
2. *To promote feelings of competence, trophies can be used as a form of performance feedback.*
3. *To promote user engagement, trophies should be presented intermittently and must be earned rather than expected.*
4. *To promote user engagement, trophies can be used as a form of goal setting.*
5. *To promote feelings of autonomy, include multiple goals to support different styles of play.*

3.3.5.3 Novelty

Novelty can be a powerful short-term tool to capture user interest (Schell, 2014). New technologies or changes from traditional interaction methods, genre, and mechanics are all ways in which designers have successfully harnessed novelty to drive interest in games. Furthermore, as discussed in Chapter Two (Section 2.1.5, p. 27), creating a novel component within the goals of a game are essential to cognitive training which involves EF, a series of skills provoked readily in novel circumstances (Rabbitt, 2004).

Despite this, an ill-advised game design which relies purely upon novelty to capture user interest without developing additional means for providing intrinsically motivating experiences is likely to impact the longevity of the game. This is a problem synonymous with both exergames (Macvean & Robertson, 2013) – i.e. Fish N Steps (Lin et al., 2006) and the American Horsepower Challenge (Eiriksdottir et al., 2011), and suspected in current CTGs (Mishra et al., 2016) where it is necessary to sustain users in play for long periods of time or even indefinitely to see a positive effect of game play or to encourage behaviour change.

3.3.5.4 Challenge

A reoccurring idea present in the PENS model; Leblanc's taxonomy; and the Lepper and Malone's framework, is creating challenge requiring persistence but which remains both achievable and fair. Games must balance challenge with success, using techniques such as increasing difficulty with each success; letting skilled players progress quickly to challenging difficulty levels; and by creating layers of challenge, such as incorporating additional ways of scoring performance (Schell, 2014).

If challenge is executed effectively, users can submit to deep feelings of engagement during gameplay and enter a psychological state known as flow where perceptions of time and reality become blurred (Schell, 2014). To achieve flow, a phenomenon identified by Csikszentmihalyi (1990), games should suspend the user in a golden channel between anxiety and boredom by exponentially increasing the challenge as an individual's skill increases. The result is to create a cycle in which users experience a range of emotions which promote competence - moments which require a degree of perseverance but are not too frustrating, and other moments of relative ease (Schell, 2014; Csikszentmihalyi, 1990).

In exergames, however, flow may need to be applied as much to physicality as psychology. Laine & Suk (2015) stress the need for 'adaptability' in exergames to make sure that players of different fitness levels can enjoy the game. Computer software can achieve this using artificial difficulty systems in single player games but in social games this may be harder as players of different abilities must play together. This is a common problem with traditional sports which can lead to demotivating experiences making it less likely for an individual to play again. However, mitigating this problem can be difficult (in some situations impossible) and usually involves grouping certain individuals together in a specific way, such as age or ranking, or to introduce some form of handicap (Stach & Graham, 2011). Video games can build in mechanisms to mediate such issues by creating an 'asymmetrical structure' (Schell, 2014). Such ways of doing this include: giving players other ways to explore a game – providing multiple aspects of the game for players to discover, master or measure their performance as opposed to one single game or measure of ability; and levelling the playing field by allowing the game to challenge each user in different ways, while allowing them to continue playing together.

Design Methods:

1. *To promote user autonomy and competence, challenge should be layered by incorporating more than one way of scoring performance.*
2. *To promote feelings of competence, physical activities should be adaptable to different ability levels and attempt to mitigate ability to let users of mixed ability to play together competitively.*

3.4 Designing for Serious Games

3.4.1 The Difficulty of Designing Serious Games

As stated by Winn (2008, p. 3), “*Making a good game is hard. Making a good serious game is even harder. The reason it is so difficult is that rather than simply trying to optimize the entertainment aspect of the game or the so-called fun factor, one must also optimize to achieve a specific set of serious outcomes.*” Hence, often serious games are the product of interdisciplinary research positioned at the centre of a 3 circle Venn diagram bringing together – game design, content, and knowledge.

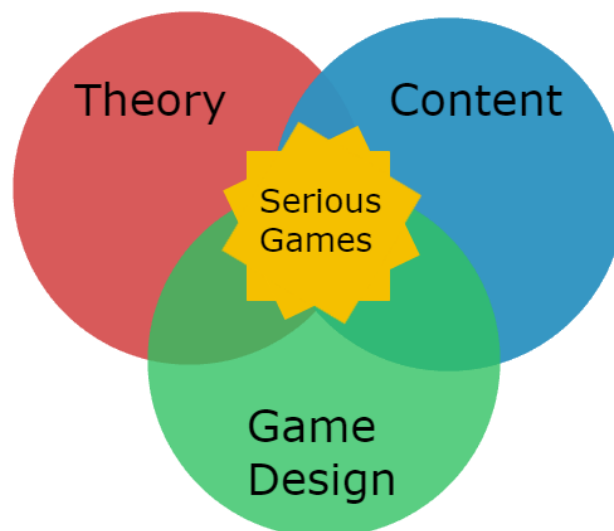


Figure 12: Winn (2008) Serious Games

3.4.2 Development Approaches

3.4.2.1 User-Centred Design

“User-centred design means understanding what your users need, how they think, and how they behave - and incorporating that understanding into every aspect of your process.”

Garrett (2002).

User-centred design (UCD) is a broad term used to describe development processes in which end-users influence how a design takes shape. UCD advocates fully exploring user needs and desires, the intended uses of the product and to involve users in the environment in which they would use the product (Abrams et al., 2004). One common UCD technique is participatory design in which users co-design a product through evaluation of high and low fidelity prototypes. It is championed by Alison Druin, an academic who pioneered the technique while designing technology with children (Druin, 2002). Recently, UCD has also become a typical approach in exergame design with the human-computer interaction (HCI) field (Toscos et al., 2006; Macvean, A. and Robertson, J., 2013; 2012).

The success and subsequent mainstream adoption of UCD within HCI communities has been built on helping researchers gain a deeper understanding of the product end-users, their needs, desires, frustrations, as well as the environment in which they operate, thus, assuring the product will be suitable for its intended purpose (Druin, 2002). This may be consequent of spending more time within the user’s domain and establishing a working relationship with end-users. Additionally, UCD teams generally benefit from the inclusion of people from different disciplines, particularly psychologists, sociologists, and anthropologists, because they can view the product from an alternate lens.

The child as...

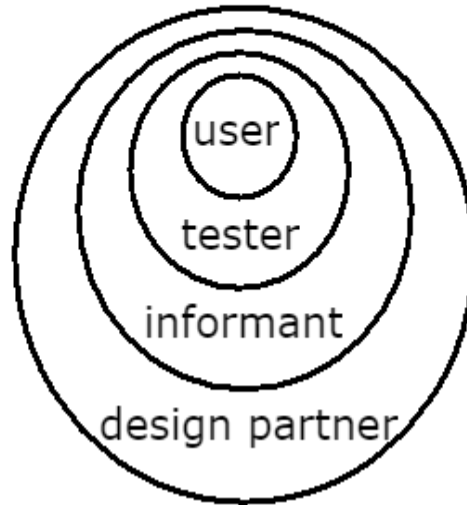


Figure 13: Druin (2002) Onion Diagram

Users may assume different roles within the UCD process which are shown in Druin's Onion Diagram in Figure 13. There are varying degrees of user involvement, with each inner layer encapsulating and adding to the responsibilities of roles towards the outside. The role most pertinent to the work presented in this thesis was that of 'Informants' – the second most intensive involvement after 'partner'. In the informant role, children play a part in the design process at various stages, based on when researchers believe children can influence the design process. Before any technology is developed, children may be observed with existing technologies or they may be asked for input on design sketches or low-tech prototypes. Once the technology is developed, children may again be involved in input and feedback (Druin, 2002).

Methodological Concern:

At each stage of the development cycle, the designer should plan, implement or evaluate the game with respect to (1) learning outcomes, (2) storytelling or the story to be created by the user's experience, (3) gameplay mechanics, dynamics, and aesthetics, (4) the user experience of the interface, and (5) the technology platform.

3.4.2.2 Boehm's Spiral

In 1986 Barry Boehm introduced the Spiral Model – a software process model which incorporated aspects of alternative models to create a 'risk-driven' approach to developing software (Munassar et al., 2010; Boehm, 1988). Thus, the Spiral Model allows for early identification of risks to the successful completion of the project throughout the entire development, allowing developers to take correcting action (Munassar et al., 2010; Boehm, 1988). The model's emphasis on design and evaluation with end-users, development of incremental prototypes, and iteration, align well with the UCD methodologies.

The model (Figure 14) stipulates users follow an iterative approach consisting of the following stages:

1. Determine objectives – product requirements are gathered, usually with the help of end-users. Constraints on the project are identified and alternative solution implementations are outlined. (Munassar et al., 2010; Boehm, 1988)
2. Risk analysis – the alternative implementations are evaluated relative to the objectives and constraints of the project. This process leads to highlighting aspects of the project which are uncertain and which may present a risk to the objectives. To explore these uncertainties, prototyping of single or alternative solutions may be implemented – these prototypes may or may not software-based i.e. paper prototyping, simulations etc. (Munassar et al., 2010; Boehm, 1988)
3. Development and test – software is created from the prototype and is then tested before being evaluated against the requirements, usually with the help of an end-user. Consequently, decisions are taken either to reduce risks which could not be addressed by the current product or to use the current product as the base for additional functionality. (Munassar et al., 2010; Boehm, 1988)
4. Planning next iteration – a review of requirements and objectives are undertaken. Plans for the next prototype and its evaluation are defined. (Munassar et al., 2010; Boehm, 1988)

Elements of Boehm's spiral, including the rapid prototyping approach, have been commonly used in the serious game design field. This was the development approach taken to the design of the iFitQuest exergame Robertson and Macvean (2013; 2012) as well as the Savannah Project educational game described in Section 3.4.2.3 (p. 101).

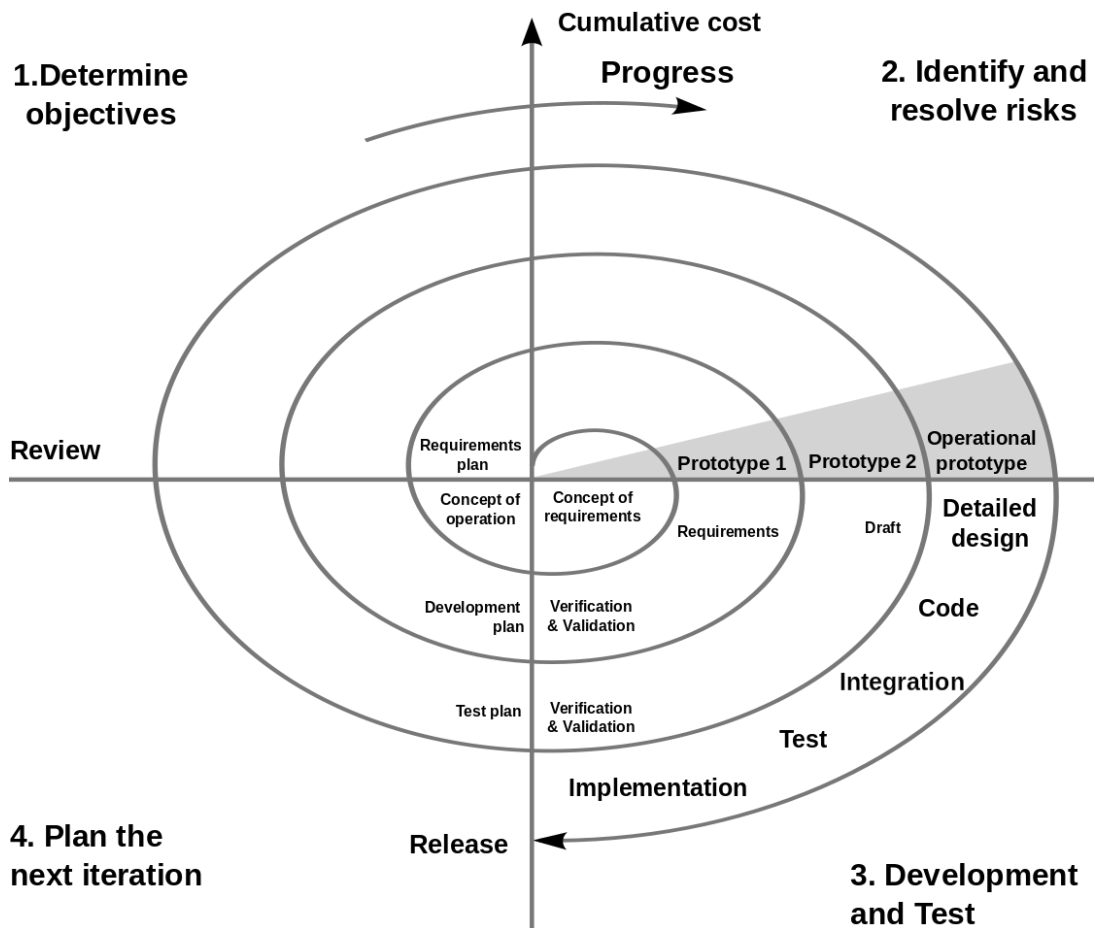


Figure 14: Bohem's Spiral Model 1986

3.4.2.3 An Example: The Savannah Project

The Savannah Project, a location-based GPS game, was a game which employed a UCD approach and integrated learning content with an engaging user experience. The game sought to educate children about lion behaviour and their survival in the wild (Benford et al., 2004; Facer et al., 2004). The research team iteratively developed the game using workshops, prototype developments, and evaluations with end-users (Benford et al., 2004).

They used rapid prototyping to determine and refine game rules. Instead of automating rules in initial prototypes, the researchers improvised some game mechanics depending upon the actions taken by the user – i.e. manipulating points or rewards because of user actions, such as time spent in certain areas of the savannah (Benford et al., 2004). Rules deemed to be engaging were later hard-coded in subsequent iterations (Benford et al., 2004).

One of the game's learning goals was to encourage for collaboration between game players (Benford et al., 2004). This was not only to increase user enjoyment but sought to teach the

children about the way lions must cooperate in the wild in pursuit of a common goal. Sounds and graphics were implemented to be engaging but educational and integrated savannah sound and graphics to the user's mobile device interface as they moved in the real world (Benford et al., 2004).

Striking a balance between immersive gameplay and opportunities for reflection on the lessons learned, the game's designers structured engaging gameplay aspects as a series of 'missions' which were interspersed by periods where the children return to a 'den' (Benford et al., 2004). Den periods provided an opportunity to review mission performance as well as receive further educational content from an adult facilitator (Benford et al., 2004).

Methodological Concern:

Development for serious games should be implemented in an incremental way, designing and implementing prototypes based on experience goals before seeking feedback from end-users. Following user evaluation, changes in the design can be made to start a new prototype evolution.

3.4.3 Applying Motivational Design to Exergames

Recently several authors, such as Mellecker et al. (2013), have posited the application of motivational theory to exergames, citing the similar difficulties in promoting sustained engagement in both PA and serious games. The application of motivational theory in video games is explored by the PENS model in Section 3.3.3 (p. 82) but such theories have also been used in PA research. Cognitive Evaluation Theory (Deci & Ryan, 1985), a facet of SDT was deployed to exercise classes with children and young adults and was positively associated with greater activity enjoyment and, more importantly, adherence – fundamental for behaviour change, and physical fitness (Peng, Crouse, Lin, 2012). Thus, this supports the idea that motivational theories are generalizable across activities.

Mellecker et al. (2013) referenced several of the theories outlined earlier in this chapter – SDT (Ryan and Deci, 2000); Flow theory (Csikszentmihalyi, 1990) – as possible models for integration with exergames. Focusing on Flow Theory, Mellecker (2013, p. 145) proposes balancing challenge and success may be especially suitable and “*may provide the basis for a next level development of active video games.*” However, Mellecker et al. (2013, p. 146) state the need for longitudinal studies “*to relate aspects or components of game playing fun or enjoyment to maintained exergame play duration.*”

A small number of studies have evaluated motivationally designed exergames in practice. Peng et al. (2012) experimented with exergames to examine how game features relating to each of the 3 SDT needs may impact players' satisfaction and game experience (Peng et al., 2012). Evaluating a research-specific exergame – a fantasy role-playing game incorporating PA in its narrative – the authors undertook a 2 (autonomy-supportive game features: on vs off) x 2 (competence-supportive game features: on vs off) experiment and discovered following post-game self-reporting questionnaires, that both autonomy and competence-support features led to “*greater game enjoyment, greater motivation for future play, greater likelihood of game recommendation, and greater game rating*” (Peng et al., 2012, p. 191). To promote competence in the game, users were supported with a dynamic difficulty mechanism which adjusted according to player performance and presented informative feedback following games, direct feedback following game actions, and various achievement badges. Meanwhile, autonomy-supports included control over character customization and development but also the ability to choose from a constrained series of answers during game dialogs – hence, emphasising that autonomy can be fostered even when a finite number of choices are available to the user.

3.4.4 Addressing the Design of Cognitive Training Games

In Chapter Two (Section 2.3.3), the strengths and limitations of CTGs were discussed with respect to their conceptualization and evaluation but this subsection addresses their design.

Some authors have raised the fact that mainstream video games can elicit greater benefits to cognitive and non-cognitive skills than brain training games while also being more enjoyable. This may seem arbitrary but the enjoyment of cognitive training is key to Diamond's intervention model (2012) and the longevity of any EF training intervention. Green and Seitz (2015) highlight that CTGs are, almost exclusively, gamified cognitive tests which overlay a sugary coating of aesthetically pleasing visuals and rudimentary game elements to capture user interest. While the importance of pleasing sounds, graphics, and aspects of gamification can be useful, it is not always a case of ‘if’ to employ such techniques, but ‘how’ the techniques are deployed. To take one example common to CTGs, what is the benefit of including a leaderboard to promote socialization when there are no outlets for people to communicate, as opposed to a game where individuals may play and share an experience together, learn to regulate their behaviour and decide when to collaborate and when to work in one's own interests. Additionally, pure gamification is

synonymous with making otherwise boring activities more palatable – Schell (2014) points out that every successful game should be fun to play irrespective of traditional gamified components.

In Chapter Two (Section 2.3.3.5, p. 53) Gazzaley addressed the need for engaging cognitive training game design through his research into closed loop video games (CLVG). In CLVG's the game monitors user performance in real time to provide feedback to the user, display the game environment, and dictate in-game events and challenge. With respect to CTGs, Gazzaley feels it "*prudent for us to slow down and approach this opportunity with scientific rigor and conservative optimism*" rather than to view cognitive training as a "*clever, profitable start-up idea that can be conquered with a large marketing budget*" and to be "*led by overinflated claims*" (Mishra, Anguera, Gazzaley, 2016, p. 214). Mishra, Anguera, and Gazzaley (2016) explain that cognitive scientists are "*not typically the most proficient video game developers*" (p. 214) and approach the development of CTGs through "*layering on of simple graphic skins and low-level reward to standard cognitive task paradigms*" (p. 214), thereby, the "*gamification approach often involves sprinkling game elements on top of low-engaging cognitive tasks, creating slightly less boring exercises*" (p. 214). Instead, they draw parallels with many of the motivational theories outlined earlier in this chapter by seeking to provide immersive experiences that harness the power of fun – "*a factor why video games may be more impactful than gamified cognitive exercises*" (p. 216).

Gazzaley's CTGs, 'Neuroracer' (Anguera et al., 2013) and 'Project Evo' (Anguera et al., 2016) offer gameplay experiences more akin to traditional video gaming. As described in Chapter Two (Section 2.3.3.5, p. 53), instead of gamifying cognitive assessments, Neuroracer resembles an animated racing game which incorporates a multitasking cognitive challenge. However, it also integrates many of the game design principles highlighted in this chapter. For example, the game uses a variable difficulty system to create increasing challenge and multiple layers. One challenge layer manipulates the maximum and minimum speeds the car can achieve, forcing the player to pay attention, to judge inclines and declines and the amount of acceleration/deceleration required. Another layer concerns the maximum amount of time participants have to respond to signs. The game also provides performance feedback following each attempted level as well as reporting overall game progression. The evaluation results are detailed in Chapter Two (Section 2.3.3.2.4, p. 42).

Mishra, Anguera, and Gazzaley (2016) propose the following recommendations for future CTGs – note the parallels with the design theory presented throughout Chapters 2 and 3:

- CTGs should generate immersive gameplay, encouraging repeated and long durations of play – a prerequisite for harnessing the neural plasticity (neural structure changes) required to drive cognitive improvements.
- To enhance immersion, CTGs should include rich interactivity – rewards, art, music, and story – from the initial development, rather than added as an ‘afterthought’ (i.e. gamification).
- Neurocognitive targets (i.e. what the cognitive goals of the game are) and the strategies for facilitating achievement of targets should also be present early on.
- Neurocognitive targets should be supported by performance feedback and performance-based challenge.
- Challenge should be tailored using real-time performance algorithms and challenge should sustain individuals at the cusp of their abilities.
- Performance feedback is a primary source of motivation for players and should be provided in continuous or punctuated forms. Continuous feedback (like direct feedback in this chapter) concerns real-time feedback in response to user choices. Punctuated feedback may be delivered performance summaries following gameplay, conveying measures of personal growth or performance comparisons with other players.
- CTG design should involve experts from a diverse range of disciplines – video game designers, user interface experts, psychologists and neuroscientists, and multimedia engineers.
- Engaging CTGs should enable socialization.
- Immersive experiences can be created by paying attention to motivational theories, goal setting, and habit formation practices.
- It would be useful for future games to aid in the real-world and real-time – comprehensive and accurate tracking of neural and cognitive performance providing a ‘snapshot’ of ability.
- CTGs and CLVG’s could benefit from capturing ubiquitous user inputs e.g. making use of mobile technologies and synthesizing advances in virtual and augmented reality.
- Integrating CTGs with other cognitive training methodologies, including physical exercise, musical training, and meditation, could be beneficial.

While Neuroracer remains a tool for academic study, Project Evo, which follows many of the design recommendations outlined by Gazzaley, is being developed as a commercial tool

to support cognitively disadvantaged conditions, such as ADHD, autism, depression, and the results of brain damage (Anguera et al., 2016) – the game is even undergoing clinical testing to become an FDA approved treatment which could be prescribed by medical practitioners.

Design Requirements:

- 1. The game should make use of ubiquitous, mobile, and augmented reality technologies to create immersive experiences.*
- 2. The game should be able to assist in the real world in real time while providing a snapshot of cognitive performance.*

Methodological Concern:

Designing CTGs should involve experts from a diverse range of disciplines across game and technology design as well as psychology.

3.5 Summary

While the previous chapter highlighted the importance of EF to children’s psychological health, this chapter establishes the important contribution of PA to their physiological wellbeing and introduces exergames as a means of supporting PA. A review of current exergame research concludes exergames to be a promising vehicle for promoting PA, yet there remain general shortcomings with respect to fostering the engaging user experiences needed to sustain play over time.

The chapter outlines how the integration of motivational theories (Self-Determination Theory, PENS model) and game design frameworks (Lepper and Malone, LeBlanc Taxonomy) may be the key to providing user experiences in serious games which more closely resemble popular mainstream games while maintaining their learning focus. The chapter moves on to describe how some researchers have attempted to do this within the fields of exergames and CTGs and the design recommendations produced from this research. Throughout the chapter, game design principles are identified from the literature to inform the design of BrainQuest – these principles are reviewed in Chapter Four.

4. Guidelines Review

Following a review of the literature, Diamond’s (2012) theoretical model of EF building pathways was identified as a suitable paradigm around which to mould the BrainQuest system presented in this thesis. Diamond’s model collates a breadth of research threads involving EF training and provides broad-based requirements for suitable activities but it does not inform training programme designers on **how** best to implement the activities. Requiring interventions be “*fun*” and “*engaging*” or stating that EF “*should be challenged*” to the cusp of ability, is somewhat equivocal. Consequently, further literature subsumed by Chapters 2 and 3 sought to provide additional requirements overlooked by the Diamond model (2012) as well as methods for their implementation.

Throughout Chapters 2 and 3 a series of ‘design requirements’ (**R**), ‘design methods’ (**MD**) and ‘methodological concerns’ (**MC**) were highlighted. This chapter creates taxonomies for each and forms a reference point for ‘ID’ code references (R, MD, MC) in later chapters. Note, for location columns on all tables ‘C’ = Chapter and ‘S’ = Section.

4.1 Design Requirements

The design requirements described in Table 4 were created as a high-level guide to the development of the BrainQuest system. They are later compared with the design decisions made in Chapter Four.

Pathway	ID	Game Design Requirement	Location	Key Sources
EF Challenge	R1	<i>The game should have a holistic structure, targeting many different EFs in different ways and utilizing established training techniques.</i>	C2 S2.1.3; C3 S3.4.4	[214, 10, 11, 96]
EF Challenge	R2	<i>The game should target ages 8-12 – a critical age range for inhibitory, WM, and strategic EF skills as well as social skills.</i>	C2 S2.1.9	[91, 49, 25]
EF Challenge	R3	<i>The game should integrate game design theory and motivational qualities rather than simply gamification to increase user engagement.</i>	C2 S 2.3.3; C3 S3.4.4	[214, 10, 11]

EF Challenge	R4	<i>The game should make use of ubiquitous, mobile, and augmented reality technologies to create immersive experiences.</i>	C3 S3.4.4	[214, 10, 11]
EF Challenge	R5	<i>The game should be able to assist in the real world in real time while providing a snapshot of cognitive performance.</i>	C3 S3.4.4	[214, 10, 11]
Social	R6	<i>The game should be mobile to take advantage of the greater social interaction and engagement associated with pervasive over console exergames.</i>	C3 S3.2.2	[204, 265, 201, 202]
EF Challenge	R7	<i>The game should necessitate the use of WM in its challenge as it is a core EF which forms the basis of more complex skills.</i>	C2 S2.1.3	[220, 94, 14, 15, 16, 17]
EF Challenge	R8	<i>The game should train complex EFs directly and including WM rather than simply training of WM in isolation.</i>	C2 S2.3.3	[214, 220, 219, 144]
EF Challenge	R9	<i>The game should challenge WM beyond incremental and contextually specific refinement of specific processes.</i>	C2 S2.3.3	[285, 210, 209, 214, 220, 219, 144]
EF Challenge	R10	<i>The game should involve (1) planning or decision making, (2) problem solving, (3) requiring a novel sequence of action, (4) challenge, (5) overcoming strong habitual response or temptation.</i>	C2 S2.1.3	[233, 95, 96]
EF Challenge	R11	<i>The game should require switching between sustained, selective and inhibition of attention – present in action video games and associated with EF challenge.</i>	C2 S2.3.2	[133, 134]
EF Challenge + Social	R12	<i>The game should create situations involving hot EF by using rewards, penalties, social implications or personal feelings.</i>	C2 S2.1.8	[96, 91, 170]
EF Challenge	R13	<i>The game should create situations requiring IC because they are particularly challenging for children.</i>	C2 S2.1.3	[95, 121]
EF Challenge + Social	R14	<i>The game should train for real-world relevance by challenging both (emotionally effective) hot and (logical) cool EF.</i>	C2 S2.1.8	[91, 170, 5, 116]

EF Challenge + Social	R15	<i>The game should involve social activities testing emotional regulation to promote character development.</i>	C2 S2.1.3	[94, 96, 32, 87]
EF Challenge	R16	<i>The game should train cognitive skills in a way which is applicable to different contexts and more likely to foster far transfer.</i>	C2 S2.3.3	[209, 214, 285, 220, 144]
EF Challenge	R17	<i>The game should train cognitive skills used in diverse and novel situations.</i>	C2 S2.3.3	[214, 215, 284, 219, 8, 252, 56, 233, 96]
EF Challenge + Joy	R18	<i>The game should encourage repeated use as it is key to making EF improvements.</i>	C2 S2.1.3	[214, 96]
Joy + Pride/Confidence/ Self-Efficacy + Social	R19	<i>The game should facilitate competence, autonomy, and relatedness to positively influence an individual's motivation and adherence.</i>	C3 S3.3.2	[96, 260, 159, 270, 271, 89, 88, 205]
Joy	R20	<i>The game should include both intrinsic and extrinsic motivators.</i>	C3 S3.3.5	[275, 93]
Joy + Confidence/Pride/ Self-efficacy + EF Challenge	R21	<i>The game should implement challenge at the cusp of ability or else the user may disengage.</i>	C2 S2.1.3, S2.3.3; C3 S3.3.5	[243]
Pride/Confidence/ Self-Efficacy	R22	<i>The game should support EF by cultivating children's pride, confidence, and self-efficacy.</i>	C2 S2.1.3; C3 S3.3.2	[275, 96, 77, 159, 260, 81, 188]
Pride/Confidence/ Self-Efficacy	R23	<i>The game should avoid creating feelings of inconceivable challenge which may damage self-efficacy.</i>	C2 S2.1.3; C3 S3.3.3	[96, 260, 88, 89, 270, 271, 188]
Joy + Pride/Confidence/ Self-Efficacy	R24	<i>The game's controls should be easy to learn and not distract from the experience.</i>	C2 S2.3.3	[96, 260, 88, 89, 270, 271, 188]

4.2

PA	R25	<i>The game should incorporate PA component to accelerate EF improvements by coupling motor and cognitive engaging demands.</i>	C2 S2.4.1	[260]
PA	R26	<i>The game should include 'cognitively engaging PA' which involves the regulation of emotion, thoughts or action.</i>	C2 S2.1.3	[33, 32, 31, 36, 96]
PA	R27	<i>The game should promote higher intensity PA (MVPA) to accelerate EF improvements.</i>	C2 S2.4.1	[33, 32, 31, 36, 96, 214]
Social + PA	R28	<i>The game should involve social play to sustain engagement and longevity, as well as PA intensity.</i>	C3 S3.2.2	[32, 153]

Table 4: Design Requirements Design Methods

The design methods in Table 5 were created a series of ways to implement the requirements (R) in the development of the BrainQuest system. They feature heavily in Appendix A in the description of the BrainQuest development process and the design decisions made for individual prototypes.

Pathway	ID	Game Design Method	Location	Key Sources	Associated R
EF Challenge	MD1	<i>Making a task's goals clear can help to elicit planning, reasoning, and strategizing skills.</i>	C2 S2.1.3	[5]	R10
EF Challenge	MD2	<i>To create a dynamic EF challenge for user: switch between tasks; anticipate actions of in-game characters and objects; and update plans.</i>	C2 S2.3.2	[133]	R11
EF Challenge	MD3	<i>To preserve novelty challenge, change task demands to disrupt pre-learned solutions and effect re-planning of actions.</i>	C2 S2.1.5	[252, 8, 214]	R16, R17, R9, R10
EF Challenge	MD4	<i>Task demands should be incrementally increased to continue to challenge EF ability.</i>	C2 S2.1.3	[95]	R21

EF Challenge	MD5	<i>To challenge WM, game activities involve temporary storage and manipulation of spatial, visual or auditory information.</i>	C2 S2.1.3, S2.3.2	[14, 15, 16, 17, 220]	R7, R9
EF Challenge	MD6	<i>To challenge WM in a way which may benefit complex EFs: create situations requiring the user to store and manipulate information in both short and long term memory as well as controlling attention according to an overriding goal.</i>	C2 S2.3.3	[220, 311]	R16, R7, R9
Pride/Confidence/Self-Efficacy	MD7	<i>To provide challenge, difficulty can be determined by (A) automatically according to how well the player does, (B) chosen by the learner or (C) determined by the opponent's skill.</i>	C3 S3.3.4, S3.3.5	[188, 204, 205, 159, 77, 275]	R18, R10
Pride/Confidence/Self-Efficacy	MD8	<i>To promote feelings of competence, (1) Include a type of variable difficulty level (2) Support self-esteem through appropriate but achievable challenge.</i>	C3 S3.3.4, S3.3.5	[188, 81]	R22, R23, R18, R19
Pride/Confidence/Self-Efficacy	MD9	<i>To promote user autonomy and competence, challenge should be layered by incorporating more than one way of scoring performance.</i>	C3 S3.3.5	[275, 260]	R19, R23, R18
Pride/Confidence/Self-Efficacy	MD10	<i>To promote feelings of competence, include frequent, clear, constructive and encouraging feedback.</i>	C3 S3.3.4	[205, 204]	R22, R23, R18, R19
Joy	MD11	<i>To promote user engagement, keep gameplay at the core of the game and at the centre of the user experience rather than being used as a reward or distraction.</i>	C3 S3.3.4, S3.4.4	[53, 138, 214, 215, 10, 11]	R3, R1, R11, R18
Joy + PA	MD12	<i>To promote user engagement and physical exertion, model game activities and patterns of play</i>	C3 S3.3.2	[216, 164, 256]	R3, R4, R6, R12, R14, R18, R26, R28

		<i>around the mechanics of playground games.</i>			
Joy	MD13	<i>To promote user engagement and elicit emotional regulation, fantasy should (1) be intrinsic and fully integrated into gameplay and (2) harness popular interests.</i>	C3 S3.2.2	[188, 204, 138, 139, 140]	R20, R15, R3
Joy	MD14	<i>To promote user engagement, sensory curiosity can be created through graphics, animations, music and be used to decorate, enhance fantasy, to reward, or to describe.</i>	C3 S3.3.4	[188, 204, 159, 275]	R20, R15, R12, R3
Joy	MD15	<i>To promote feelings of autonomy, allow the user to be (1) in control of their environment and outcomes should be dependent on the user's choices, and (2) have a range of choices to choose from.</i>	C3 S3.3.3, S3.3.4	[188, 204, 260]	R19
Joy	MD16	<i>To promote feelings of autonomy, include multiple goals to support different styles of play.</i>	C3 S3.3.3, S3.3.4, S3.3.5	[188, 204, 260]	R19
Joy	MD17	<i>To promote feelings of autonomy, include opportunities for self-expression, personal tactics and strategies, and goals within the gameplay experience</i>	C3 S3.3.4, S3.3.5	[188, 204, 260]	R19
Social	MD18	<i>To foster social interaction and competition, historical game rewards, such as trophies, can be used.</i>	C3 S3.3.5	[142, 323, 170, 275]	R20, R12, R28
Social	MD19	<i>To foster social interaction, leaderboards can be used.</i>	C3 S3.3.5	[142, 323, 170, 275]	R28, R20, R12, R18
Joy	MD20	<i>To promote user engagement, leaderboards can be used as a form of goal setting.</i>	C3 S3.3.5	[332, 193]	R20, R21, R18

Joy	MD21	<i>To promote user engagement, trophies can be used as a form of goal setting.</i>	C3 S3.3.5	[106, 142, 163]	R20, R21, R18
Pride/Confidence/Self-Efficacy	MD22	<i>To promote feelings of competence, leaderboards should be opt out for those of a non-competitive nature.</i>	C3 S3.3.5	[60, 231]	R23, R22, R18, R19
Pride/Confidence/Self-Efficacy	MD23	<i>To promote feelings of competence, trophies can be used as a form of performance feedback.</i>	C3 S3.3.5	[151, 142, 163, 275]	R23, R22, R18, R19
Joy	MD24	<i>To promote user engagement, trophies should be presented intermittently and must be earned rather than expected.</i>	C3 S3.3.5	[151]	R22, R18, R19
EF Challenge + PA	MD25	<i>To facilitate 'cognitively engaging PA', integrate complex EF skills, such as strategizing to overcome ever-changing task demands.</i>	C2 S2.4.1	[33, 96]	R1, R8, R9, R25, R26
EF Challenge + PA	MD26	<i>To facilitate 'cognitively engaging PA', activities can involve complex motor control, such visual motor control while coordinating phone screen activities and real-world movements.</i>	C2 S2.4.1	[33, 96, 97, 3]	R1, R8, R9, R25, R26
EF Challenge + PA	MD27	<i>To facilitate 'cognitively engaging PA', activities can make use of direct cooperation or competition with others.</i>	C2 S2.4.1	[33, 87]	R1, R8, R11, R13, R14, R15, R25, R28
PA	MD28	<i>To promote moderate to vigorous intensity PA (MVPA), activities should elicit aerobic and anaerobic exercise.</i>	C3 S3.2.1	[329]	R27
PA	MD29	<i>To mimic PA experiences common to children in playground games, exercise should follow a pattern of intermittent high-intensity (i.e. sprinting) interspersed with lower intensity periods of PA (i.e. walking or jogging).</i>	C3 S3.2.2	[256]	R27

Pride/Confidence/Self-Efficacy + PA	MD30	<i>To promote feelings of competence, physical activities should be adaptable to different ability levels and attempt to mitigate ability to let users of mixed ability to play together competitively.</i>	C3 S3.3.5	[183, 201, 202]	R23, R22, R21, R19, R18, R28
Social	MD31	<i>To encourage feelings of relatedness, social play should strengthen companionship by (1) pursuit of a common goal, (2) chances to receive attention from others, and (3) impacting other people.</i>	C3 S3.3.3	[260, 270, 271, 88, 159, 205]	R1, R3, R12, R14, R15, R19, R28
Social	MD32	<i>To encourage positive social interactions, competition and cooperation should both be included in designs but must be endogenous and direct rather than turn based.</i>	C3 S3.3.4	[205, 188, 204]	R28, R26, R19, R15, R14, R12
Social	MD33	<i>To encourage positive social interactions and challenge EFs, cooperation should be focused towards children helping or teaching each other.</i>	C2 S2.1.3	[96]	R28, R26, R19, R15, R14, R12, R13
Social + PA	MD34	<i>To encourage feelings of competence, constructive competition can be used to enable one to test new skills, learn from opponents or exhibit one's talents.</i>	C3 S3.3.3	[188, 204, 271, 260]	R19, R21, R22, R28

Table 5: Design Methods

4.3 Methodological Guidelines Summary

The methodological concerns in Table 6 were identified by the literature has helped to shape the BrainQuest development and evaluation methodologies detailed in Chapter Five and Chapter Six, respectively.

Concern Type	ID	Methodological Concern	Location	Key Sources
Development Methodology	MC1	<i>A UCD process involving end-users can be useful in encouraging enjoyment and engagement.</i>	C3 S3.2.2, S3.4.2	[131, 130, 265, 266]
Development Methodology	MC2	<i>Designing CTGs should involve experts from a diverse range of backgrounds, including those across game and technology design as well as psychology.</i>	C3 S3.4.4	[214]
Development Methodology	MC3	<i>Development for serious games should be implemented in an incremental way, designing and implementing prototypes based on experience goals before seeking feedback from end-users. Following user evaluation, changes in the design can be made to start a new prototype evolution.</i>	C3 S3.4.2	[159, 246]
Development Methodology + Evaluation Data	MC4	<i>At each stage of the development cycle, the designer should plan, implement or evaluate the game with respect to (1) learning outcomes, (2) storytelling or the story to be created by the user's experience, (3) gameplay mechanics, dynamics, and aesthetics, (4) the user experience of the interface, and (5) the technology platform.</i>	C3 S3.4.2	[159, 246]
Evaluation Methodology	MC5	<i>Caution should be taken with experimental designs short of the gold standard as they can pose complex methodological challenges with the potential to negatively impact the quality of findings.</i>	C2 S2.3.3	[285, 209, 264]
Evaluation Methodology	MC6	<i>Non-experimental designs may be suitable for initial or exploratory work regarding novel cognitive training approaches but are unable</i>	C2 S2.3.3	[285, 209]

		<i>to provide concrete conclusions regarding cognitive improvements.</i>		
Evaluation Methodology	MC7	<i>Small sample sizes contribute to a lack of replication within experimental designs.</i>	C2 S2.3.3	[285, 209, 264]
Evaluation Methodology	MC8	<i>EFs can be hard to isolate in assessment because they are not process pure and may overlap with each other and non-executive processes.</i>	C2 S2.3.3	[285, 209, 157, 56, 268]
Evaluation Methodology	MC9	<i>Multiple measures of the same construct are required to validate isolated function improvement.</i>	C2 S2.3.3	[285, 209, 258]
Evaluation Methodology	MC10	<i>Repeated cognitive assessment may be incompatible with measuring novel cognitive skills over time.</i>	C2 S2.3.3, S2.5.1	[252, 56, 92]
Evaluation Methodology	MC11	<i>Games based on a cognitive assessment must include additional outcome measures to ensure performance changes go beyond 'training to task'.</i>	C2 S2.3.3	[220, 285, 209]
Evaluation Methodology	MC12	<i>There is a need to understand the skills being challenged in CTGs over time before the mechanisms of transfer can be fully understood.</i>	C2 S2.3.3	[220, 209]
Evaluation Methodology	MC13	<i>Cognitive tests utilized in cognitive training studies rarely coordinate hot EF measures of emotion, which are a factor upon their ecological validity.</i>	C2 S2.3.3	[170]
Evaluation Methodology	MC14	<i>EF assessments vary in age appropriateness.</i>	C2 S2.5.2	[114, 191]
Evaluation Methodology	MC15	<i>Testing batteries can capture a wide spectrum of EF skills, many of which overlap.</i>	C2 S2.5.2	[114]
Evaluation Methodology	MC16	<i>EF assessments may be more sensitive to abnormal or dysexecutive behaviour rather than differences in healthy individuals.</i>	C2 S2.5.2	[114, 191]
Evaluation Methodology	MC17	<i>Understanding the process of change as well as evaluation outcomes may help to develop more engaging user experiences.</i>	C3 S3.2.2	[201, 202, 265]

Evaluation Methodology	MC18	<i>A structured school environment may be an appropriate venue for exergame intervention, given the time spent there during weekdays</i>	C3 S3.2.2	[22, 201, 202, 112]
Evaluation Methodology	MC19	<i>Given the novelty effects on user engagement synonymous with serious games, studies need to evaluate impact longitudinally</i>	C3 S3.2.2	[201, 202, 265]

Table 6: Methodological Concerns

4.5 Areas of Focus for User-Centred Design

The design requirements and methods provided a strong theoretical rationale for making certain design decisions, especially those concerning cognitive training approaches. However, with regards to harnessing user engagement and contextual interests of users, there were some areas which required some further clarity, as well as holding the opportunity for creativity, and which could not be established from additional literature alone. Consider how trends and interests change with time; did the literature reflect the opinions of the children? Were there any opportunities to innovate?

Hence, it was desirable for the end-users to validate the theoretical user engagement, game activity, and PA assumptions. Furthermore, we wanted them to contribute creatively to the CTG planned in the following areas:

- Popular playground games and their associated mechanics and patterns of PA (MD12)
- How to ensure feelings of competence for all users engaged in PA (MD29-MD30)
- Specifics regarding the fantasy involved in the game, including player roles and the game's narrative (MD13-MD14)
- What is the value of including reward systems and leaderboards? (MD18-MD21)
- The nature of social interaction undertaken in the game i.e. competition, collaboration or both (MD31-MD34)

4.6 Summary

This chapter collated the design requirements (R), design methods (MD), and methodological concerns (MC) identified in Chapters 2 and 3. This chapter forms a point of

reference for the remainder of the thesis, particularly Chapters 5, Chapter Six, and Appendix A.

5. The Design of BrainQuest

This chapter describes the design of BrainQuest, the cognitive training exergame used as the tool for the research presented in this thesis. The chapter begins by providing an overview of the completed BrainQuest game before describing the system and architecture used to run the game, including languages and development environments. Following this, with the completed game established as a point of reference, the chapter then takes a closer look at design process. This starts by defining the user-centred methodology undertaken in the design, implementation, and evaluation of the BrainQuest system. Then a chronological account of the critical design milestones and related game changes is presented for each iterated prototype. The key focus is placed on the evaluation sessions for each prototype and how they influenced the design decisions. The full theoretical relationship between the prototype design decisions and the literature is provided in Appendix A. Furthermore, an extended summary can be found in Gray, Robertson, and Rajendran (2015). Throughout the chapter references are made to the design requirements (R), design methods (MD), and methodological concerns (MC) outlined in Chapter Four.

5.1 Completed BrainQuest Game Overview

5.1.1 Overview

An introduction and overview of the working game can be viewed in the video presented in Gray (2015) and is described in further detail in Appendix A. BrainQuest was developed first as a game, placing priority on user development of the plot, themes, and activities present within the game and integration methods of creating engaging gameplay before integration of direct EF challenge. Hence, it sought to avoid the simplicity of cognitive assessment gamification or the isolation of WM training.

The plot of BrainQuest focuses around a fantasy ‘animal rustling’ theme where users assume one of 3 roles. The main role, designed to most exhaustively challenge EF, is the ‘hero’ who must:

- Collect animals (cows and sheep) and return them to designated ‘hero’ animal pens
- Chasing and catch 2 ‘rustler’ adversaries who attempt to steal the hero’s animals and take them to their ‘rustler’ pens

- Save animals who have been captured inside rustler pens

While doing the hero also must hold in mind and adhere to a set of task ordering rules which govern the number of points awarded for each successful task and present an additional challenge to EF skills.

The additional 2 roles are those of the rustlers, designed to promote physical and social activity – two key user/expert and literature requirements – while providing a dynamic and strategic problem for the user playing as a hero. One rustler is dedicated to stealing cows from hero animal pens, the other does the same for sheep. Following each 5-minute game, the 3 users switch roles.

5.1.2 Game Space Setup

The game space is an area of approximately 15 square metres consisting of the following:

- Sheep pens - 1 red hula hoop as a hero sheep pen (top left corner of square), 1 red hula hoop as a rustler cow pen (bottom right corner of square)
- Cow pens - 1 blue hula hoop as a hero cow pen (top right corner of square), 1 blue hula hoop as a rustler cow pen (bottom left corner of square)
- Pen signs (1 in each pen) – 1 blue hero cow sign, 1 blue rustler cow sign, 1 red hero sheep sign, 1 red rustler sheep sign
- Play space Animals (6 animals) – area in the middle of the square where toy sheep and cow bean bags (palm sized) are scattered
- Pen Animals (2 animals per pen) – each of the sheep and cow pens are populated with toy sheep and cow bean bags



Figure 15: BrainQuest - Bird's-eye View



Figure 16: BrainQuest - Pitch-side View

5.1.3 NFC-based User Interface

BrainQuest packaged as an app for Android smartphone devices and employs an NFC-based interface. NFC or near field communication is a wireless connectivity technology facilitating short-range communication between electronic devices or between an electronic device and scannable tags. In BrainQuest the technology is utilized using inbuilt smartphone NFC communication modules to communicate with scan-able NFC stickers attached to game objects.

Thus, characteristic of augmented reality, the technology allows the user to integrate elements of real and virtual worlds – coupling objective performance measurement, historical data tracking, tailored challenge, engaging game fantasy, goal-setting, and meaningful feedback with PA and social interaction akin to real-world or playground games.

5.1.4 Rules and Scoring

The rules and structure of the 6E test (Chapter Two, Section 2.5.2, p. 63) were assimilated by the BrainQuest gameplay to overlay an explicit, pre-established EF challenge (for the hero role) on top of activities hypothesized also to challenge EF through indirect routes (social interaction, PA, joy, pride/confidence/self-efficacy).

5.1.4.1 Hero Task Procedures & Task Ordering Rules

Like the 6E test, the hero has 5-minutes to successfully complete 6 tasks of 3 types – one for sheep and one for cows. E.g., in the order: Return Sheep, Save Sheep, Stop Sheep Rustler, Return Cow, Save Cow, Stop Cow Rustler.

The tasks are described below:

- **Return Task Type (1. Return Sheep, 2. Return Cow):** the hero must first collect an animal from the play space by scanning it before taking it to the appropriate hero animal pen. On arrival at the pen, the hero scans the pen to open it and then scans the animal and drops it into the pen.

- **Save Task Type (3. Save Sheep, 4. Save Cow):** the hero must go to a rustler animal pen and scan the pen to open it, then pick up an animal from the pen and scan it before throwing it back into the play space to set it free.
- **Stop Rustler Type (5. Stop Sheep Rustler, 6. Stop Cow Rustler):** the hero must chase and catch a rustler by physically tagging them. If the rustler is holding an animal, they must relinquish it to the hero who scans it, then returns to the appropriate hero animal pen, scans the pen to unlock it and then scans the animal before dropping it into the pen. Meanwhile, the rustler must return to their animal pen. If the rustler does not have any animals in their possession when caught, they must return to their animal pen, while the hero presses the ‘no animal’ button to complete the task.

However, the hero must also adhere to a series ‘task ordering’ rules which map exactly those governing the 6E test and present an EF challenge:

- **Rule 1:** For each task choice, the hero must change task type
- **Rule 2:** Within the 5-minute time limit, the hero must make sure that they have attempted all 6 subtasks while following Rule 1.

5.1.4.2 Hero Scoring

The scoring system awards the hero player 10 points multiplied by a combo bonus per successfully completed task. For every completed task that follows task ordering rule 1, the combo bonus is incremented by 1 until the user breaks the rule. E.g. the points awarded for completing one correct task in a row is 10 points (combo = 1), points awarded for completing 2 correct tasks in a row is 20 (combo = 2), points awarded for 10 correct tasks in a row is 100 (combo = 10). At this point, the combo bonus is reset to its initial value of 1. Furthermore, 100 overall bonus points are awarded for accurately following task ordering Rules 1 and 2. The Java code underpinning the scoring is shown in Table 7.

```
//Initial Variables

Int ComboBonus = 1;

Int CorrectTaskChoices = 0;

Int CompletedTaskPoints = 0;
```

```

Total Hero Points = 0;

// Program Function

If (TaskChoice = CorrectTaskChoice) {

    ComboBonus = ComboBonus + 1;

}

Else {

ComboBonus = 1;

}

CompletedTaskPoints = 10 x ComboBonus;

TotalHeroPoints = TotalHeroPoints + CompletedTaskPoints;

```

Table 7: Hero Points Algorithm

5.1.4.3 Rustler Procedure

The rustler task procedure was, by comparison to the hero, relatively straightforward and there were no task ordering rules to follow:

Steal Animal (Steal Cow or Steal Sheep) – The rustler must run around the perimeter of the play space to the hero pen which corresponds to their chosen animal (i.e. sheep or cow), steal the animal, and run back around the perimeter of the play space to deliver the animal to their rustler pen.

5.1.4.4 Rustler Points Scoring

The rustlers earn 20 points for each successful shuttle run in which they return an animal, and 10 points for unsuccessful shuttle runs. The Java code underpinning the scoring is shown in Table 8.

```

//Initial Variables

Boolean SuccessfulRustlerRun;

Int RustlerRunPoints = 0;

Int TotalRustlerPoints = 0;

// Program Function

If (SuccessfulRustlerRun==True) {

    RustlerRunPoints = 20;

}

Else {

    RustlerRunPoints = 10;

}

TotalRustlerPoints = TotalRustlerPoints + RustlerRunPoints;

```

Table 8: Rustler Points Algorithm

5.1.4.5 General Rules

There were some additional general rules governing the game:

1. Rustlers must stick to one type of animal throughout an entire 5-minute game e.g. sheep rustlers carry sheep and cow rustlers carry cows.
2. The hero must adhere to the task type which has been chosen e.g. if the hero opts to do a return task, they are forbidden at interrupting that task in favour of another until their chosen task has been completed (Note, the player can press the back button before the first scanning operation of the process).
3. Moreover, the hero must also adhere to the type of animal which is chosen e.g. if the hero selects to save a cow, he cannot save a sheep.

4. Heroes and rustlers are permitted only to carry one animal at one time.
5. Each player plays in their initial role (hero, cow rustler, sheep rustler) for 5 minutes before swapping roles, until every player has played in every game role. Therefore, a total game lasts for 15 minutes.

5.1.5 BrainQuest App Screens

The final core app activities - the screens presented to the user, and their structure are shown in Figure 17 and described in the following subsections.

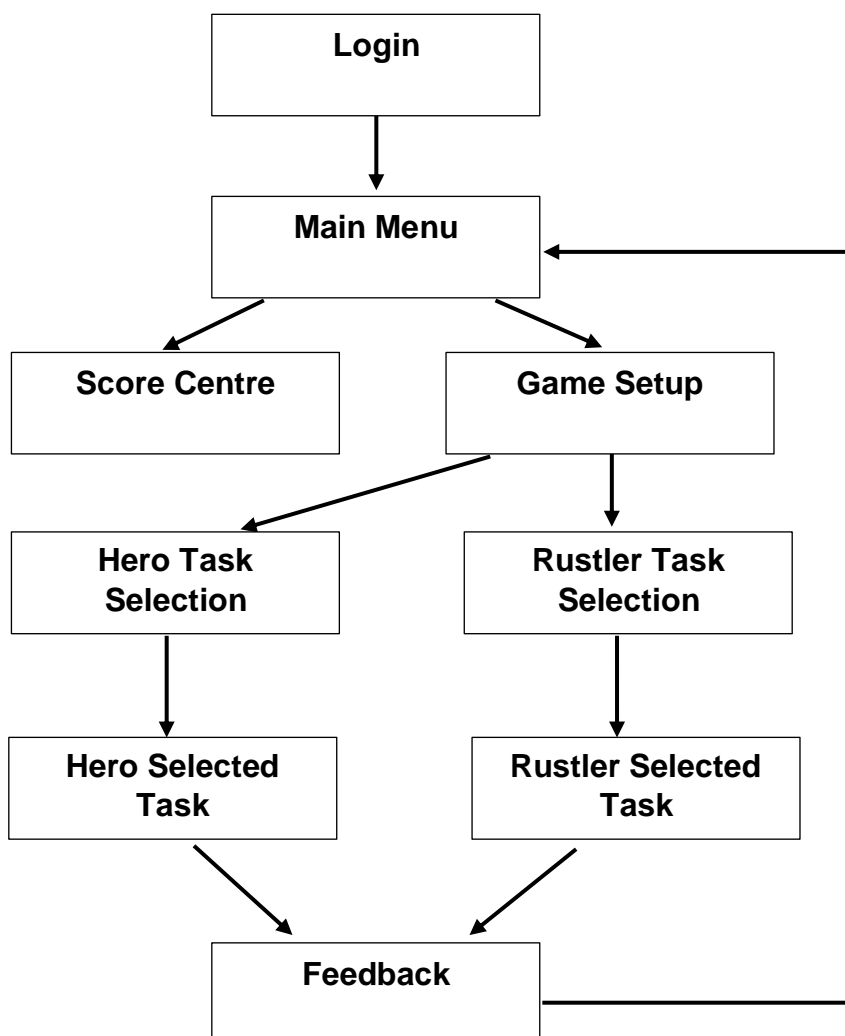


Figure 17: BrainQuest Activity Overview

5.1.5.1 Setup

5.1.5.1.1 The Login Screen

On startup, the user is presented with a splash screen (Figure 18) which plays the BrainQuest themed animation of the neon Rubix cube logo dripping neon paint towards the bottom of the screen before the request for login details appears. The user can sign in using an existing account or sign up before logging in.

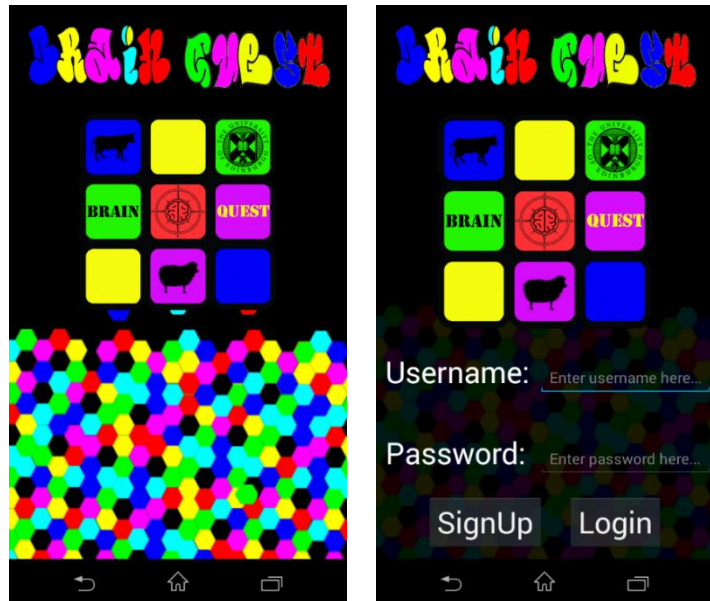


Figure 18: BrainQuest Splash and Login Screens

5.1.5.1.2 The Main Menu

The main menu (Figure 19) allows the user to choose from several options, displayed as thumbnails –select ‘play game’, view the score centre, setup objects for play, view the about page, or press the log out button to finish their session.

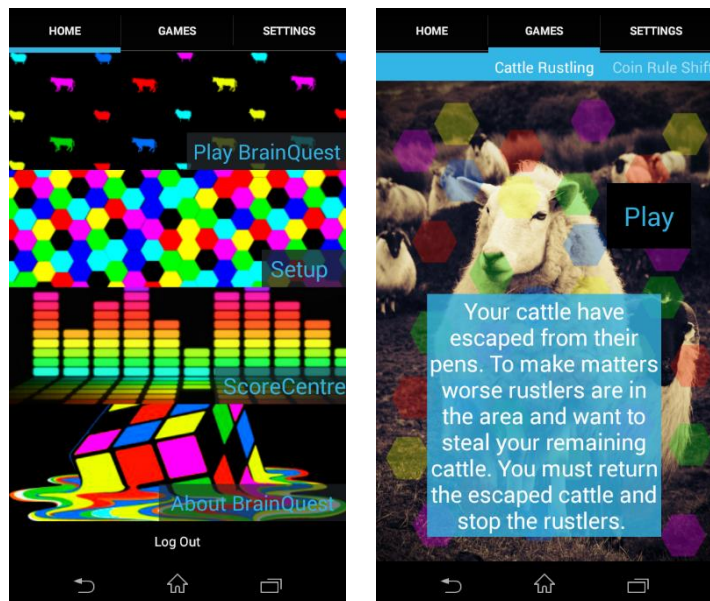


Figure 19: BrainQuest Main Menu Screen

5.1.5.1.3 Game Setup Screens

The game setup screens (Figure 20) are accessed from the main menu. The first game setup screen gives the user the choice of game role. After selecting a role, the user progresses to the second setup screen where they must select difficulty and time limit.

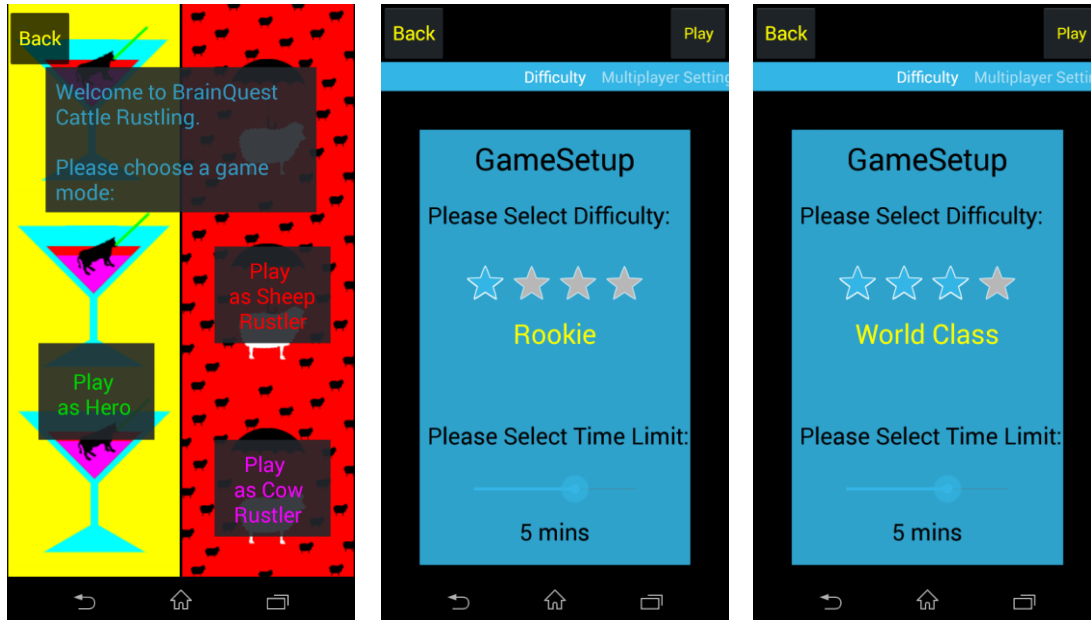


Figure 20: BrainQuest Game Setup Screens

5.1.5.2 Gameplay

5.1.5.2.1 Hero Task Selection Screen

The Task Selection screen (Figure 21) is the main gameplay screen presented to the user on game start and following completion of each task. Playing as the hero, the user is presented with 6 thumbnails (in 3 rows of 2, grouped by task type) from which to choose, denoting the different tasks. This aspect of the game sought to remind the user of their different objectives, creating obvious decision points by asking the user to choose a task type before acting. The thumbnail artwork matches the designs of the physical pen signs, creating a visual association between virtual and real worlds.

The Task Selection screen also includes the following components:

- Game points display – displaying a running total of amassed points for the current game.
- Time Limit display – a countdown timer of the game time remaining.

- Instructions prompt button - allowing the user to see game rules at any point.
- Quit button – allowing the user to exit the current game.

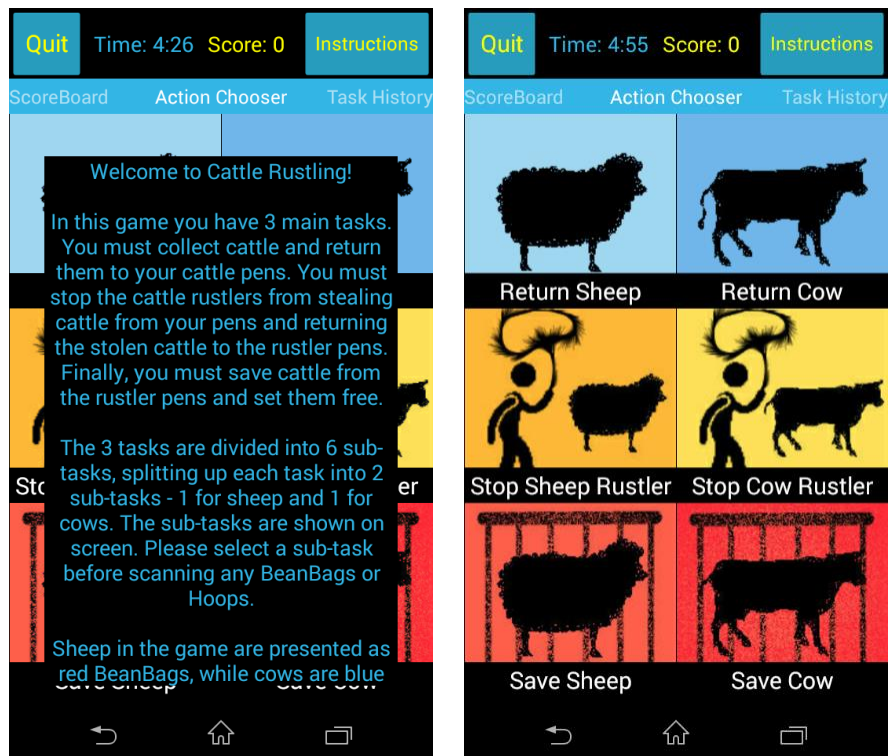


Figure 21: BrainQuest Hero Task Selection Screen

5.1.5.2.2 Rustler Task Selection Screen

Playing as the rustler, the Task Selection screen (Figure 22) was again the main gameplay screen presented to the user on game start and following completion of each task. However, the screen presented only one task, a single option to choose. The Task Selection screen included the following components:

The Task Selection screen also includes the following components:

- Game points display
- Time Limit display
- Instructions prompt button

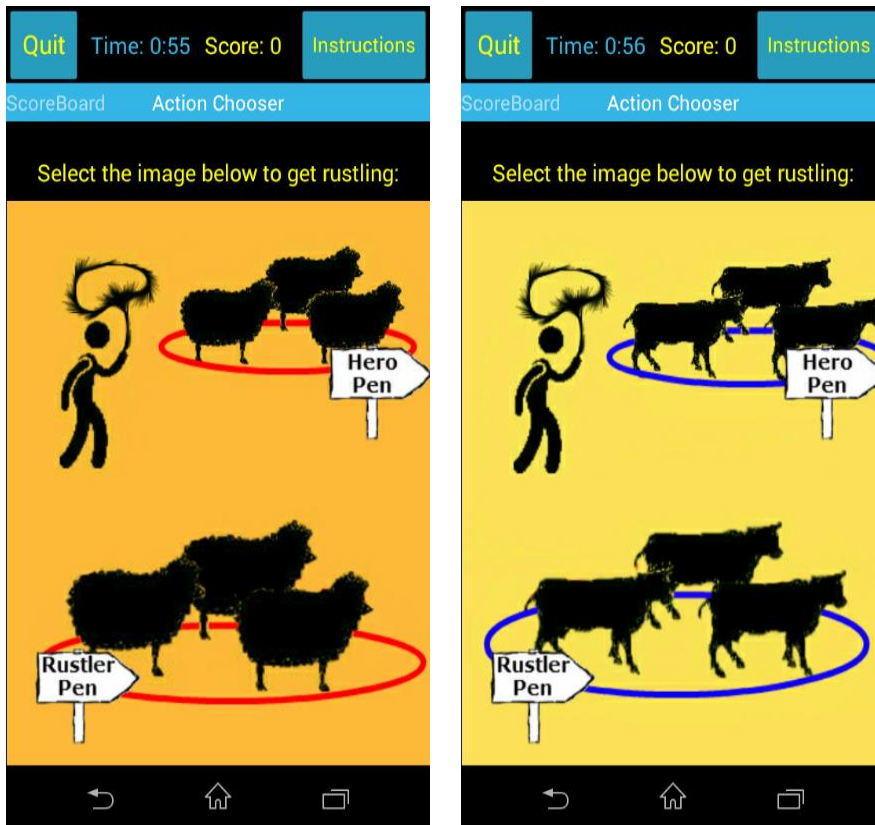


Figure 22: BrainQuest Rustler Task Selection Screen

5.1.5.2.3 Hero Selected Task Screens

After the hero selects a task thumbnail on the ‘Hero Task Selection’ screen, the ‘Selected Task’ screen appears (Figure 23) – the area of the application which enables the phone to interact with NFC objects. It also overlays images and audio relating to the cattle rustling fantasy following scanning operations and task completions.

The Hero Selected Task screen also includes the following components:

- Combo bonus display – a form of immediate feedback regarding the success of the user’s task choice. A task selection adhering to the rules increments the value displayed by the combo bonus while a rule break resets the value to 1.
- Game points display – displaying a running total of amassed points for the current game.
- Time Limit display – a countdown timer of the game time remaining.
- Stop Rustler button – During ‘stop rustler’ tasks, an additional button appeared on the Selected Task screen, called the ‘No Animal’ button. The hero could press this

button in situations where they caught a rustler who had not yet stolen animals or if they were unable to catch a rustler following a chase. Doing so enabled the hero to complete the process and earn points.

- Commentary toggle – this switch allowed the user to engage/disengage audio commentary of written instructions.
- Back button – function in the event of the user selecting the wrong task by mistake.

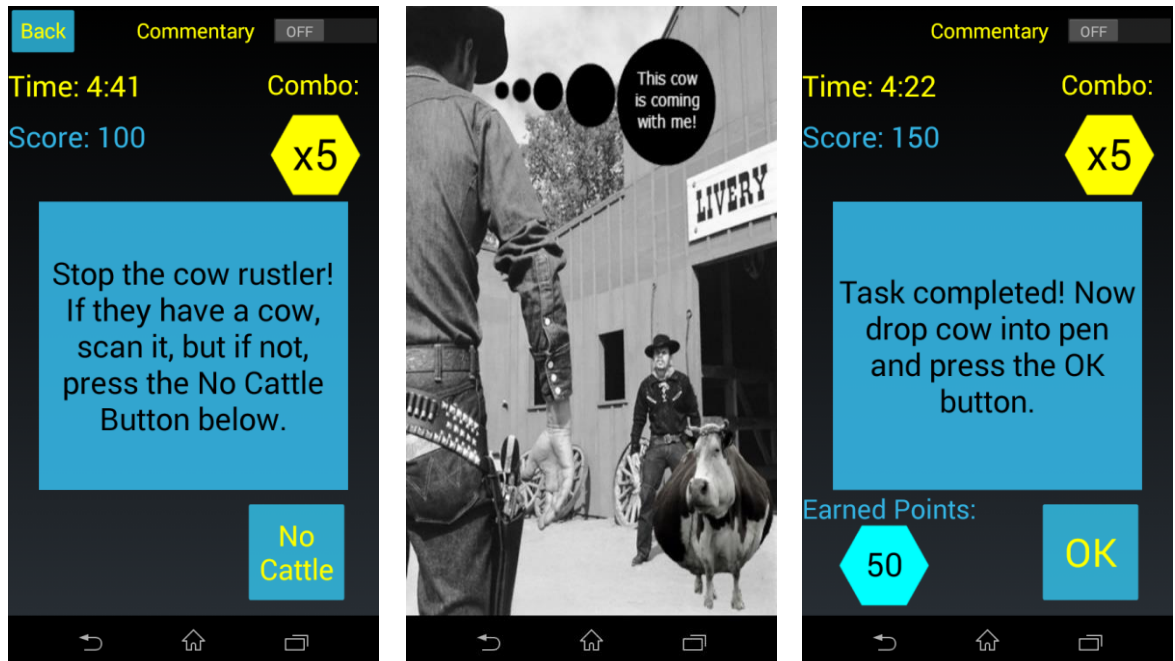


Figure 23: BrainQuest Hero Selected Task Screens

5.1.5.2.4 Rustler Selected Task Screens

This screen (Figure 24) is the rustler equivalent of the ‘Hero Task Selection’, allowing NFC interaction and image/audio overlay. However, there was a greater range of buttons available to guide the rustler through the stealing process:

- Open Pen – the rustler presses this button when arriving at the hero animal pen if animals exist in the pen. Pressing this button enables the rustler to interact with the animal pen.
- Pen Empty – the rustler presses this button when arriving at an empty animal pen, where they receive a message telling them to return to their own animal pen to earn points.

- Caught by Hero – this button remains from the previous prototype and is pressed when the rustler is caught by the hero, regardless of the stage in the rustling process, resulting in a message advising the rustler to return to base.

The Rustler Selected Task screen also includes the following components:

- Game points display – displaying a running total of amassed points for the current game.
- Time Limit display – a countdown timer of the game time remaining.
- Commentary toggle – this switch allowed the user to engage/disengage audio commentary of written instructions.

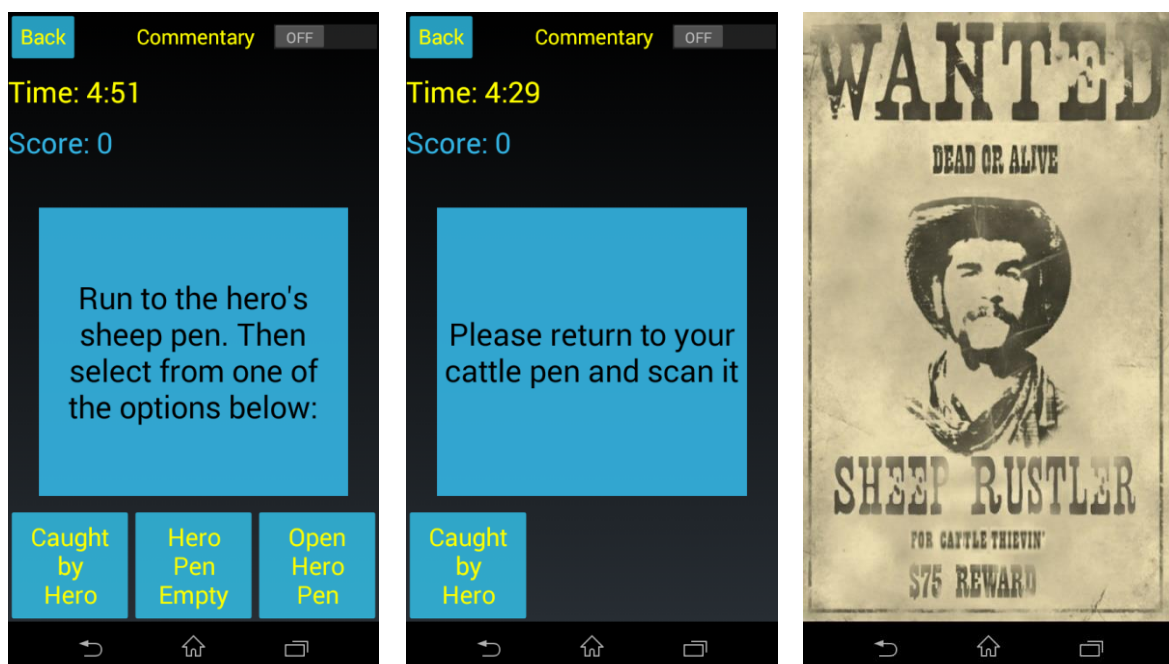


Figure 24: BrainQuest Rustler Selected Task Screens

5.1.5.2.5 Feedback Screens

This feedback screens (Figure 25) are presented following the end of each hero game and include:

- A trophy celebration screen – on occasions where the user has won a trophy
- A main feedback screen showing:
 - Total points score
 - Highest combo score

- Number of tasks completed
- Number of errors made
- A historical task choice list (Task History Tool – Section 5.1.6.2.2, p. 138) with correct/incorrect coloured feedback

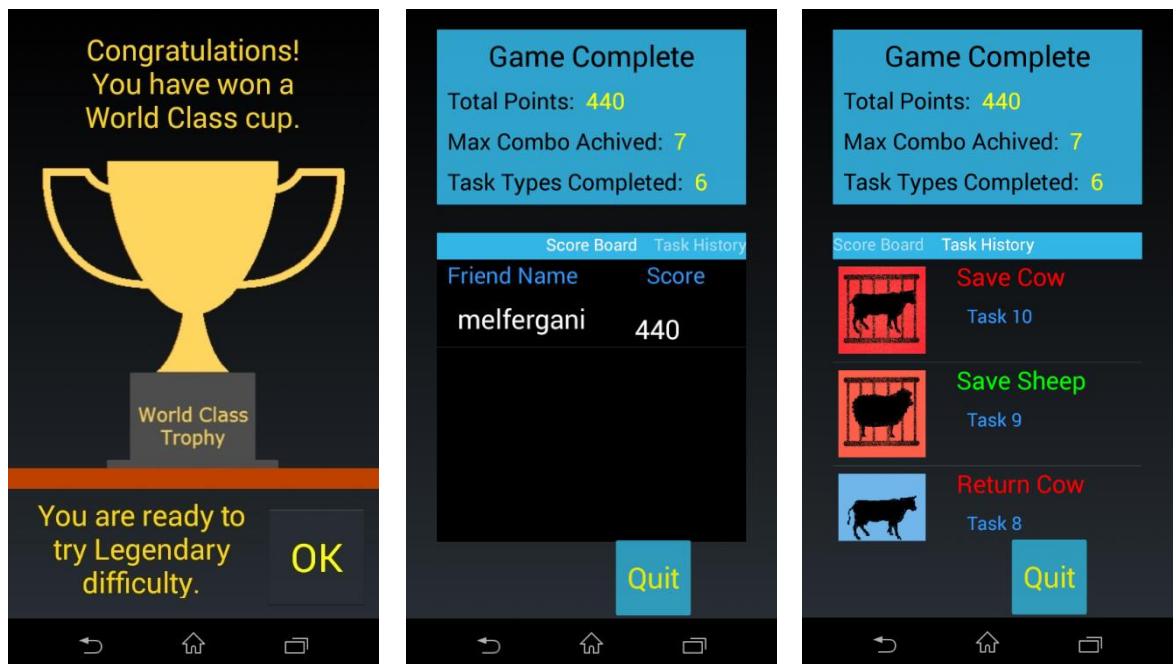


Figure 25: BrainQuest Feedback Screens

5.1.5.3 Score Centre Screens

The score centre provides a means for users to view their performances within a wider context – looking at historical records, a range of progressing performance totals, in-game achievements/trophies and performance in comparison to other players. There are two general merits of reward systems and trophies – providing the user with a means of goal setting with the power of capturing and sustaining their engagement, and providing the user with feelings of competence when reviewing their achievements (R20-R22)

The score centre can be selected from the main menu of the game and is viewable after initial login and during intermissions between gameplay. It is fragmented into 4 screens – trophies, leaderboard, game statistics and game records, which the user may swipe between.

5.1.5.3.1 Trophies

Trophies are presented to users following completion of a game session in the hero role, where the task ordering rules were followed without any mistakes (Figure 26). There are different coloured trophies for each difficulty level: Rookie – bronze, Professional – silver, World Class – gold, and Legendary – purple.

On successful completion of a hero game, a trophy screen appears showing the name and image of the trophy won. The user can review accomplished trophies by visiting the ‘Score Centre’ and swiping to the ‘Trophy Cabinet’ – which depicts two wooden shelves upon which trophies are displayed.



Figure 26: BrainQuest Trophy Room

5.1.5.3.2 Leaderboard

The leaderboard creates an overall ranking list of all players according to total overall points score and is synchronized with the database to update in real time, whenever the screen is accessed (Figure 27). The leaderboard is ‘opt out/in’ giving players control on score publication.

5.1.5.3.3 Game Statistics and Records

The score centre (Figure 28) adds an additional dimension to performance feedback by enabling users to review their historical game statistics and records.

The game statistics and records recorded are as follows:

- Highest difficulty level attempted
- Total play duration
- Total games played as hero
- Total points earned as the hero
- Total number of hero tasks completed
- Combo bonus record
- Highest number of correct tasks completed
- Highest number of rule breaks



Score Centre		
Trophy Room	LeaderBoard	General Stats
Friend Name	Score	
melfergani	1760	
lrobertson	1240	
mbold	1200	
jigoe	830	
nconstantino	820	
srowinski	780	
fyoung	690	
akennedy	650	
jmackay	630	
...	...	

Figure 27: BrainQuest Leaderboard

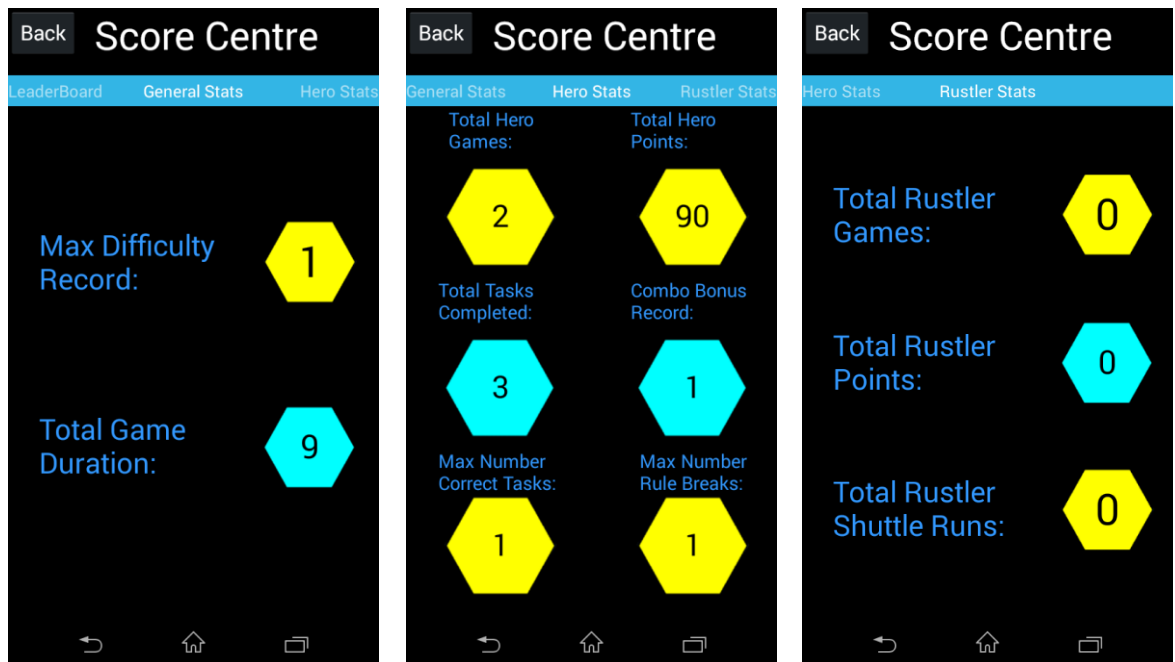


Figure 28: BrainQuest Game Statistics & Records

5.1.6 Variable Difficulty Levels and Support Tools

The support tools and variable difficulty were designed to keep challenge at the cusp of ability while supporting the user to feel competent. The following design decisions address requirements R21-R24.

5.1.6.1 Variable Difficulty

There are 4 difficulty levels for the hero in BrainQuest, designed to incrementally increase the challenge of following the task ordering rules and fundamentally change the EF demands by rendering previously viable solutions useless and forcing novel strategizing solutions to an evolving problem.

The easiest level has the most inbuilt support for EF but as the difficulty increases the support scaffolding is incrementally removed, while in the final level additional elements are introduced. Thus, forcing the user to develop compensation strategies to adhere to the rules. The levels each have their own descriptive name. Though for testing purposes, the user could select a difficulty level of their choice, in the main evaluation described in Chapter Six, children were asked to set difficulty depending on their performance.

The different difficulty levels and associated support tools are shown in Table 9.

Rookie Difficulty (Level 1) Tools:	Professional Difficulty (Level 2) Tools:	World Class Difficulty (Level 3) Tools:	Legendary Difficulty (Level 4) Tools:
Task Choice Support Tool (EF Support)	Task History Stack (EF Support)	Task History Feedback	Task Randomizer (EF Aggravator)
Task History Stack (EF Support)	Task History Feedback	Written Instruction	Task History Feedback
Task History Feedback	Written Instruction	Audio Commentary	Written Instruction
Written Instruction	Audio Commentary		Audio Commentary
Audio Commentary			

Table 9: BrainQuest Difficulty Levels

5.1.6.2 Support Tools

5.1.6.2.1 Task Shading Tool

The Task Shading tool (Figure 29) helps users follow the task ordering rules. The Task Shading tool shades out the most recently completed task type on the interface, thereby advising the user on the suitable tasks to choose to follow the rules. Thus, it helps prevent the user from breaking one of the task ordering rules – do not undertake the same task type in succession. However, the user must still hold the other rule in memory and implement each of the 6 task types at least once.

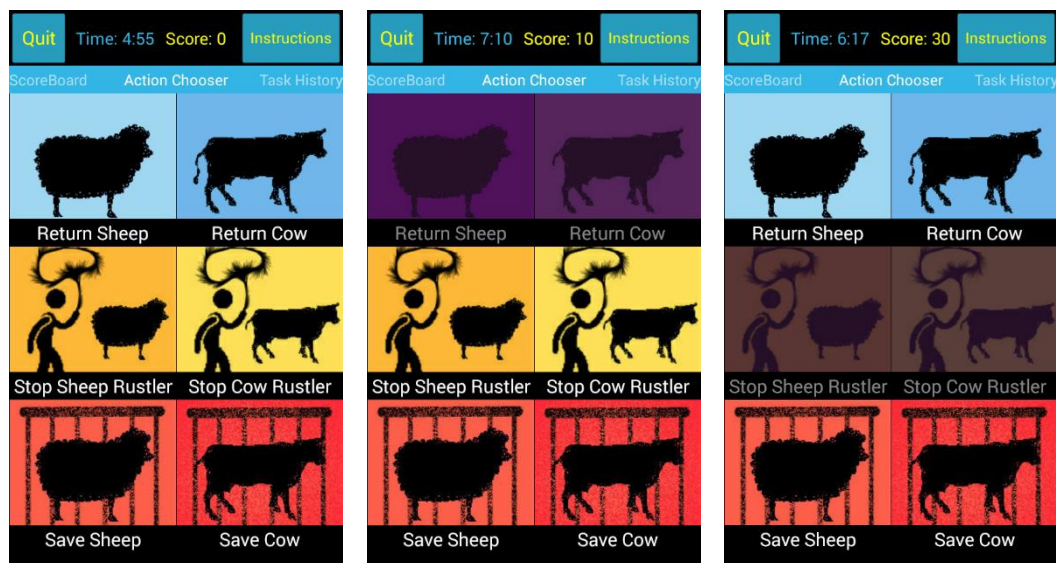


Figure 29: BrainQuest Task Shading Tool

5.1.6.2.2 Task History Tool

The Task History tool (Figure 30) is presented as a tabbed screen accessible by swiping to the left on the Hero Task Selection screen. It allows the user to view an ordered list of all completed tasks. Previous tasks conforming to the task ordering rules are written in a green coloured font, while tasks breaking the rules were written in red. Although the task history does not explicitly suggest task choices, it reduces the amount of information to be held in working memory by storing a list of previously completed tasks which the user can use to inform new task choices. The Task History tool is also present in the end of the game Feedback screen. In the Feedback screen, the user may access the tool to view a record of their task choices for the completed game and reflect on performance.



Figure 30: BrainQuest Task History Tool

5.1.6.2.3 Task Randomizer

Unlike the previous tools, the Task Randomizer (Figure 31) is not a ‘support tool’ per se. Where the Task Shading and Task History tools attempt to reduce cognitive load and support WM, the Task Randomizer seeks instead to make decision-making harder for the user. With respect to the design consistency required to provide a satisfactory user experience (Mandel, 1997), the breakage of an HCI rule was permitted within the game because of the overriding goal of challenging the user’s cognition.

It is used only at the highest game difficulty level. The tool mixes up the order of the choice thumbnails on the Hero Task Selection screen following completion of a task. Therefore, it interferes with any expected mental representations of the interface (held in WM) and encourages the user to think carefully before choosing their next task. Thus, it was proposed to require a degree of additional mental manipulation and attention, exercising WM and IC towards a pre-potent (automatic and routine) response

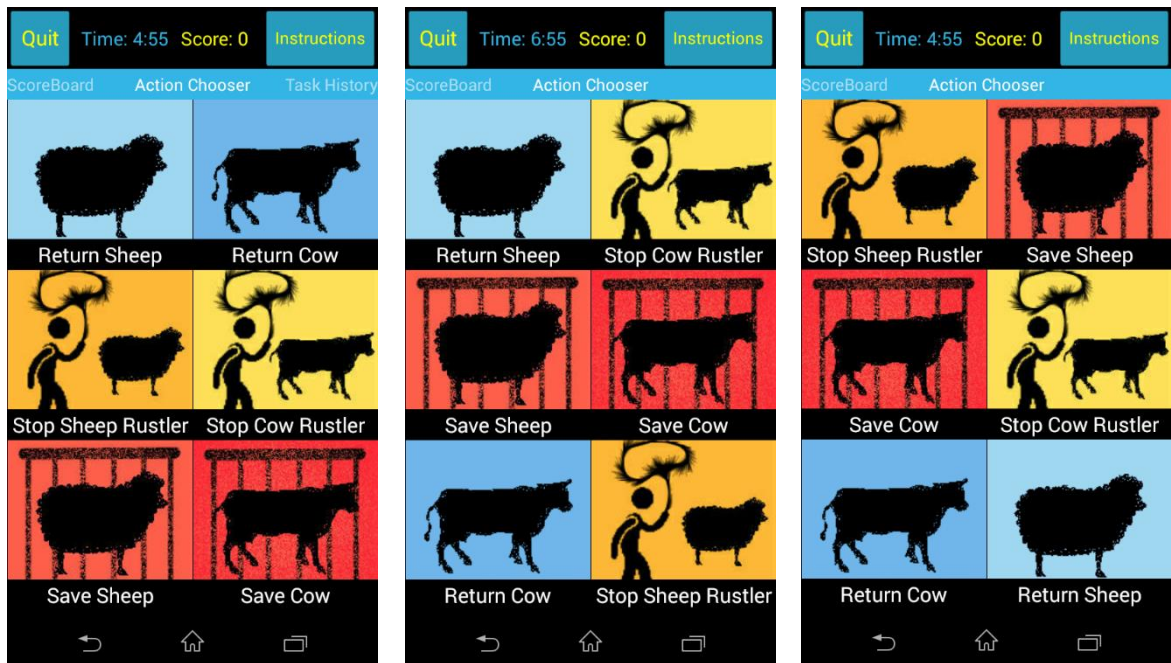


Figure 31: BrainQuest Task Randomizer

5.1.7 Data Logging

To aid analysis of user EF and physical ability performance (R5), data logs tracking user decisions are collected behind the scenes in the app. The logs are stored locally on phones and an online database server to ensure data preservation. The online database communicates with the Score Centre to display a user's historical data and the Login process, to validate usernames and passwords.

An example data log is shown in Table 10.

```

New Session:
Username: User
Session Start Time:19.03.2015-09.46.25

START GAME:
Start Time: 19.03.2015-09.52.12
Role: SheepRustler
Difficulty: 1
Duration: 300000
ScoreBoard Members: [user1] [user2] [user3]
  
```

Task Completed: Return Cow-19.03.2015-09.52.12
Task Completed: Return Cow-19.03.2015-09.52.12
Task Completed: Return Cow-19.03.2015-09.52.12
Task Completed: Return Cow-19.03.2015-09.52.12

END GAME:

End Time: 19.03.2015-09.59.00

Role: SheepRustler

Points: 50

Sheep Rustler Shuttle Runs: 4

Viewed LeaderBoard: 0

All6Raw: 0

RawErrors: 0

START GAME:

Start Time: 19.03.2015-10.04.04

Role: Hero

Difficulty: 1

Duration: 300000

ScoreBoard Members: [user1] [user2] [user3]

Task Completed: Return Sheep-19.03.2015-10.04.04

Task Completed: Stop Sheep Rustler-19.03.2015-10.04.04

Task Completed: Save Sheep-19.03.2015-10.04.04

Task Completed: Stop Cow Rustler-19.03.2015-10.04.04

Task Completed: Return Cow-19.03.2015-10.04.04

Task Completed: Return Sheep-19.03.2015-10.04.04

Task Completed: Stop Sheep Rustler-19.03.2015-10.04.04

Task Completed: Save Sheep-19.03.2015-10.04.04

END GAME:

End Time: 19.03.2015-10.09.06

Role: Hero

Points: 310

Combo: 5

Tasks Completed: 8
Rule Breaks: 1
Viewed Task History: 0
Raw Tasks Attempted Score: 10
Raw Tasks Errors: 1

Table 10: Example Data Log

The game log is explained:

- Username – the name of the user
- Session Start Time – the time and date of the session beginning
- Start Time – the time where the game begins
- Role – the role assumed by the player
- Difficulty – the difficulty of the game
- Duration – the duration of the game selected
- ScoreBoard Members – the different users involved in the game
- Task Choice List – these are the user’s task choices during the game with associated time stamp
- End Time: the time where the game ends
- Points – the number of points earned during the game
- Combo – the maximum combo bonus earned during the game
- Tasks Completed – the total number of completed tasks
- Rule Breaks – the number of times task ordering rules were broken
- Rustler Shuttle Runs – the number of runs made in the role of rustler during a game
- Viewed Task History – the number of time the user used the task history tool
- Raw Tasks Attempted Score – the 6E equivalent score earned by the user
- Raw Tasks Errors - the 6E equivalent error score earned by the user

Capturing this data is designed to help understand user performance, particularly EF. Ability to conform to the rules is measured by recording ‘Raw Tasks Attempted Score’ and ‘Raw Tasks Errors’ and is applied to the formula ‘Raw Score = (Raw Tasks Attempted Score) – (Raw Tasks Errors)’ which gives a score comparable to that of the 6E test subtotal score.

The total (raw score + bonus points) 6E score also considers deployed strategies, with bonus points calculated by the tester writing down task choices and timings. However, the

attribution of strategy bonus points is not currently possible in BrainQuest without the development of an automatized formula. Given the variety of different strategies afforded by BrainQuest’s user interface and their suitability for different difficulty levels (a more complex issue than in 6E test), it was decided the assessment of strategies to be conducted manually by human analysis of data logs. Other measures, such as Combo are designed to measure the maximum number of correctly chosen tasks, while the number of Tasks Completed indicates the cumulative speed they can make decisions – each enabling conclusions regarding the user’s ability.

To assess PA, Rustler Shuttle Runs (making a run to and from the hero pen regardless of the success of the animal rustling mission) aims to show the amount of PA undertaken by the rustlers, given an approximate (30 metre) distance between animal pens. e.g. more runs indicate a higher level of PA. Finally, Viewed Task History is designed to understand the extent of reliance on the Task History tool.

5.1.8 BrainQuest: Meeting Requirements

5.1.8.1 Addressing Requirements

Appendix A describes the implementation of specific design methods (DM) for each prototype. This section explains how BrainQuest addresses the requirements established by the literature. Each requirement is linked to the Diamond (2012) model at the heart of this thesis by highlighting the related pathways the requirements tap into – EF Challenge, Social, Joy, Pride/Confidence/Self-efficacy, and PA.

EF Challenge

R1 – The game should have a holistic structure, targeting many different EFs in different ways and utilizing established training techniques

The game provides direct hot and cool EF challenges, involving a purely cognitive challenge – following task ordering rules, influenced by hot EF social and motivational challenges – hero/rustler interactions, leaderboard and reward systems. EF is also addressed by integrating cognitively engaging PA using the exergame implementation.

EF Challenge

R2 – The game should target ages 8-12 – a critical age range for inhibitory, WM, and strategic EF skills as well as social skills

The integrated rules of the 6E test are deemed comprehensible for this age group and the UCD process prioritized establishing rule understanding with the end-user group aged between 11 and 12. Despite difficulty understanding in the evaluation sessions, it was hoped that simplification of the task ordering rules made in the completed game would ensure BrainQuest's appropriateness.

EF Challenge

R3 – The game should integrate game design theory and motivational qualities rather than simply gamification to increase user engagement

BrainQuest was designed through a UCD process which defined the nature of activities involved in the game as well as themes before integrating any EF or cognitive challenges – in this case the task ordering rules of the 6E test. Furthermore, extrinsic motivations like trophies and the leaderboard, synonymous with the gamification process, were introduced late in the development process and designed to complement rather than be the focal point of gameplay.

EF Challenge + Social Interaction

R4 – The game should make use of ubiquitous, mobile, and augmented reality technologies to create immersive experiences

BrainQuest is implemented as a mobile cognitive training exergame for Android smartphone devices which synthesizes technology and the real world. There is a synergy between the

screen and the real world, characteristic of augmented reality games, which makes the real world more immersive and the user experience more engaging.

EF Challenge

R5 – The game should be able to assist in the real world in real time while providing a snapshot of cognitive performance

BrainQuest is played in an environment which is analogous to that of a playground game and, therefore, enables practice of EF skills which may be used in similar real-world contexts. Data logging and performance feedback occurs in real-time, allowing users to identify and learn from their mistakes in their goal of following the task ordering rules. BrainQuest uses task support tools to assist the user in learning how to strategize, plan, and utilize feedback during the activity.

Social

R6 – The game should be mobile to take advantage of the greater social interaction and engagement associated with pervasive over console exergames

R28 - The game should involve social play to sustain engagement and longevity, as well as PA intensity

The UCD process highlighted the importance of BrainQuest being multiplayer to enable social interactions. Children play together in groups of 3 and must interact face-to-face rather than indirectly through a digital medium. Moreover, following games can socialize with larger groups who may also be playing the game to compare achievements and the leaderboard.

EF Challenge

R7 – The game should necessitate the use of WM in its challenge as a core EF which forms the basis of more complex skills

By integrating the 6E task ordering rules, users must use WM to adhere to the rules and make the correct decisions to complete BrainQuest levels. See Section 5.1.8.2 (p. 151).

EF Challenge

R8 – The game should train complex EFs directly and including WM rather than simply training of WM in isolation

Unlike other CTGs, BrainQuest does not try to isolate cognitive skills during training. Though, as described in Section 5.1.8.2 (p. 151), the individual challenges to specific EFs can be hypothesized, the different skills are more likely used synchronously. Hence, like the 6E, the game is designed to be ecologically valid. The design of the game has also emphasized encouraging high-order EF skills like strategizing.

EF Challenge

R9 – The game should challenge WM beyond incremental and contextually specific refinement of specific processes

BrainQuest's variable difficulty forces users to reformulate their strategies at every incremental level increase – sustaining the use of EFs rather increasingly automating specific cognitive processes. See section 5.1.8.2 (p. 151).

EF Challenge

R10 – The game should involve (1) planning or decision making, (2) problem solving, (3) requiring a novel sequence of action, (4) challenge, (5) overcoming strong habitual response or temptation

Following the task ordering rules requires planning and decision making. Successfully following the task ordering rules becomes a novel problem with the interface changes and additional human rustler variables. Hence, no two games should will be identical. The desire to be overcome is for the hero to ignore rustlers when catching them would contravene the task ordering rules.

EF Challenge

R11 – The game should require switching between sustained, selective and inhibition of attention

R13 – The game should create situations requiring IC because they are particularly challenging for children

This is typified by the hero-rustler interactions. The hero should keep track of rustler movements to time catching them perfectly and must switch the attention between the two rustlers, as well as sustaining concentrating on the task at hand and the status of the task ordering rules. Inhibition involves ignoring rustler distractions where necessary. Further IC challenges are stated in Section 5.1.8.2 (p. 151).

EF Challenge + Social

R12 – The game should create situations involving hot EF by using rewards, penalties, social implications or personal feelings

The short-term rewards, social implications, and elicitation of personal feelings is derived from the hero-rustler interactions – the reward being the player who finishes the interaction in possession of the animal. These interactions may evoke emotion from enjoyment, comradery of engaging in a shared activity or feelings of competitiveness – there is a broad spectrum of possible emotional outcomes. In the long-term, the reward systems and leaderboard provide further motivational hot EF challenges.

EF Challenge + Social

R14 – The game should train for real-world relevance by challenging both (emotionally effective) hot and (logical) cool EF

R16 – The game should train cognitive skills in a way which is applicable to different contexts and more likely to foster far transfer

As stated, integrating BrainQuest with 6E test rules was designed to evoke the test's involvement of combinations of different EFs – representative of how these skills are used in everyday contexts. Following these rules without any human rustler involvement would be a purely cool cognitive test like the 6E but with the social aspect of the game, an otherwise cool EF task is effectively heated at certain points – infiltrated by emotion. Adding to this heat is the motivational impact of the reward and leaderboard systems.

The novel problem solving in a social environment generalizes well to several everyday situations, such as team sports, playground games and even to certain classroom challenges. These include opportunities for competition and collaboration, as well as reward and ranking systems – all which children encounter throughout life and especially in school contexts.

EF Challenge + Social

R15 – The game should involve activities testing emotional regulation to promote character development

Hero-rustler interactions are an opportunity to test emotional regulation as if caught the rustler must do something which they do not wish to do – give up possession of an animal. Hence, they may have to inhibit their overriding desire to run away and submit to the hero. Likewise, as stated, the hero may have to inhibit catching the rustler in favour of a task choice which adheres to the current task ordering rule state.

EF Challenge

R17 – The game should train cognitive skills used in diverse and novel situations

By using the Diamond model as a blueprint there are multiple approaches used to target EF – including direct EF challenge and indirect supporting pathways like PA, social challenges, support for competence, and user engagement. Every game is also made novel and diverse with the inclusion of human variables, different game roles, and the variable difficulty system.

EF Challenge

R18 – The game should encourage repeated use as it is key to making EF improvements

The UCD process was used to identify user interests as well as activities which they personally find fun or enjoyable upon which to create the game. This added to an extensive review of motivational and game design literature and the assimilation of these principles within BrainQuest’s design. The trophy and leaderboard systems, as well as historical record keeping, may also facilitate goal setting that encourages sustained play.

Joy + Confidence/Pride/Self-efficacy + Social

R19 – The game should facilitate competence, autonomy, and relatedness to positively influence an individual’s motivation and adherence

R20 – The game should include both intrinsic and extrinsic motivators

Competence is fostered by incremental challenge increases in response to user progress, the inclusion multiple tools to support the user, performance feedback, the leaderboard and trophy systems. The leaderboard and trophy systems are initially an extrinsic motivation, yet these components may, in turn, become intrinsic motivators in the long term - leaderboard

and trophies can spawn interactions with others as well as be used to provide performance feedback.

Relatedness is achieved by the social dynamic of the heroes and rustlers. By not constraining the player to follow the rules, giving them free choice in the game to express themselves and set their own goals and providing opportunities for both cooperation or competition, autonomy is somewhat provided. However, autonomy is limited by the mechanics of task procedures and having to work within the structure of the 6E rules.

EF Challenge + Joy + Confidence/Pride/Self-efficacy

R21 – The game should implement challenge at the cusp of ability or else the user may disengage

R22 – EF promoting activities should cultivate children’s pride, confidence, and self-efficacy

R23 – The game should avoid creating feelings of inconceivable challenge which may damage self-efficacy

This is achieved by the variable difficulty level system and the 4 levels – Rookie, Professional, World Class, Legendary. Users only move up when they have exhibited an ability to follow task ordering rules correctly. Furthermore, users of different abilities can play together with the interface adding personal layers of challenge without changing the group dynamic. Hence, seeking to preserve user pride, confidence, and self-efficacy. BrainQuest’s difficulty levels have been tuned by the UCD process.

Joy + Pride/Confidence/Self-efficacy

R24 – The game should provide easy to learn controls which do not distract from the experience

BrainQuest evolved from a map-based implementation which users found hard to control, to an NFC-based system which aims to be an extension of a physical version of the game. BrainQuest presents the user with written instructions before the game and uses on-screen instructions as well as optional audio commentary to support users through tasks on a step by step basis.

On the initial difficulty level, the Task Shading support tool helps to guide the user through the activity and learn the rules by suggesting tasks to implement. However, on the last difficulty level, the Task Randomizer randomizes the choice thumbnails to disrupt the user's plan. It is unclear what effect doing this may have and is explored in the 5-week evaluation.

PA

R25 – The game should incorporate a PA component to accelerate EF improvements by coupling motor and cognitive engaging demands

R26 – The game should include ‘cognitively engaging PA’ which involves the regulation of emotion, thoughts or action

R27 - The game should promote higher intensity PA (MVPA) to accelerate EF improvements

BrainQuest typifies ‘cognitively engaging PA’ because the physical challenges are coupled with hot and cool cognitive challenges, as well as spatial and procedural challenges. E.g., coordinating one's real-world movements with onscreen events, anticipating opponent movements, and remembering the procedures of each task.

Though all activities in BrainQuest require PA but stop-rustler tasks are designed to encourage more intensity than other hero activities and evaluations suggested vigorous intensity could be achieved in these moments. However, the intensity of hero-rustler activities may vary depending on the physical ability of the players. In other activities moderate to vigorous may also be possible as the hero is battling against the clock to score as many points as possible.

Meanwhile, the rustler role is designed to provide a more purely PA challenge as there is only one task to perform and likely a smaller cognitive challenge. The rustler role is likely

much more steady state than the hero and less intermittent with respect to intensity. E.g., the hero must split their chases over two rustlers. Furthermore, the rustler is rewarded for the number of shuttle runs completed.

5.1.8.2 Hypothesized EF Challenge

Appendix A describes a more detailed mapping between specific design methods and BrainQuest’s EF challenge for each prototype. Table 11 below summarizes the hypothesized EF challenge of BrainQuest and compares these skills with their involvement in the 6E test, the EF assessment BrainQuest’s rules have been modelled on to provide an element of direct EF challenge:

EF Skill	EF challenge in 6E	EF challenge in BrainQuest
Motor Cognitive Coordination	Not challenged in the 6E test.	Integrated use of a diverse range of cognitive and additional EF skills during PA. Coordinating on-screen activities (instructions, task choices, animations, feedback) with PA and actions, as well as interactions with other players.
Working Memory	WM in the 6E is required to remember the previously completed task and whether the planned action is compliant with task ordering rules.	An attentional WM component must coordinate: <ul style="list-style-type: none"> • Recall previously completed tasks in short-term memory and use WM to check whether planned action is compliant with task ordering rules (also held in short-term memory). • Store and update visual, spatial, and auditory information of opponent’s movements in WM. • Review information from long-term memory regarding opponent characteristics and tactics, previously successful strategies, task procedures. The support tools – Task History, Task Shading, Task Randomizer attempt to support and challenge WM incrementally and at an appropriate level.

		<p>The Task Shading tool on difficulty level 1 supports WM by helping the user to change task type each time and follow one of the task ordering rules.</p> <p>The Task History tool on difficulty levels 1 and 2 helps the user track previously completed tasks. This removes the need to remember a span of tasks – held in WM to be compared against the applicability of a potential task choice.</p> <p>At difficulty level 3, all supports are removed, comparable to the 6E test.</p> <p>If the user was using the task choice interface as a representation system and holding it in WM, difficulty 4 sought to disrupt that visual image stored in WM by randomizing the thumbnails in a different order using the Randomizer tool – requiring the user to manipulate the image in their mind.</p>
Inhibitory Control	<p>The 6E requires cool IC, such as sustained attention to compliment WM in staying focused on the goals of the task. Furthermore, there may be an element of selective attention required in keeping track of the time limit.</p>	<p>There are multiple perceptual stimuli and the movement patterns of life rustlers are less predictable than virtual rustlers. Thus, the hero may have to switch more regularly between sustained attention, selective attention and inhibition of action.</p> <p>Hot EF required due to the social component of the game and the need to regulate emotions. Interactions may challenge IC.</p> <p>There is potentially added temptation for the hero to catch rustlers to impact on their opponent’s score. This exploits the competitive element of the game to increase the level of self-control required during interactions.</p> <p>Rustlers can also optionally behave cooperatively to make the hero’s job as hard as possible and help each other earn points.</p> <p>The nature of the interaction and the amount of self-control required may depend on the different mix of</p>

		competitors involved in the game. Thus, teaching interactions with friends, acquaintances, and rivals – relevant to real-world contexts.
Planning / Strategizing	In the 6E planning / strategizing are required to optimally sequence tasks in terms of developing a pattern of task choice and designating equal chunks of time to each task.	Planning/strategizing skills are challenged by optimally sequencing tasks at each difficulty level. However, the incremental removal of supports and the later introduction of extra challenge may require changes in strategy and reformulation of plans – changing the task demands rather than training a specific strategy or process.
Cognitive Flexibility/Set Shifting	<p>Cognitive Flexibility/Set Shifting is required to shift between different tasks in the 6E test often enough so that they undertake all 6 tasks but not so much that they waste time.</p> <p>Furthermore, some task changes include changes, such as the “<i>how many</i>” cards actively change an individual’s predicted task demand - e.g. the user must count the number of different objects on a card after experiencing multiple cards with objectively</p>	<p>The user must time manage to complete all 6 tasks within the time limit.</p> <p>While playing as the hero during chasing tasks, the user must make sure not to spend too much time chasing the rustler or else they may run out of time to complete the remaining tasks.</p> <p>The user is also challenged to react to changes in the game environment or arising opportunities e.g. because of rustler behaviour or positioning.</p> <p>Cognitive flexibility required when attempting a new difficulty level for the first time and discovering a previous strategy has been rendered redundant.</p>

	written sums upon them.	
Task Scheduling	Task scheduling is required when the user allocates time to the 6 different subtasks.	The user must allocate time to each subtask to complete all 6 tasks.
Performance Monitoring	The user must monitor one's own thoughts and actions, as well as to self-correct those thoughts and actions to follow the task ordering rules completely.	The user has points scores and a combo bonus to use as a reference of performance. Graphics and sounds are also used for reinforcement of action. The task history tool's in-game choice feedback is also a way to monitor performance.

Table 11: BrainQuest Implementation of EF Challenge

5.2 Completed BrainQuest System Overview

5.2.1 Hardware

The hardware involved in BrainQuest changed over the course of project prototype iterations. However, throughout all iterations, BrainQuest was deployed to Android devices, and for several reasons. Firstly, Android dominates the worldwide smartphone market share at a current figure of 82.8%, in comparison to Apple iOS at 13.9%, Windows Phone 2.6%, and others 0.7%. Hence, it was decided that developing the game for Android would open the doors to a wider audience, making it more accessible to greater numbers. Moreover, the necessity of developing for Android was realized during the interaction redevelopment from a map-based to an NFC-based interface – up until the iPhone 6 (released September 2014), there was no NFC hardware included in iOS equipped phones, and the price of the iPhone 6 (brand new at the time) was far beyond the budgets of the research team. Indeed, affordability was a big factor in a project planned to be used in future evaluations by upwards of 30 school children.

The game was run on NFC-equipped Sony Xperia M2 phones running Android version 4.3 (JellyBean) to cope with the resource intensive Async-task threading and high-resolution graphics. The phones used a 1.2 GHz Quad-core CPU in comparison to an 800MHz Dual-core, and 1GB RAM and it was found that phones with less performance, proved unreliable at running later versions of BrainQuest. Finally, and perhaps most importantly, the Sony's could provide telecommunications at 4G speeds which was very beneficial when attempting the transferal of data often in real time – due to the Score Centre feature.

There was also the need for peripheral hardware in the form of re-writeable NFC tags containing a memory of 44 Bytes. The tags were placed upon plush beanie cow and sheep toys, as well as sign holders denoting animal pens. Each pen consists of a specifically coloured hula hoop containing the sign and any associated cows or sheep.

5.2.2 Software

Software developed for Android devices can be written in several different languages, but the official and most common language used is Java. Most the software developed for BrainQuest system is local to the Android smartphones themselves, which play host to the most complex aspects of programming by way of an application. The app was written mainly in Java, an object-oriented language for which all the official and a wealth of unofficial Android library modules have been written and can be freely used. BrainQuest was developed using the popular free and open-source Eclipse ADT (Android Development Tools) IDE, which includes an embedded Android plugin provided by Google within Eclipse, to enable developers set up new Android projects, create an application UI, add packages based on the Android Framework API (Application Programming Interface) via an SDK (Software Development Kit) manager, debug their applications using the Android SDK tools, and create and export .apk files to both virtual and physical devices. The Android Framework API consists of a set of rules, packages, and specifications that software programs can follow to communicate with each other. It serves as an interface between different software programs and empowers their interaction, like the way the user interface enables interaction between humans and computers.

Within an Android application project, the programmer writes related Java code structured within a series of packages, which can interact with a hierarchy of associated resources, written as XML (a language used to store and transport data), also stored under the project umbrella. E.g., each screen presented to the user when using an application makes use of an

'Activity' coded in Java which references an XML layout defining sizing, positioning and referencing of resources to be displayed. The ADT plugin for Eclipse enables the developer to simulate the look and feel of these layouts from within the IDE, allowing for ease and speedy growth of an application.

BrainQuest also makes use of the Apache Http Client library, a client side HTTP transport library, commonly used for data communications over the internet. HttpClient's purpose is to transmit and receive HTTP messages. This was used initially in communication PHP scripts on a university server but has been retained for communication with PHP scripts upon the Google Cloud Server.

The minimum required API level to run BrainQuest is API Level 10 or Android version 2.2.3 due to the required inclusion of the android.nfc packages. However, it is likely that some small changes may have to be made in future for using the app with Android 6.0 (API 23) and higher due to the depreciation of the Apache Http Client in favour of a new method.

BrainQuest communicates with the SQL database stored on the Google Cloud by making requests to a series of PHP scripts also stored on the same server. The benefits of using a commercial data service provider used for big business, such as Google Cloud, are being able to easily scale up concurrent data communication depending on the number of users playing the game, ensure rigorous backup and security of data, and reduce the chance of much down time. This was essential to BrainQuest, due to the multiple points throughout the game where communication with the database is required and the fact that in study context, up to 30 children may need to use the app concurrently. However, it was understood from the outset that data of a personal nature such as real names and other personal information, would be inappropriate to be stored on servers beyond control and responsibility of the University.

5.2.3 Architecture

The architecture of the BrainQuest system is shown in Figure 32. It details the interaction between the smartphone user interface and the backend services, including the flow of data at different points in the app.

Beyond the scope of the Android application, BrainQuest communicates with an SQL database storing user game data and hosted on a Google Cloud server, through PHP scripts running on another part of that server. At several points during the game, data communication occurs:

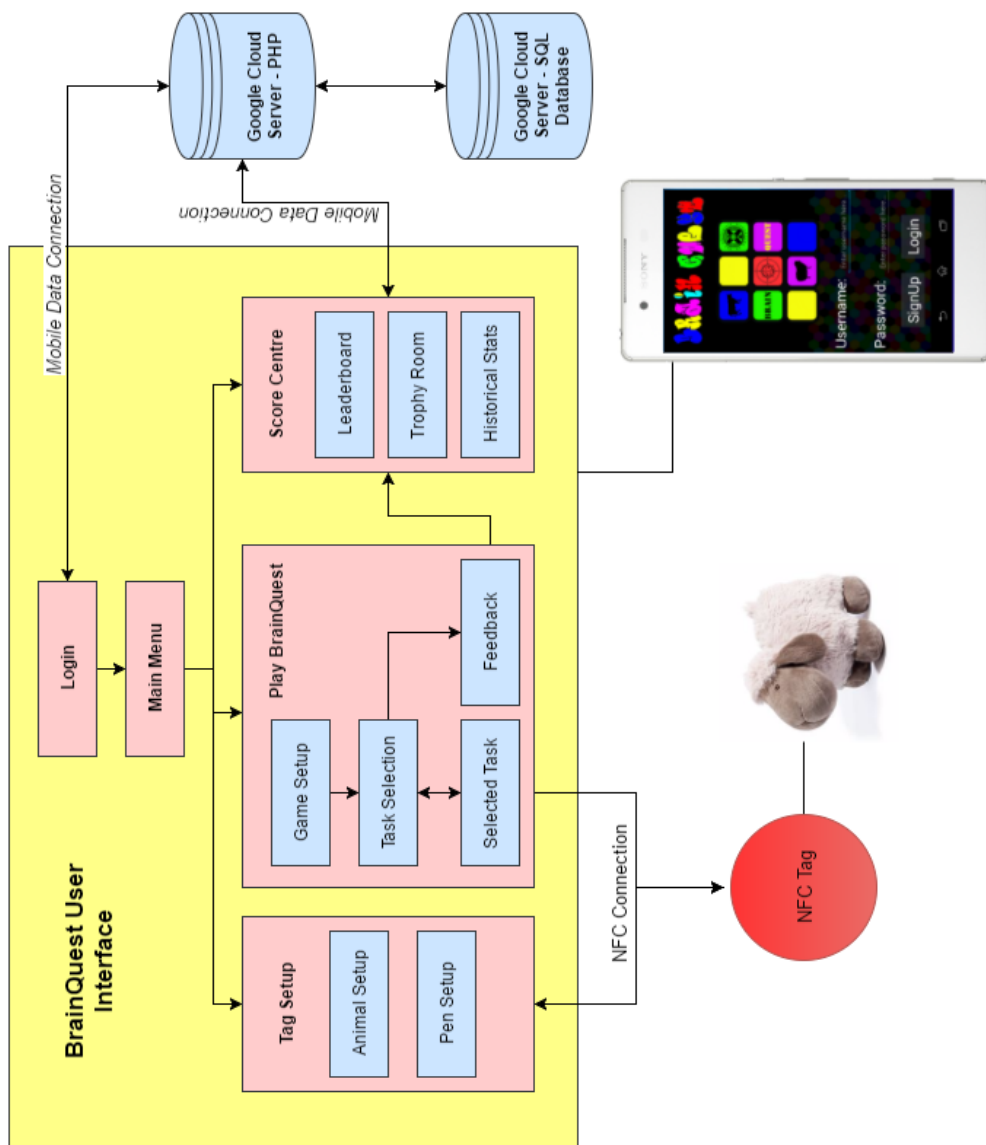


Figure 32: BrainQuest Architecture

1. User login and authentication: when the user attempts to log into the app, the data which they provide is handled via the Login.php script (see Appendix D7) and used to query the User table in the database to check that the user exists and the password matches before encoding the result of the query as a JSON object, to be delivered and decoded by the app. If successful the user is logged in, if not (depending on the type of error) the user is asked to re-enter their details.
2. App sign up: when the user signs up a new username and password from within the app, the data is handled via the register.php script (see Appendix D4), which queries the User table in the database to an existing entry of the provided username. If no entry exists, the details provided by the user are inserted into the User table, as well as creating a user profile which creates a record for a specific username in every table of the database, before returning a JSON encoded success message to the app which signs in the user. If a profile already exists for a user, a failure message is returned and displayed on the screen to the user informing them that the account already exists.
3. Updating user game performance: following the end of each game, when the user selects to finish the game, their game data is inserted into the database via the following PHP scripts:
 - bqgamelog.php – creates a stores a record of their game log
 - bqupdatePoints.php – updates the point statistics field of the BQPoints table to reflect the new total

Retrieving score centre data: when the user opens the score centre, their historical game data is pulled as a JSON message from the database, via bqgetallfromdatabase.php historical game data, before being used by the app to determine which trophies to show in the trophy cabinet and variables to be displayed alongside their related titles in the historical data and record pages, informing leaderboard.

5.3 Development Methodology

5.3.1 Methodology Overview

Table 12 lists a subset of the methodological concerns pertinent to the development of serious games which were adopted during the creation of BrainQuest.

ID	Development Methodological Concern
MC1	<i>A UCD process involving end-users can be useful in encouraging enjoyment and engagement.</i>
MC2	<i>Designing CTGs should involve experts from a diverse range of backgrounds, including those across game and technology design as well as psychology.</i>
MC3	<i>Development for serious games should be implemented in an incremental way, designing and implementing prototypes based on experience goals before seeking feedback from end-users. Following user evaluation, changes in the design can be made to start a new prototype evolution.</i>
MC4	<i>At each stage of the development cycle, the designer should plan, implement or evaluate the game with respect to (1) learning outcomes, (2) storytelling or the story to be created by the user's experience, (3) gameplay mechanics, dynamics, and aesthetics, (4) the user experience of the interface, and (5) the technology platform.</i>

Table 12: Literature Methodological Concerns Recap

Robertson and Macvean (2013; 2012) presented the merits of adopting a UCD process to develop technology which more closely meets end-user needs and spawns engaging experiences (MC1). UCD is synonymous with design and evaluative cycles and consistent with development methodologies for serious game design (MC3, MC4). It is also suitable for involving a diverse range of expertise in their design and seeking contributions from a diverse range of experts during requirements gathering and evaluative processes – consistent with Mishra, Anguera, and Gazzaley (2016) (MC2). Hence, UCD was apt for the development of BrainQuest. Rapid prototyping (Boehm, 1988) was chosen as a complimentary methodology. Each prototype development comprised planning, execution and analysis stages.

5.3.2 User-Centred Design

UCD, a participatory design approach described in Chapter Three (Section 3.4.2.1, p. 98) was the principle technique employed in BrainQuest's development. The role of 'informants' was chosen for the BrainQuest development to keep children of the target age (11-12 years) involved as fully as possible, providing indirect input through observation, as well as feedback to the research team regarding all stages of the technology development – ideas, prototypes and the finished product. Thus, the roles of user and tester were inappropriate (Druin, 2002). However, as we were working with Primary 7 children aged between 11 and 12 (in accordance with R2) from a local Primary School, there were challenges related to the children's availability with curricula commitments, as well as the scheduled transition to High School midway through the project, which prevented them from being considered equal stakeholders and partners in the process. Finally, the prominence of EF within the project, a complex subject which, though comprehensible to children, required psychology expertise to design cognitive challenges. Hence, this restricted the scope of the role which children would be able to play in the design.

5.3.3 Development Method

A 'Spiral' (Boehm, 1988) developmental approach was taken towards BrainQuest's development, characterized by rapid prototyping involving multiple iterations of the following activities to create a series of high-fidelity prototypes:

1. Planning: Gathering user requirements, as well as requirements predicated by pertinent literature and the opinions of experts
2. Execution: Development of the prototype design and implementation
3. Evaluation: Prototype evaluation with end-users
4. Analysis: Expert reflections upon prototype evaluation

In total, there were 4 distinct prototyping cycles (prototypes 1-3 + the completed game) over the course of one year. In total, the design phase (excluding the evaluation of the final system, described in Chapter Six) involved 36 children from 2 Primary 7 classes from the same Edinburgh Primary School. The project length overlapped in terms of the school year (January 2014-December 2014) and one of the contributing P7 classes moved to High School following the completion of term in June 2014. Thus, 2 prototyping cycles were

undertaken with the first class (28 children) and the remaining 2 prototyping cycles undertaken with a subset (8 children) of the second class.

Utilizing the Spiral approach presented several advantages to the BrainQuest project:

1. In a complex project like BrainQuest, assimilating different models from different fields of study as well satisfying user requirements, the Spiral approach enabled concepts and technical functionality to become functional in stages, thereby allowing to core components to take precedence.
2. The Spiral approach enabled end-user feedback throughout the development, which is desirable, especially in designing games with children, where eliciting initial requirements can be hard. This helped to identify problems early, as well allow the design to be flexible to changing end-user needs.
3. The Spiral model was suitable within our UCD as a way of keeping end-users engaged in the process by being able to tangibly experience how their feedback was influencing the design.
4. From the perspective of the developer, the Spiral approach allowed for creativity, enabling the user to create alternatives (meeting user requirements in different ways) within the design for the end-users to choose from.

The UCD process began in the planning stage with a ‘Gamestorming’ session to generate game content (fantasies, themes, activities) stories as well as to produce general feedback regarding previously experienced successful/unsuccessful game designs, and finally, establish some end-user requirements. Meetings with experts from the fields of HCI and cognitive psychology were also conducted to corroborate the literature defined requirements (R), help prioritize them, and suggest methods for their implementation. Each prototype development was planned while attempting to consolidate or balance the views of the children with those of the experts and the literature defined requirements. The main researcher implemented every prototype before some limited testing was undertaken with colleagues. Every prototype was subjected to a formal evaluation session with the end-users. These evaluations sought to establish the value of BrainQuest and its ability to meet the design requirements through a variety of activities, such as comparison with a physical alternative, expert observation during playtesting, a verbal recital of rules, peer feedback sessions, and interviews. Analysis of these evaluation sessions contributed to many fundamental design decisions, such as the evolution from a location, map-based interface to the NFC-based interface seen in the final game.

5.4 BrainQuest Development Process

5.4.1 Requirements Gathering

5.4.1.1 Initial Expert Consultations

Gazzaley et al. (2016) recommends CTG development should include game design and psychology experts (MC2). Hence, a series of meetings took place between the main researcher, the supervising researcher and two academic experts – one specialized in developmental psychology, the other in human-computer interaction (HCI).

The psychologist informed the research team of relevant cognitive training and EF literature which incorporated technology as well as specific cognitive assessments. The HCI expert identified ways serious games could be designed to be engaging, long-lasting and, therefore, promote behaviour and ability change. It was concluded that initial gameplay should be established in participation with end-users before integrating cognitive challenges (R3).

5.4.1.2 Gamestorming

The research team approached a local Edinburgh Primary School, which had recently hosted a previous exergame intervention, to begin UCD with one of their Primary 7 classes (children aged 11-12). Thus, involving children with previous pervasive exergame experience and of the targeted intervention age (R2).

A ‘Gamestorming’ session was held at the school and comprised a 2-hour focus group with a class of 26 children. During the session, the children undertook Gamestorming-inspired activities, designed to generate creative ideas and confirm literature assumptions. The activities included are detailed in further detail in Appendix A1 but included a mixture of open-ended creative activities to generate new ideas, blank space and structured questions to inform specific design decisions, and whole group discussion. The session was planned and run by the main researcher, with assistance during the session provided by the class and PE teachers.

The session results were analysed by identifying reoccurring keywords before being sorted into themes. 2 game-themes emerged: 10 children suggested animal based game plots while 14 recommended plots featuring a battle between the player and an antagonist. The most popular game activity suggestions were: chasing between players or in-game characters (14 children), running to collect items (5 children). Another notable idea, which was well

received during the group discussion, was a game plot where the player had to save baby wolves from an evil demon.

With regards to the design priority of the game: 9 children emphasised providing PA benefits and 13 insisted the game be “fun” to play. 25 children said that the exergame should enable them “to play with friends” – 9 children wanted to interact “competitively”, 8 wanted to interact “co-operatively”, and 8 wanted to do “both”. Note, with respect to previous exergame experience, 5 children reported a leaderboard as being fundamental to their enjoyment, while 2 children praised variable difficulty levels.

These results informed the initial end-user requirements for our BrainQuest:

- The plot of the game should implicate the user in a battle against an insipid adversary.
- The characters in the game should be animal themed and contain an evil or criminal theme.
- Activities should include chase/catch dynamics, item collection, and saving items from an adversary
- The game should include both competitive and cooperative conditions
- There should be a leaderboard feature
- There should be variable difficulty

5.4.2 Prototype 1

5.4.2.1 Prototype 1: Choosing a Design

The research team chose between a series of paper game mock-ups according to their ability to satisfy both end-user and literature requirements. The mock-ups were created by the main researcher and focused on fundamentals: fantasy (MD13) and activities (MD15). The chosen mock-up plot is described and compared with end-user requirements in Table 13.

Mock-up Plot	Meeting End-User Requirements
<p>The plot focuses around a fantasy ‘animal rustling’ theme. The user assumes the role of a ‘hero’ who must collect virtual animals and return them to their base as well as chasing and catching ‘rustler’ adversaries. Rustlers attempt to steal the hero’s animals and take them to their base. The hero can also save animals who have been captured inside the rustler base.</p>	<ol style="list-style-type: none"> 1. The plot of the game incorporates both the animal and good vs evil themes. 2. The game places the user as the hero in a battle against two adversaries. 3. As there are three characters involved in the game, it provides the opportunity for cooperative and/or competitive social play. 4. The choice of activities in the game integrates the suggestions captured by the game storming session – chasing, collecting, and saving. 5. The challenge of the game can be influenced by the skill of the opponent.

Table 13: BrainQuest vs End-user Requirements

5.4.2.2 Prototype 1: Integrating EF Challenge

With many user-specific aspects of the game confirmed, the game activities; themes; and physical challenge had to be integrated with the challenge of executive skills. Though gameplay rather than a cognitive assessment was to be the focal point of the game (MD11), the psychologist recommended integrating the structure of a cognitive assessment to ensure the direct challenge of EF abilities and to model tasks requiring a combination of complex EFs rather than WM in isolation.

The psychologist referred the research team to the BADS-C testing battery, described in Appendix C and Chapter Two (Section 2.5.2, p. 63), which was appropriate for the end-user age group (11-12 years old). One specific subtest, the 6E was deemed to be especially representative of real-world executive functioning, therefore, relevant to the project goals (consistent R10, and R14).

Hence, the structure and rules employed in the 6E were integrated in BrainQuest’s design:

- Keeping in mind multiple rules and evaluating them against several options while decision making
- Task switching to complete 6 different tasks
- Developing a task ordering strategy to most efficiently follow the rules.

We contrast between the initial BrainQuest mock-up and the mock-up integrating 6E in Table 14:

6E Integrated Mock-up

The user still has 3 different activities to undertake – returning animals, stopping rustlers, and saving animals. However, each activity is comprised of 2 subparts, one involving cows and the other involving sheep, e.g. save cow OR save sheep – thus, mimicking the 6 parts of the 6E test.

The user is also provided with a clear goal, to attempt to undertake each of the 6 parts at least once and change the activity type each time.

Thus, like the 6E, the user must hold in mind multiple rules and evaluate them against several options while decision making and develop a task ordering strategy to most efficiently follow the rules.

Table 14: Integrating 6E in Mock-up

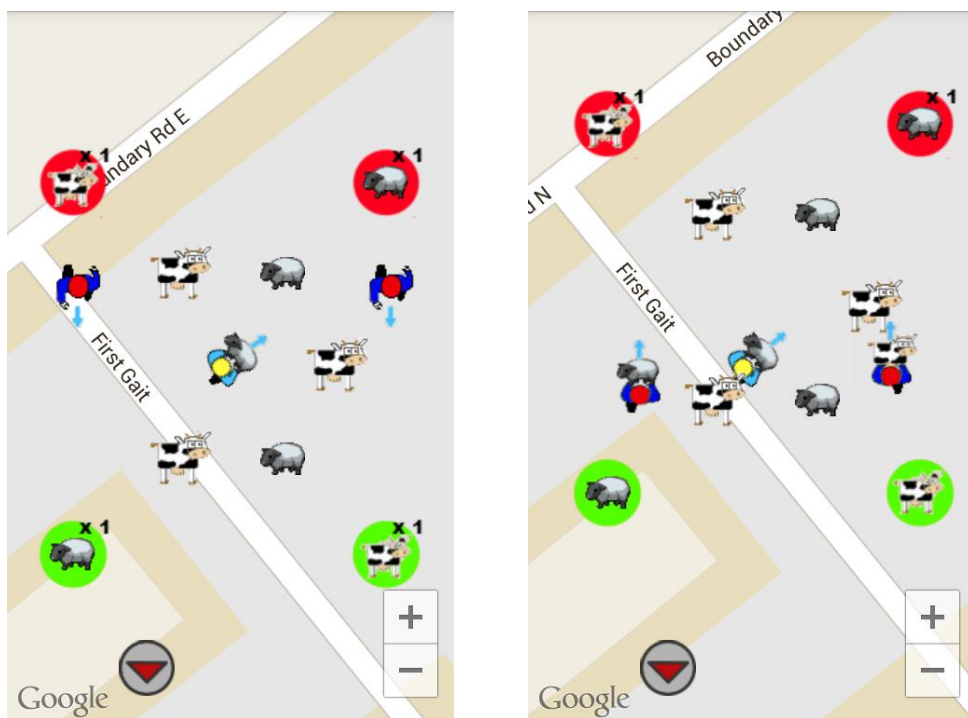


Figure 33: Prototype 1 Interface

5.4.2.3 Prototype 1: From Paper to Phone

The technology prototype portrayed BrainQuest on a map, thereby, taking a location-based approach, prominent in previous literature. This approach allowed for a rapid prototype to be created as the main researcher had previous experience with the relevant technology.

Moreover, the end-users had previous experience with location-based exergames, thereby, reducing the chances of confusion caused by technology learning.

The main researcher developed the first high-fidelity prototype for the Android mobile device platform. The game gathered the user's real-world location using a combination of GPS and radio signal triangulation, plotting the user's position on a Google Map (Figure 34). The activities involved were the same as the completed BrainQuest game: the user played in the role of the hero (yellow/blue man) and collected virtual cow and sheep before returning them to hero animal pens (green circles) to score points while trying to stop 2 rustlers (red/blue men) from stealing and returning animals to their own pens (red circles). However, the rustlers were portrayed by computer AI rather than other players.

To control the hero's on-screen position, the user had to physically move in the real-world. To interact with virtual objects and characters, the user maintained a proximity fewer than 3 metres from the GPS coordinates of their target. When the user entered the proximity of static objects – pens and animals, a green 'pick up' button was overlaid on the interface. Pressing the button enabled the user to interact with the object. The user could then cancel



Figure 34: BrainQuest Prototype 1

the interaction by pressing a red 'put down' button. Interactions with moving objects – the rustlers, occurred automatically when the hero entered their proximity.

5.4.2.4 Initial Task Ordering Rules

The task ordering rules which governed the order activities could be performed were implemented slightly differently than envisaged in the paper prototype. It was initially

thought that the 6E rules might be easy to master if played repetitively and, therefore, not have enough longevity of challenge.

Rule 1 was the same the 6E:

Attempt all 6 tasks within the 5-minute time limit

However, rule 2 was slightly different. In the 6E test, one must simply change task type at each change of task. Initially BrainQuest asked users to:

Change task type at each change of task AND only return to the current task type after completing tasks from each of the other types.

5.4.2.5 Non-Technical Prototype: From Paper to Reality

Though several design guidelines suggest technology integration in EF training could be valuable to create more immersive and engaging experiences, tailoring challenge and facilitating performance review (R4, R5, R21). However, the experts felt that the lack of research on the subject required the creation and evaluation of a purely physical ('non-technical') version of BrainQuest without integrated technology. Evaluation of this physical version would consider:

- the physical and EF challenges present within the game without an added layer of technical complexity.
- the benefits and costs of the technology more clearly to help drive future design iterations.

The non-technical version closely resembled the structure and setup of completed BrainQuest game – see Game Space Setup (Section 5.1.2, p. 121). E.g. there was a 15-square metre play space and the game was a 3-player multiplayer. The props were also similar:

- Red hula hoops – 1 red hoop as a hero sheep pen, 1 red hoop as a rustler sheep pen
- Blue hula hoops – 1 blue hoop as a hero cow pen, 1 blue hoop as a rustler cow pen
- Red bean bags (palm sized) were used as sheep
- Blue bean bags (palm sized) were used as cows

5.4.2.6 Prototype 1: Evaluation

5.4.2.6.1 Overview

Following the completion of prototype 1, the main researcher and supervising researcher returned to the same Primary School and P7 class which had participated in the Gamestorming session. The researchers undertook a 60-minute evaluation with a subset of 6 children from the class where they played prototype 1 and the non-technical alternative before answering questions about the games. The goal of the session was to evaluate both games for understandability, their ability to engage users, the levels of PA involved, and their relationship with EF skills.

The main researcher ran the session, explaining the game and troubleshooting, while the other researcher took observation notes. The session was split into three periods:

- 15-minute tutorial – the main researcher explained the rules of the game to the children.
- 35-minute gameplay – the children were split into 2 groups to play the game, 1 group played Prototype 1, while the other group played the physical version. The groups swapped after 15 minutes.
- 10-minute feedback – the children came together as a group to provide their game feedback, directed by the main researcher and audio recorded by the other researcher.

5.4.2.6.2 Results

The children said that concept of both games was “easy to learn how to play and understand quickly”. However, the children later contradicted this account for prototype 1, when several stated it to be “confusing”. The non-technical game was undoubtedly easier to understand with an observed increase in speed and fluidity of activities but nearly all children still initially broke the task ordering rules. Unfortunately, the confusion exhibited during prototype 1 play made it hard to ascertain whether EF skills were required during gameplay. Therefore, this was labelled a priority for future evaluations to address following the confirmation of satisfactory usability.

With regards to PA, the observations reported users exhibiting low intensity PA while playing prototype 1 – enabling only walking with much of the time spent standing as the user struggled to navigate. Thus, falling short of the desired contributions to MVPA. In comparison, the non-technical version followed a more intense pattern of PA, including

walking, jogging, and sprinting, in addition to shorter periods of inactivity. Moreover, the children appeared fatigued and described themselves “tired”.

Feedback and observations suggested both games were “fun” and the animal rustling theme had widespread appeal but the physical game was unanimously preferred by all. One reason was that it was easier to “navigate” in the non-technical version. Another was its multiplayer structure because it let them “play with their friends” rather than computer AI. This was supported by the observation notes which reported enjoyable social interactions in the physical game. Furthermore, they found prototype 1 “hard to play properly” because of a noisy user interface where there was “a lot going on” on a small phone display.

Prototype 1 had one notable benefit over the alternative non-technical version – the ability to record task choice and rule adherence made it possible to differentiate between individual performances. However, in general, the experts felt the non-technical game was better equipped to foster motivation as well as PA. Hence, the HCI experts suggested a dual approach to improvement:

- Changing the interaction design of future prototypes to more closely resemble the non-technical game.
- Retaining logging abilities and persevering with the game design literature.

This would involve abandoning the location-based approach in favour of enabling physical interactions with characters and objects. Following the session, it had become apparent that the GPS technology was the biggest limitation of the current prototype, reducing usability, fun, the intensity of exercise involved, and inhibiting game rule understanding.

5.4.3 Prototype 2

5.4.3.1 *Prototype 2: Game Redesign*

5.4.3.1.1 Introduction of NFC Approach

As highlighted during the evaluation of prototype 1, though the location-based approach allowed for rapid prototyping, it was unable to provide the accuracy needed to meet the game’s user experience requirements. To make the interaction design resemble the non-technical prototype while retaining the benefits of technology, the NFC approach, involving tangible objects and real-life opponents and present in the completed BrainQuest game, was introduced.

The play space structure, dimensions, and tangible game objects introduced, matched those described in the non-technical prototype (Section 5.4.2.5, p. 167) but the palm sized red and blue bean bags were replaced with bean bag toy sheep and cows. NFC tags were attached to the hula hoops and to the toy animals. It was hoped the NFC implementation of the game would provide more technological ubiquity, using tangible objects and providing opportunities for face to face interactions between players capable of creating a closer relationship between the game and reality. Hence, making it more likely for the transfer of skills beyond the scope of the game.



Figure 36: NFC Tag Animal



Figure 35: NFC Tag Animal Scan

5.4.3.1.2 Introduction of Human Rustlers

The rustler roles were converted from virtual characters to an additional role for users. The rustler role sought to satisfy the end-user desire for social play and supporting the design guidelines advocating the social benefits to EF and PA.



Figure 37: BrainQuest - Pitch-side View

The rustler roles were a selectable game mode in the app and used NFC interactions. One player was designated 'Sheep Rustler', the other played as 'Cow Rustler'. The objective remained the same – steal hero animals and return their plunder to the rustler pens. A further

motivation for enabling the user to play as the rustler, was also to prolong the PA involved in the game, especially for individuals learning to play BrainQuest. The rustler role was less complex than the hero's but allowed for practice upon scanning operations and rule familiarization. Note: in this prototype, the rustler role was a trial introduction and was not interactive within the game's score system.

5.4.3.1.3 Interface Redesign

To provide users with easier to learn controls (R24) and strengthen competence (R19, R22) which was absent in prototype 1, the interaction design was modified. Much of the redesigned interface remains in the current completed BrainQuest game.

Task Selection Screen

The Task Selection screen was introduced to represent the choice between 6 tasks in a more obvious way than in prototype 1 and create clear decision points for the user. Playing as the hero, the user was presented with 6 horizontally arranged thumbnails from which to choose, denoting the different tasks. Thumbnails of the same task type used similar symbols (return, stop rustler, save), just as the 6E separates task types into different colours.

Selected Task Screen

The Selected Task screen was also introduced in prototype 2 – the area of the application which enabled the phone to interact with NFC objects. At this stage, the Selected Task screen closely resembled that present in the completed BrainQuest game (Section 5.1.5.2.3, p. 130) but instead of a different screen for both heroes and rustlers, the same screen was edited programmatically according to the user's role.

For both roles, the screen introduced written instructions at the centre of the display. The instructions were split into different actions making up the task so user knowledge of task



Figure 38: Prototype 2 Hero Task Selection Screen

stages could be expanded cumulatively. E.g., if the hero chose to ‘Return a Sheep’, the instruction displayed the message, “Pick up a sheep from the play space and scan it.” Following the successful completion of this step, the message would change to say, “Take this sheep to the hero sheep pen and scan the pen to unlock it.” There was also the option to activate audio commentary which spoke the written instructions presented and enabled the user to listen to the task objective while observing the play space.

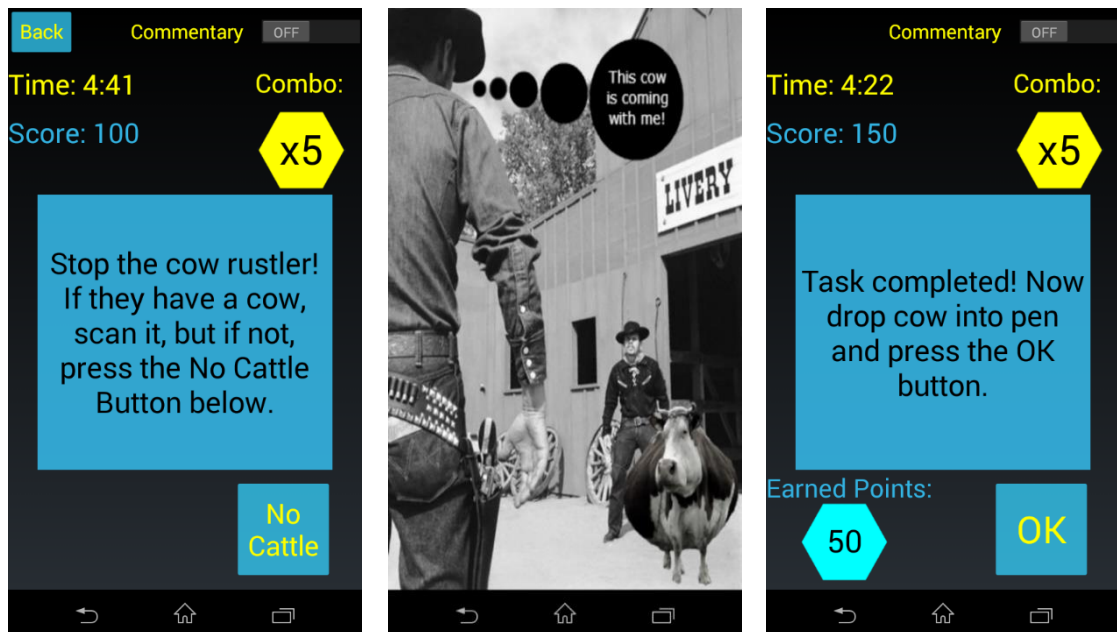


Figure 39: Prototype 2 Selected Task Screen

The fantasy sounds and graphics, overlaid on the screen on the Selected Task screen in response to object interactions, were also introduced. These were designed to bolster the fantasy and provide a source of amusement. For the hero, these included the following interactions:

- Simple sheep / cow scanning involves a picture of the animal facing the user with an accompanying ‘baa!’ or ‘moo!’
- Pen opening depicts a picture of many sheep / cows in a pen with a chorus of accompanying ‘baas!’ or ‘moos!’
- Saving a sheep /cow presents a sheep / cow climbing a ladder over a fence with an accompanying ‘escape’ tune playing.

- Capturing a sheep /cow from a sheep / cow rustler shows two cowboys in a showdown scenario with a sheep / cow cowering for cover and an accompanying ‘cowboy’ tune playing.

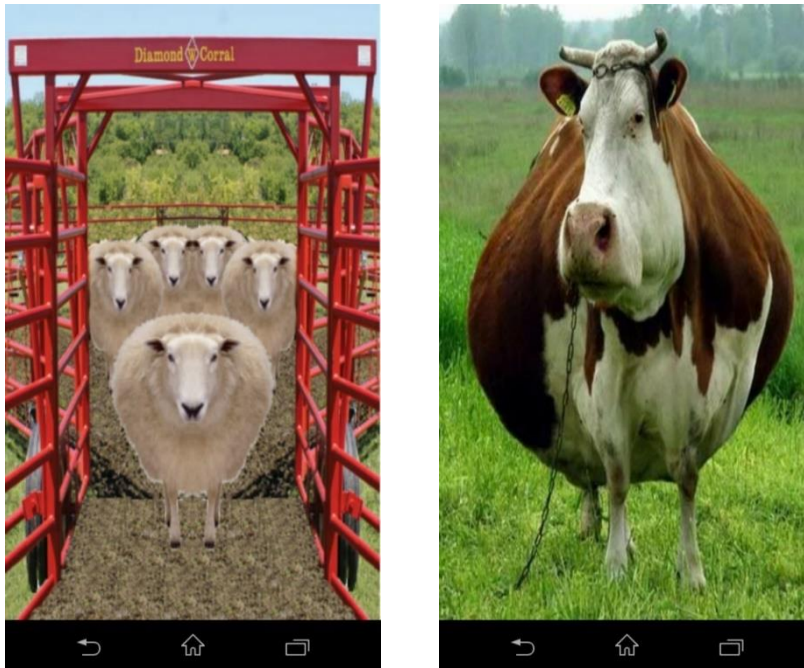


Figure 40: Example Prototype 2 Animations

Meanwhile, the rustler had an interface in very limited detail – only a single fantasy sound and graphic overlay and only one additional button, the ‘Caught by Hero’ button, to account for situations where they were caught by a hero or had opened an empty hero pen. Moreover, at this point the Selected Task screen only displayed current game points and combo statistics for the hero.

Feedback Screen

At this stage, the feedback screen was minimalist and was only provided for the hero. The user was presented with their total points score, highest combo score and the number of errors made.

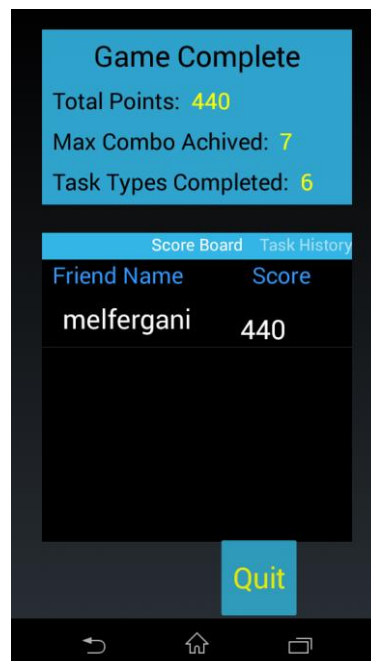


Figure 41: Prototype 2 Feedback Screen

5.4.3.2 Prototype 2: Evaluation

5.4.3.2.1 Overview

The prototype 2 evaluation involved the same 6 children from previous Gamestorming and evaluation sessions, at the same Edinburgh primary school. During the session, the children, again, played the non-technical version before playing BrainQuest prototype 2. This time, the goals of the session were to evaluate whether the new prototype had increased user understanding, user engagement, and PA from the previous iteration and how it compared to the non-technical version.

Three observers were present at the session – the main researcher, the supervising researchers, and the psychologist. As before, the main researcher ran the session, explaining the game and troubleshooting while the other researchers took observation notes and asked questions during the feedback component of the session.

The session was split into three periods:

- 10-minute tutorial – the main researcher refreshed the rules of the game to the children.
- 40-minute gameplay – the children were split into 2 groups to play the game. First, the groups took it in turns to play the non-technical version – for around 20 minutes. Then the groups played prototype 2 for 20 minutes. During this time, while one group of 3 children played the game, the other group observed. The groups swapped after each game.
- 10-minute feedback – the children converged to a single group to provide game feedback, directed by the main researcher and audio recorded by the other researchers.

5.4.3.2.2 Results

There was a marked improvement in game understanding in comparison to prototype 1, likely due to the change from location-based to NFC-based interface. Furthermore, the written and audio instructions were useful in helping the children learn the activity procedures for each of the game tasks.

However, the horizontal thumbnail arrangement of the Task Selection screen led was too narrow a contact area and resulted in accidental task choices which frustrated users. Furthermore, though 5 children deemed prototype 2 “easier to understand” than both prototype 1 and the non-technical version, the observers observed some remaining

confusion. The lack of support for learning the task ordering rules was a concern for both the prototype 2 and the non-technical version. It remained unclear whether the task ordering rules, in addition to the task procedures and additional challenges (all of which absent from the 6E), made the game too complex for the age group identified. One procedural confusion concerned the children, who regularly mixed up hero and rustler pens. Hence, the experts recommended future designs support task ordering rule learning.

Improvements in cultivating user engagement were the biggest successes of prototype 2. All 6 children deemed the new tech prototype to be “much better” than its predecessor, and 4 children found it to be more “fun” than even the non-technical version. The fantasy graphics and sounds for the hero were described as “cool” and “funny” with all children making positive comments but they also felt that the rustler graphics/sounds should have more variety. Furthermore, they also wanted the rustler role to contribute to point scores. The NFC interface itself was the favourite game aspect for 3 children but this may be consequent of the technology’s novelty as they had never encountered NFC before.

Borrowing the social elements from the non-technological version also appeared to be beneficial and encouraged, at times, much more intense PA than prototype 1. However, the pace and fluidity of the game remained noticeably less intense than the non-technical prototype. Hence, for children who valued physical exertion, the scanning operations involved in the prototype were cumbersome and diminished both PA and engagement. Consequently, 2 children stated preferring the non-technical version and all 6 children reported that game “more tiring”. The experts suggested BrainQuest be made more fluid and physically exerting by shortening the duration or number of scanning operations involved.

5.4.4 Prototype 3

5.4.4.1 *Prototype 3: Game Redesign*

5.4.4.1.1 NFC Scanning Update

In prototype 2, object interactions required reading the NFC tag before writing to the tag to update the object’s ownership details. Not only did this take more than double the time of a simple read operation (<1 second) but if the scanning process was interrupted it caused a loss of connectivity between the tag and the phone, thus requiring the scanning process to be restarted. Furthermore, occasionally a loss of connectivity, such as in the scenario described, resulted in the data wiping of a tag.

The main researcher decided these issues could be mitigated by implementing additional code within the app. This would consider the user's chosen task and previous choices, to appropriate the correct response to a new scanning operation. Additionally, the display duration of graphics was reduced from 5 to 3 seconds and unlike before, the user could skip the graphic by pressing on the screen overlay (the fantasy sound continued to play in the background).

Table 15 describes the changes to processes for each task and the associated reductions in scanning operations:

Task Type	Prototype 2: Scanning Process	Prototype 2: Number of Operations	Prototype 3: Scanning Process	Prototype 3: Number of Operations
Return Animal	<ol style="list-style-type: none"> 1. The hero collects an animal from the play space by scanning the cow/sheep 2. The hero scans the hero animal pen to open it 3. The hero scans the animal before dropping it into the pen. 	3	<ol style="list-style-type: none"> 1. The hero collects an animal from the play space by scanning the cow/sheep 2. The hero scans the hero animal pen to open it and drops animal into the pen 	2
Save Animal	<ol style="list-style-type: none"> 1. The hero scans the rustler animal pen to open it 2. The hero picks up an animal from the pen by scanning it, before throwing it back into the play space to set it free. 	2	<ol style="list-style-type: none"> 1. The hero scans the rustler animal pen to open it and set animal free before throwing it back to play space 	2
Stop Rustler	<ol style="list-style-type: none"> 1. The hero must chase and catch a rustler by physically tagging them before scanning any animal 	3	<ol style="list-style-type: none"> 1. The hero must chase and catch a rustler by physically tagging them before scanning any animal in 	2

	<p>in possession of the rustler</p> <p>2. The hero then scans the hero pen to open it</p> <p>3. The hero scans the animal to drop it into the pen</p>		<p>possession of the rustler</p> <p>2. The hero scans the hero animal pen to open it and drops the animal into the pen</p>	
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Table 15: Refinement of NFC Scanning

5.4.4.1.2 Interface Redesign

To further increase the ease of controls (R24), other on-screen interactions were redesigned.

Task Selection Screen Update

The Task Selection screen was redesigned from horizontal choice thumbnails to 3 rows of 2 thumbnails. This allowed a more proportional contact area for the user when selecting tasks and kept task types together in rows. The thumbnail artwork was also simplified to match the designs shown on new physical prop signs introduced for this prototype.

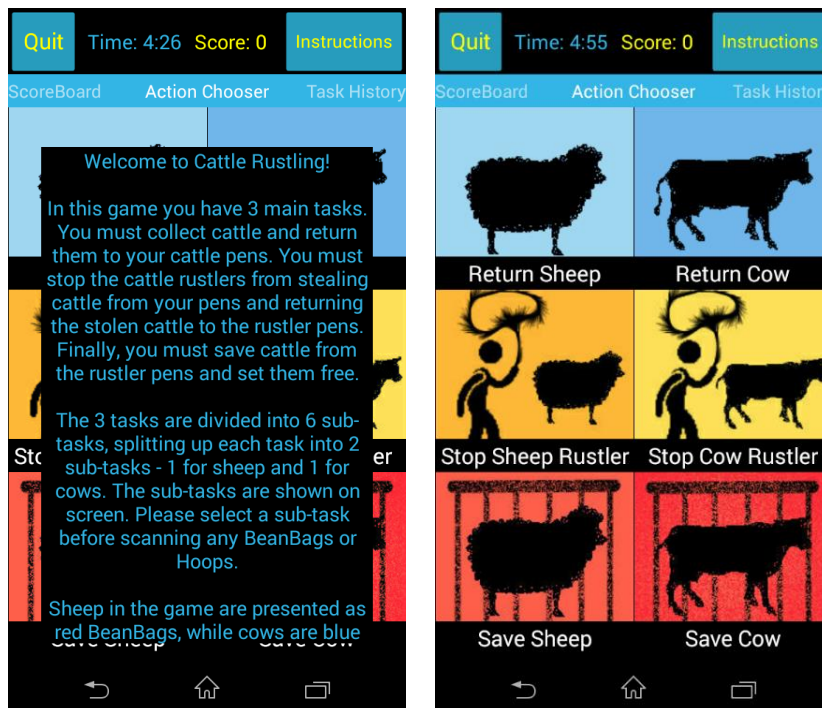


Figure 42: Prototype 3 Hero Task Selection

Rustler Selected Task Screen Update

As part of the new ‘Rustler Scoring System V2’ (Appendix A4.2), changes were made to the rustler task process so points could be attributed for rustling. Consequently, the ‘Open Pen’ and ‘Pen Empty’ buttons were added to the Rustler Selected Task screen, which accompanied the existing ‘Caught by Hero’ button. The new interface buttons remain in the completed BrainQuest game and are described in Section 5.1.5.2.4 (p. 131). Moreover, some additional rustler sounds and graphics were added to correspond with the new buttons.

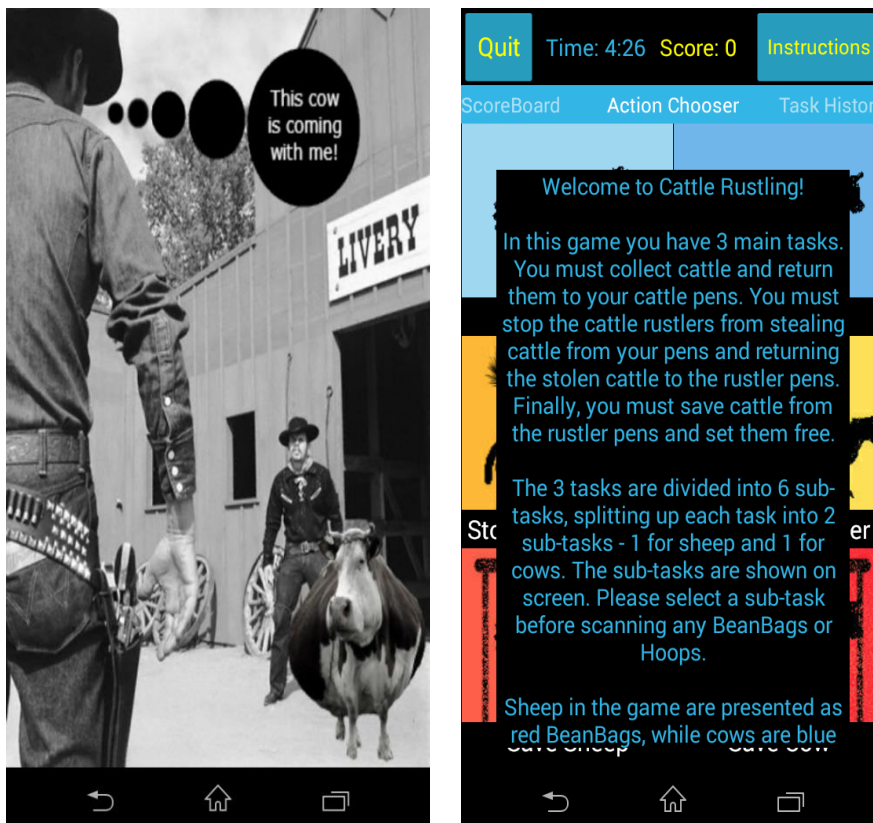


Figure 43: Prototype 3 Rustler Task Selection

Additional Props

Animal pen signs were introduced to aid user understanding and strengthen the visual connection between the interface and the physical props involved the game. The signs showed the name of the animal pen and well as a picture of either a cow or sheep, with hero signs in blue and rustler signs in red – corresponding to the thumbnails on the Task Selection

screen. The signs were encased in a plastic floor stand to keep them in easy view of the user, with NFC tags being removed from hula hoops and placed on the signs.

5.4.4.1.3 Introduction of Variable Difficulty and Support Tools

Prototype 3 marked the introduction of the variable difficulty and support tools described in Section 5.1.6 (p. 136). The Task Shading, Task History tools were designed to initially support user understanding of the task ordering rules, and continuously aid the user's WM by reducing the amount of data which must be retained during gameplay. It was felt following the previous evaluations that the user had far more information to retain than the 6E test – such as visuospatial information. Hence, though users may be able to successfully undertake the 6E, BrainQuest may have too far beyond the cusp of their abilities. The starting difficulty needed a lower floor.

Consequently, the variable difficulty level was formed by structured removal of the support tools as the levels increase. The Task Randomizer was introduced as a provision for any required additional challenge. At this stage, like the completed BrainQuest game, there were 4 difficulty levels – Rookie, Professional, World Class, and Legendary.

5.4.4.2 *Prototype 3: Evaluation*

5.4.4.2.1 Overview

The evaluation of BrainQuest prototype 3 was conducted at the same Edinburgh primary school as the previous sessions. However, since the P7 children involved in the previous sessions had departed for High School, a subset of 8 children from the new P7 class were chosen by their PE teacher to be involved in the project. Hence, the researchers prioritized establishing whether the previously successful components of BrainQuest were applicable to a demographically similar user group who were not involved in preceding development stages? However, the researchers also wanted to assess the ongoing issues of game understandability and the PA patterns.

Consequently, the evaluation of prototype 3 was divided into two distinct sessions. Session 1 concentrated upon the fundamental aspects of the design - activities and themes designed by the previous children, and the current user interface, while session 2 appraised the remaining short term goals. There was a 2-week intermission between evaluation sessions and the same children were present at both sessions.

5.4.4.2.2 Procedure

In both sessions, the children played Brain Quest on the school AstroTurf playing field for 60 minutes, while the PE teacher taught a hockey class on the other half field and observed the group's progress intermittently. Both sessions consisted of an introductory tutorial, BrainQuest gameplay, and then a chance to submit feedback. The procedure for each is summarised below:

Session 1

- Introduction (20-minutes): The main researcher introduced the game and administered an interactive demo of gameplay and rules for each role, involving the children as volunteers throughout.
- Game Play (30-minutes): During the next phase, each child had an opportunity to play 3-minute games of BrainQuest in every role – hero, cow, and sheep rustler. As only one game space involving 3 players was available, the remaining 3 children observed the game and were asked to identify incidences where their peers had broken the rules which they fed back at the end of each game. During the session, the children played the game on 'World Class' (Level 3) difficulty mode in a bid to assess how understandable the task ordering rules were in the default difficulty mode and unaided by support structures.
- Feedback (10-minutes): Following the session, everybody returned indoors for a feedback interview, where the researchers gathered qualitative data by recording answers to a series of open-ended questions.

Session 2

- Introduction (20-minutes): The returning children were asked to set up the playing field to remind them of the game structure before the main researcher led an interactive demo, like session 1.
- Game Play (30-minutes): The gameplay phase was structured similarly to session 1 but there were a couple of changes. The children played the game on 'Rookie' difficulty to allow a comparison of performance with session 1 and to understand the importance of the support tools. Also, following each hero game, children had to

recite the task ordering rules as well as their hero score to one of the observers – a means of assessing understanding.

- Feedback (30-minutes): This phase was identical to session 1.

Following the sessions, the interview audio files were transcribed and added to the session observation notes before being imported into NVivo. Children's game performance data was compared with transcribed recitals of task ordering rules. Only 5 of the 8 children's performance data were reviewed because 3 children did not play the game in both sessions. Task ordering rule explanations were categorized as: full understanding (complete description of rules without needing to be prompted for more information), mostly understood (missing some details), major misunderstandings, no understanding. The main researcher and one of the observers independently assessed the children's explanations before comparing ratings and resolving discrepancies.

5.4.4.2.3 Results & Discussion

Engagement & Opinions

Despite no previous involvement, the children's positive responses towards the game in both sessions appeared to justify many design decisions, such as the fantasy 'good versus evil' battle and the provisions for social play – 5 children reported hero-rustler interactions as being their favourite things about the game.

However, the game could have further encouraged autonomy and the roles of the game may have been too constrained. 2 children wanted to permit the rustler to catch the hero, whereas 4 children wanted to increase the opportunities for hero-rustler interactions during gameplay. This hinted at the need for greater user control but the research team felt such changes could detract from the game's purpose i.e. the structure imposed by the 6E test. Hence, further evaluation was required in the main study presented in Chapter.

3 children disliked what they viewed as 'cheating', where the hero would wait for a rustler to open their pen and pick up an animal, forcing the rustler to return empty handed without the chance to run away. In contrast, from the perspective of the designers this was considered as an example of strategic thinking and good timing by the user playing as the hero.

Nevertheless, every child gave favourable reviews, with one-word descriptions including "awesome", "energetic", "challenging", and "exciting". General thoughts included

“BrainQuest is the best game ever”, “BrainQuest is in my top 5 favourite games”, and “would there be an app on the store eventually? I’d want to play it.”

Game Understanding

The first evaluation session reinforced the suspicion that the task ordering rules were too difficult to understand within the context of the game for children of the target age group. While all children quickly grasped how to play as a rustler, the hero role appeared more challenging. Although they all could complete the 6 tasks at least once, they varied in speed at choosing and completing tasks. From observations, not all children could follow the task ordering rules but 1 child, who could, scored 10 correct tasks without any rule breaks – considerably higher than his peers. Many children reported that the game was “hard” at the beginning but “easy” by the end of the session.

There was an improvement in session 2, following the introduction of the support tools, and many children could follow the task ordering rules without making any mistakes. The Task Shading tool was described as “helpful” and “useful to find out what you’ve done” by all 8 children in the session. 3 children said that they would “struggle” to play the game correctly without being able to use the tool. The usefulness of the Task History was less clear but 5 children found it to be beneficial – it was “good at keeping track” of what tasks they’d done. Contrarily, 3 children stated solely using the Task Shading tool.

Though their ability to follow the task ordering rules improved in session 2, it remained unclear as to whether they were appropriately complex for the target user group. The desire not to make any mistakes made many children play at a slow pace and require regular reassurance from the researchers. Thus, impacting the level of physical intensity involved in the game. Furthermore, though the children could follow the task ordering rules, no child could verbally recount the rules in full without prompting which may have reflected: an inability to verbally recount them in the expected level of detail, a misunderstanding about the researcher’s question, or a lack of understanding of the rules themselves. This issue is hard to untangle given that some of the children mentioned relying on the cognitive support tools to know what to do next. However, the psychologist remarked, “attempts to plan and strategize are severely impaired if one does not fully understand the task at hand.” Once graduating from the easiest difficulty level, would a potential lack of understanding make the step up in difficulty too severe? It was suggested that for the next version of the game, the task ordering rules be simplified to match the complexity of the 6E test with scope to increase rule challenge as an option for future BrainQuest prototypes.

Physical activity

Observations indicated that reducing the number and length of scanning procedures improved the fluidity and the PA involved. Varied intensities, some characteristic of MVPA were each observed – walking, jogging and running, and all children reported running during gameplay following both sessions. Session 1 observations suggested different user roles account for some intensity variation. E.g. heroes played at low intensities during their first game before picking up speed (in some cases), whereas rustlers achieved moderate intensities so long as there were available animals to steal. There were intermittent spikes of high intensities for both roles during ‘stop rustler’ tasks. 5 children echoed this by stating the ‘chases’ to be the most physically intense situation. No children felt the game was “tiring” but 2 felt exertion depended on upon “how much effort you put in”.

Following session 1, 3 children were frustrated during rustler roles when there were no animals left to capture or when the hero did not chase them and at these moments they “just walked”. However, rustler scoring was introduced ahead of session 2, allowing them to score points simply for running (bonus points for returning animals) and in the session children appeared to continue their shuttle runs at a moderate-intensity regardless of whether the animal pens were full or empty. Hence, these issues appeared to have been solved.

The observation of low, moderate, and vigorous intensity PA provided hope that BrainQuest may contribute to MVPA. Conversely, the slower pace of the child users and subsequently lower levels of PA in the hero role observed during the first session, was of concern. It seemed to be resultative of the increased cognitive demands of the World Class difficulty level without having a firm grasp of rules – hence, emphasising the importance of initial support from a PA perspective. Furthermore, users’ initial attitudes to PA are also likely to influence the extent to which the children undertake aerobic exercise.

5.4.5 Final Changes

5.4.5.1 Overview

The evaluation of prototype 3 was mostly very positive and at this point BrainQuest appeared nearly ready for use in a longitudinal evaluation to gather further clarity regarding the game’s efficacy. However, there were some small final changes to be made to prototype 3 to evolve it into the ‘completed’ game detailed in Section 5.1 (p. 119) and used in the 5-week evaluation in Chapter Six.

5.4.5.2 Task Ordering Rule Changes

Following the dubiety regarding the understandability of prototype 3, the rules were simplified from those described in Section 5.4.2.4 (p. 166) to instead match exactly those of the 6E test.

5.4.5.3 Introduction of Data Logging

The lack of clarity regarding game rule understanding of prototype 3 required the need for more fine-grained analysis of task choices and other measures to help understand the user's thought processes. Hence, data logging was introduced

5.4.5.4 Introduction of Score Centre

Trophy cabinets, the leaderboard, and personal records (Section 5.1.5.3, p. 133) were added to encourage additional sources of social interaction, motivation, and competence. Trophy splash screens were also added and appeared, with accompanying victory music, following successful completion of a game level.

5.5 Summary

This chapter began by delivering a description of the completed BrainQuest system and how it was used – the game rules, the user interface, and the methods of performance capture. This section ended by reviewing how BrainQuest addresses the requirements identified by the literature. Next details of BrainQuest's software and hardware requirements, and architecture were given. Following this, a more detailed account of the UCD process used to develop the game was presented, including Gamestorming and evaluation sessions and their impact on the design decisions at each prototype iteration.

6. Evaluation: 5-Week Primary School

Evaluation

This chapter describes the 5-week main evaluation of the final BrainQuest system. First, the evaluation research questions and methodology are outlined, drawing from the ‘methodological concerns’ (MC) identified in the literature review (Chapter Four, Section 4.3, p. 115). Next, the study methods are detailed before the results are presented. The results are partitioned into parts:

- General Quantitative Results – presenting the statistical evidence considering BrainQuest’s EF challenge for the entire data set
- Case Study Results – providing an in-depth explanation of individual user experiences from the perspective of a subset of the participants
- General Qualitative Results – describing the qualitative findings of the entire data set, structured by the research questions

Finally, the results are summarized and their ability to address the research questions discussed at the end of the chapter.

6.1 Methodology

6.1.1 Study Positioning

Previous CTG studies have failed to develop EF skills in a way which fosters meaningful transfer and this has led some researchers to call for greater emphasis on understanding how cognitive skills are used during training (MC11, MC12). Many studies appear to have overlooked the importance of first validating designs before establishing their effectiveness. For example, the emergence and evolution of cognitive challenge during training must be ascertained rather than assumed if we are to explain transfer (or lack thereof) in cognitive assessments and to appraise the suitability of the game design. Therefore, the main BrainQuest evaluation described in this chapter was positioned as a feasibility study focused on understanding the efficacy of the game’s design:

- The user experience according to the indirect pathways of Diamond’s (2012) model (Chapter Two, Section 2.1.3.5, p. 23) – pride/confidence/self-efficacy, joy, PA, social interaction
- The EF skills used during gameplay and the extent of their challenge over time

This approach is consistent with the Medical Research Council (MRC) guidelines for developing and evaluating complex interventions (Senn et al., 2013). A cognitive training intervention using BrainQuest is archetypical of the ‘complex interventions’ defined by the MRC as it includes a “*number of interacting components*” – i.e. the different routes of the Diamond 2012 model, with the a “*range of effects*” which “*may vary widely*” – i.e. effects on EF, PA, academic outcomes, everyday functioning. In complex models, it is also critical to know “*how the intervention works*” and why a certain effect is observed to “*design more effective interventions*” in the future (Senn et al., 2013, p.588).

The MRC guidelines state the importance of developing interventions “*systematically, using the best evidence and appropriate theory, then to test them using a carefully phased approach, starting with a series of pilot studies targeted at each of the key uncertainties in the design, and moving on to an exploratory and then a definitive evaluation.*” It is a “*trade-off between the importance of the intervention and the value of the evidence that can be gathered given these constraints*” (Senn et al., 2013, p.589). Thus, early focus on effectiveness evaluations are likely to neglect the development process and weaken interventions. This is characteristic of many of the CTG studies reported in Chapter Two and highlighted in MC5-MC11.

Therefore, following the MRC guidelines, the work in this thesis (Chapters 2-5) sought to follow the processes of:

- ‘Identifying existing evidence’ – presented in Chapters 2 and 3, notably CTGs (Chapter Two, Section 2.3.3, p. 38)
- ‘Identifying and developing theory’ – also Chapters 2 and 3, notably the Diamond 2012 model (Chapter Two, Section 2.1.3.5, p. 23)
- ‘Modelling process and outcomes’ – defined by the requirements and design methods in Chapter Four and implemented in Chapter Five

The next step before any effectiveness work using large-scale, resource-intensive methodologies was to explore the feasibility of BrainQuest as a viable EF training intervention. Chapters 6 and 7 present then discuss this feasibility study and its implications. MRC guidelines advise that feasibility studies “*need not be a scale model of the planned*

evaluation but should examine the key uncertainties that have been identified during development". In the case of BrainQuest, this pertains to how representative the game is of the Diamond 2012 model.

6.1.2 Study Constraints

As stated, the study was concerned with establishing BrainQuest feasibility. This meant that resources were focused on evaluating the game itself rather than comparisons with other control group activities. Nevertheless, in addition to the study goals, there were logistical constraints on the level of methodological rigour permitted.

First, the complexity of BrainQuest's game design produced a range of different variables (EF-challenge, pride/confidence/self-efficacy, PA, social interaction) making comprehensive outcome measures for all variables logistically infeasible, as well as difficult to find a well-matched control activity. A power analysis expecting a moderate effect ($\alpha = 0.05$, $1-\beta = 0.8$) stated a required sample size of 64 which was unachievable for several reasons:

- The host school only had less than 60 P7 children in attendance.
- The host school's timetabling stipulations could only grant the required access to one class of 28 children.
- Undertaking the evaluation across multiple schools would have introduced additional social, environmental, and logistical confounding factors.
- Undertaking the evaluation within the host school with children who helped develop the game using the UCD process was required.

Therefore, it was decided the best use of resources would be spent observing a single training group, collecting and triangulating quantitative and qualitative data sources regarding user experience and performance to capture a rich picture of the training process rather than simply focusing on outcome measures (MC11). Notwithstanding, performance change using an EF cognitive assessment battery was included as one contributing quantitative data source to compare with training performance.

6.1.3 Study Research Questions

The aims of the main evaluation were to explore the impact of BrainQuest on the EF of typically developing children (aged 11-12 years) in a school setting (MC18). As stated, the goal of the study was to understand whether an EF-focused active smartphone game (cognitive training exergame) could be used as a means of implementing Diamond's (2012) EF building model (Chapter Two, Section 2.1.3.5, p. 23) and challenging EF through repeated gameplay. Thus, the research questions sought to understand the longitudinal efficacy (MC19) of the system's contribution to each of the pathways within the model as a primary focus, rather than attempting to establish its effectiveness at this stage (MC17).

This is reflected by the relative breadth of the research questions:

- **RQ1** – indirect EF: *To what extent does the game support the indirect pathways to EF improvement identified by Diamond: joy, social belonging, physical fitness and self-confidence?*
- **RQ2** – direct EF: *What evidence is there to suggest that the children experience EF challenge and improvement through playing BrainQuest?*

6.1.4 Research Methodology: Mixed Methods and Case Studies

RQ1 involves multiple concurrent variables which are hard, and in some cases, impossible, to evaluate from quantitative statistics alone (Yin, 2013). Furthermore, RQ2 attempts to assess the EFs challenged during gameplay, how they compare to the envisaged design, and how performance evolves to better understand transfer expectations. As stated, it is important to consider the reasons behind performance changes to inform future game design and this cannot simply be understood from game scores. Hence, three simultaneous approaches were used:

- Mixed methods approach – *“a class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study”* (Yin, 2013, p. 62-63). A mixed methods approach was used to collect general data from the entire sample as well as the case studies. However, case studies benefitted from additional data sources to increase the depth of analysis to a level able to generate individual user experiences.

- Fully mixed concurrent dominant status-qualitative design – Qualitative data could be derived from all sources and took greater priority as a means of understanding the training process and phenomena relating to the research questions. However, quantitative data also took a supporting role in identifying in-game performance outcomes to be further explained. Hence, the mixed methods approach was fully mixed concurrent dominant status-qualitative design, where *“quantitative and qualitative phases occur at approximately the same point in time, with the qualitative phase being given higher priority and mixing occurring within or across the data collection, analysis, and interpretation stages”* (Powell, 2008, p. 296)
- Case studies – *“A case study is an empirical enquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident.”* (Yin, 2013) Case studies are particularly useful when attempting to establish *“how”* or *“why”* something happens in real-life contexts (Yin, 2013). They also benefit from the triangulation of multiple sources of evidence and are best guided by theoretical propositions (Yin, 2013). Consequently, the key benefit of using a case study approach is its ability to integrate reporting on individual behaviours with general events. Thus, the approach was perfect for considering the exploratory and complex nature of evaluating BrainQuest’s design model.

6.2 Method

6.2.1 Participants

The study took place in a state-funded Primary school in Edinburgh, Scotland. The school PE teacher selected 31 children (aged 11-12 years – within BrainQuest’s target age range) from the same Primary 7 class but data is only reported on a consenting subset of 28 children (16 boys and 12 girls). Nine case study participants (4 boys and 5 girls) were purposefully selected from the consenting 28 participants. Despite absences, all 28 participants completed both the pre-and post-tests and at least 3 BrainQuest sessions.

The school selected for this evaluation is a state-run primary school in the South of Edinburgh and resides in a postcode in the second most deprived quintile of the Scottish Index of Multiple Deprivation (The Scottish Government, 2016). However, the catchment area also includes postcodes in the most deprived, second most deprived, and third most

deprived quintiles. Primary schools support the education of children from the ages of 4-5 (Primary 1 starting age) to 10-11 (Primary 7 starting age).

6.2.2 Data Gathering

6.2.2.1 Overview

As stated a fully mixed concurrent dominant status design mixed-methods approach, triangulating multiple data sources was adopted. Triangulation occurred across different sources of data and, where appropriate (e.g. observations), across different researchers. The relationship between the research questions and the triangulated sources are summarized in Table 16.

6.2.2.2 Pre-and Post-test EF Assessment (DS1)

EF of every participant was benchmarked at pre-and post-test using BADS-C: an age-scaled, standardized testing battery of EF used commonly within clinical psychology, which consists of 6 subtests that test different EF components (Chapter Two, Section 2.5.2, p. 63; Appendix C, p. 389).

6.2.2.3 Background Physical Activity (DS2)

The Primary School PE teacher provided two measures of pre-test participant physical ability which had been collected prior to the study. Each measure was ranked in highest to lowest order of performance. The measures also displayed a strong correlation ($r=0.77$) for the 23 participants who completed both:

- ‘Mile time’ – the time taken for each participant to run a mile without stopping OR if they stopped before the mile, the number of minutes for which they could run for before stopping.
- ‘Beep test’ – a multistage fitness test to determine maximal running aerobic fitness, for 23 children (Tomkinson et al., 2003).

6.2.2.4 Database Logging / Phone Log Files (DS3)

Database and local phone log files were generated during BrainQuest login and logged different facets of performance (Chapter Five, Section 5.1.7, p. 139):

- a) Ability to follow task ordering rules
- b) Task selections
- c) Where successes/mistakes were made
- d) Trophies won
- e) Hero and rustler points achieved
- f) Hero support tool usage
- g) Number of hero tasks attempted
- h) Number of rustler Shuttle Runs
- i) Game bugs and crashes

6.2.2.5 Observations (DS4-SD6)

3 types of observations were taken by the observers during the study, mostly as audio recordings which were transcribed but also included written notes:

- General (DS4) – notes on the general activities of the entire dataset relating to RQ1 and RQ2 as well as technical issues, questions, and feedback. These were initially taken by 1 or 2 observers (depending on the prevalence of technical issues and misunderstandings) who split their time between the group.
- Case study (DS5) – notes on the activities of the case study subset of participants relating to RQ1 and RQ2. During all sessions, 1 dedicated observer took notes on the activities and behaviours of each case study child within each of their roles.
- Session review (DS6) – following each session the observers compared opinions and highlights before the main researcher recorded a brief session review which included consensus and any details which had evaded the general observations.

In addition to the main researcher, there were 2 other observers – one Ph.D. student and one Masters student with backgrounds in education and psychology, respectively. All observers were provided with a list of themes, representing themes of importance to RQ1 and RQ2 as a guide. They were trained on theme definitions by the main researcher.

6.2.2.6 Semi-Structured Interviews (DS7)

At post-test, the researchers conducted 20-30 minute semi-structured interviews comprising questions relating to RQ1 and RQ2 as well as specific aspects of the game’s design, and general opinions. The interviews included the 9 case study children involved in the study and the classroom and PE teachers. Interviewing the teachers who spend a great deal of time with the children on a daily basis, allowed the capture of subjective perspective regarding the game’s general reception as well as the occurrence of behavioural changes beyond the scope of the study. The interviews were audio recorded but later transcribed.

6.2.2.7 Video Footage of Gameplay (DS8)

Video recording of gameplay for case study groups was planned to provide a detailed analysis of behaviour, principally to understand EF challenge. However, video recording failed due to high winds encountered during the evaluation.

Research Question	Pathway of Model	Triangulated Sources	Triangulation Purpose
RQ1	Joy	DS4-DS7	<ul style="list-style-type: none"> • Motivations for play • Changes in motivation over time (novelty effects) • Motivational effects of design decisions
RQ1	PA	DS2-DS7	<ul style="list-style-type: none"> • The intensities of PA undertaken during gameplay • The impact of PA ability on BrainQuest user experience • The balance between EF and PA ability on BrainQuest performance
RQ1	Social Interaction	DS3-DS7	<ul style="list-style-type: none"> • Social influence on performance • The nature of social interaction • Social impact of design decisions • Relationship creation or change

RQ1	Pride/Confidence/Self-Efficacy	DS4-DS7	<ul style="list-style-type: none"> • Sources of derived pride/confidence/self-efficacy • Effects of the variable difficulty level and support tools on competence • Understanding of the game rules and procedures
RQ1	Other	DS3-DS6	<ul style="list-style-type: none"> • Documenting game bug occurrences • Documenting logistical challenges
RQ2	EF Challenge	DS1, DS3-DS7	<ul style="list-style-type: none"> • Identifying EF ability levels to form mixed ability game groups and case studies • Describing contrast between pre, post-test, and BrainQuest performance • Assessing correlation between skills challenged in BrainQuest and the 6E test • Determining the relationship between EF ability and BrainQuest user experience • Determining gameplay EF challenge and maintenance of novelty • Enabling retrospective analysis of strategies

Table 16: Data Sources

6.2.3 Ethics Summary

The following ethical procedure was followed:

Consent – Written child and parental consent (Appendix E, F) were required as a condition of the ethics clearance granted by Moray House School of Education prior to the study. Prior

to the study started, the procedure was explained to every child individually to ensure they were comfortable. They were also told that they could withdraw from any part of the study at any time. This was again repeated before pre-and post-test cognitive assessments.

Anonymization – All data reported in this thesis and additional publishable work has been anonymized to protect the privacy of the participants.

Storage – All data was stored on protected University servers.

Session – All observers present at each session had undergone police background checks and had active Disclosure Scotland approval to work with children. Furthermore, a teacher was always present and within 50 metres of each session.

Pre/Post Testing – The interviews and cognitive assessments were conducted within a public area of the school building and always in sight and earshot of the class teacher.

6.2.4 Procedure

6.2.4.1 Overview

The study took place over the course of 7 weeks between the months of February and March 2015, consisting of a pre-test week, a game tutorial week, 5 weeks (8 sessions) playing BrainQuest, and a post-test week – Figure 44.

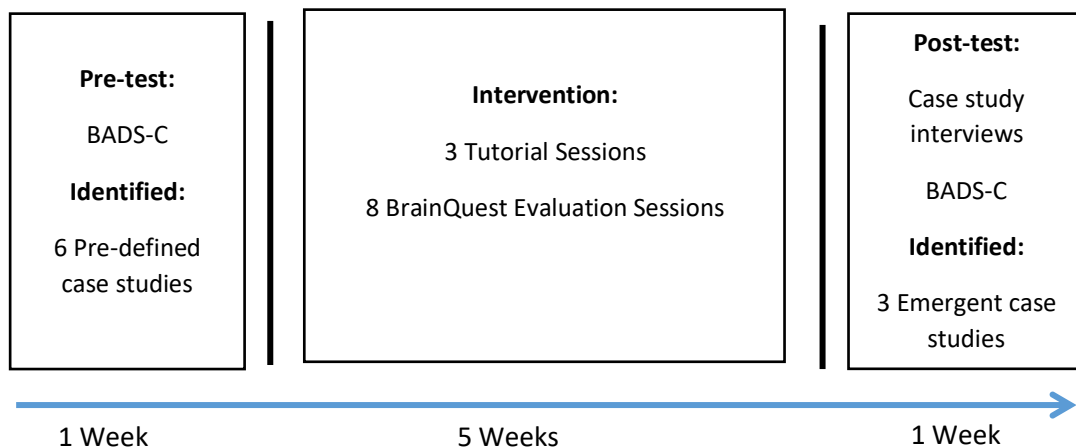


Figure 44: Study Timeline

6.2.4.2 Pre-test

During the pre-test week, the study was explained to each child before their EF was benchmarked using the BADS-C test, taking 30-40 minutes per child to administer. Two researchers conducted the study explanations and BADS-C testing independently, allowing two students to be seen concurrently within the open plan area of the school and within sight and sound of school staff members. Each pre-test benchmarking session started by giving the students an opportunity to ask questions about the study before the researchers administered the BADS-C testing battery, keeping to a script detailed in the BADS-C manual to ensure consistency throughout every test. Following the completion of BADS-C for the 28 children who had submitted their consent forms, the researchers marked the BADS-C test papers to calculate raw and age-scaled scores for each subtest and a total age-scaled score.

6.2.4.3 Pre-defined Case Study Selection

After the pre-test marking, the researchers identified (pre-defined) case study participants to generate a series of individualized experiences with BrainQuest which would inform the abstracted conclusions from the entire population. 6 (pre-defined) case study children were identified by dividing the class into 3 equal numbered segments according to their pre-test performance score:

- A high EF segment
- A medium EF segment
- A low EF segment

2 children from each segment were selected as case studies (4 girls, 2 boys) following discussion with the teachers and consideration of PA measures. The goal was to create groups of mixed ability primarily with regards to EF but also groups of mixed gender and physical ability. As there are 3 players in each BrainQuest game, the 6 case studies were split up into 2 groups of 3 children which remained the same throughout the sessions.

6.2.4.4 General Population Setup

The general population of the remaining 22 non (planned) case study children, were split into groups of mixed high, middle, and low EF ability. However, absences meant this was hard to

ensure throughout every game session and in such instances, volunteers were sought to fill in. This led to some children playing more games than others and general groups being unbalanced in terms of EF ability.

6.2.4.5 Tutorial

Following this, two researchers conducted a tutorial week including 3x60 minute sessions with the children. The goals of these sessions were to teach the children the game rules and troubleshoot any unforeseen issues.

During each session, the class was split into 4 groups – A, B, C, D – each comprising up to 7 children. For the first 30 minutes of each session, one researcher taught the tutorial activity to Group A, while the other researcher did the same for Group B. Meanwhile, Groups C and D undertook their regular PE activity before swapping with Groups A and B for the second 30-minute period of the session.

Tutorial Sessions 1 and 2 – Tutorial sessions 1 and 2 began with a game walk through where the children shadowed the researcher and undertook example game tasks. Following this, the children undertook practice games which were supervised and assisted by the researchers. The children took turns in playing the game in groups of 3, while the observing children critiqued the performance of their peers. Following the end of each game, the children communicated and discussed the feedback with their peers while the researchers provided additional advice.

Test Game – The final tutorial session (referred to as the ‘Test Game’), enabled the children to undertake a full simulation of the BrainQuest sessions planned for the training period, including timing, pre-defined game grouping, and game space setup. The children played the game on level 3 (without support tools) to provide the researchers with a benchmark of the class BrainQuest ability level.

6.2.4.6 BrainQuest Training Period

Procedure – There were 2x 60-minute BrainQuest sessions per week for 5 weeks in which each child got to use BrainQuest for 30 minutes:

- 3x 5-minute games in each of the game’s roles (hero, cow rustler, and sheep rustler).

- 3x 5-minute undirected breaks between games allowing an opportunity to view feedback screens, point scores, the leaderboard, trophies, and reset the play space.
- The equipment setup allowed for a maximum of 5 concurrent BrainQuest games to be played at one time and a maximum of 15 children. Hence, as in the tutorial sessions, while half of the class played BrainQuest for 30 minutes, the other half took part in an alternative activity before swapping for the remainder of the session. During one session per week the alternative activity was their regular PE lesson and in the other session they undertook an outdoor classwork lesson.
- During the game sessions, the two case study groups were always observed by a dedicated case study observer, meanwhile, the other observer(s) divided their time between all the groups – Figure 45. Before the start of each session, play spaces were set up by one researcher while the other researcher undertook a pre-game briefing in the classroom: detailing the difficulty levels each child would be playing, the groups for the session, repeating the task ordering rules, and answering questions. The children started at level 1, with the full range of support tools available but with each successfully completed level, they could increase the difficulty.

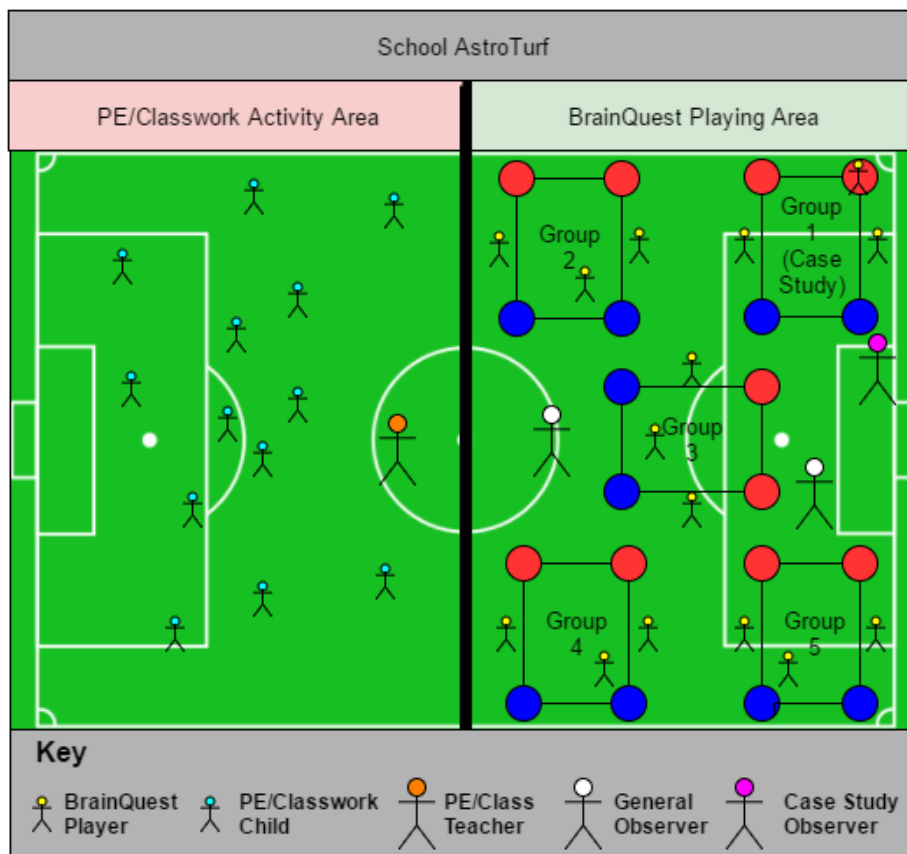


Figure 45: BrainQuest Evaluation Structure

Equipment – The games occupied one-half of the school’s AstroTurf pitch, providing game environments of approximately 15 square metres in size. There were 5 game spaces and each consisted of:

- 4 plastic hula hoop ‘pens’ (one at each corner of each game) containing 3 bean bag sheep or cow toys.
- Each hoop contained a sign denoting the purpose of the hoop – rustler sheep pen, rustler cow pen, hero cow pen, hero sheep pen.
- There were 3 sheep and 3 cow toys in the middle of the ‘play space’.

Each toy and sign had an NFC (near field communication) tag (sticker) which could be scanned using an NFC-enabled Sony Xperia M2 smartphone, so children could interact with it in the game. The phones were loaned to the school by the University for the duration of the study. All associated costs were met by the University.

6.2.4.7 Emergent Case Study Selection

Following the intervention an additional 3 emergent case studies (2 boys, 1 girl) were identified. This was necessary to mitigate any planned case study effects (i.e. Hawthorne effects) caused by the rigidly supervised nature of their gameplay in comparison to non-case study peers. The emergent case studies were chosen according to EF ability (low, medium, and high) and the frequency of data collected on them to form an understanding of their user experience.

6.2.4.8 Post-test

Following the training, a post-test week was undertaken using the same BADS-C testing battery as well as case study interviews. The post-test BADS-C was undertaken in exactly the same way as the pre-test. The interviews were undertaken in the same open plan area as the pre-and post testing, took approximately 30 minutes, and were audio-recorded for later transcription.

6.2.5 Data analysis

6.2.5.1 Quantitative analysis methodology

The quantitative analysis of data log (DS1) and cognitive assessment data (DS3) contributed to answering RQ2. The analysis was conducted using Microsoft Excel and JASP statistical packages to create graphs of performance evolution, draw descriptive performance statistics, and run inferential statistics. The inferential statistics considered the correlational relationships between BrainQuest performance and BADS-C testing battery performance, as well as the difference in means from pre-to post-test on the BADS-C using multiple t-tests for each subtest. All scores reported in the quantitative results subsection have been age-scaled to make them comparable to other samples. Furthermore, to account for multiple t-tests, a Bonferroni correction was undertaken.

6.2.5.2 Qualitative analysis methodology

Coding Scheme Creation – The qualitative analysis of all data sources and contributed to answering both RQ1 and RQ2. Thematic analysis (Guest et al., 2011; Braun & Clarke, 2006, Hayes, 2000) was used to develop a series of categories, known as a coding scheme, to populate with qualitative data from the following data sources: DS4-DS7. Deductive codes were generated (Guest et al., 2011; Braun & Clarke, 2006), corresponding to Diamond’s pathways for building EF and the research questions – the coding scheme parent categories are shown in Table 17.

The *BrainQuest* code related to general opinions of the game and opinions of specific features: difficulty levels, sound, and animations, tangible objects, leaderboards and trophies, use of support tools and understanding of the game – pertinent to establishing the enjoyment of the BrainQuest (RQ1). *Emotional Behaviour* referred to expressions of positive or negative emotions, pride, self-efficacy and confidence (RQ1). The *Physical Activity* category documented PA intensity, fatigue and ability (RQ1). The *EFs* category documented IC, cognitive flexibility, planning/strategizing and WM (RQ2).

Source Balance – The code-able data set consisted of 31 source files – 16 sources were case study exclusive (case study observations, interviews) and 15 sources concerned all participants including both case study and non-case study individuals (general observations, session reviews). Thus, the volume of data collected on individual case studies exceeded that

of non-case study children. For each code data was organised either as individual case studies (Melvin, Natalia, Angelina, Patrick, Leonard, Rose, Stevie, Rachel, Alexa) or a general non-case study group – generating a total of 10 categories.

Inter-rater Reliability – After defining the coding scheme, the main researcher coded the data set in its entirety – all 31 source files – using Nvivo 10 software. Following this, 2 additional inter-raters then coded a subset of the data set using the same coding scheme – 20% of the 10 category labels or 2 random case study children (Leonard and Angelina). In total, this amounted to a review of 24 data source files.

The purpose of this inter-rater reliability process was to validate the results of the full dataset. The results of the query were then extracted to Excel for analysis of the agreement, specifically Cohen’s Kappa coefficient which was generated for each parent node of the coding scheme – Table 17. Cohen’s Kappa = 0.7 was agreed by all coders at the outset as the minimum threshold for data to be included as part of the results without the need for further triangulation with additional sources.

‘Emotional behaviour’, *‘PA’*, and *‘BrainQuest Design’* parent codes were above the threshold for acceptable agreement – Table 17. However, aspects of *‘Social Behaviour’* and *‘EF’* failed to meet the threshold as parent codes of agreement (Table 17). Thus, these failed codes required an additional stage of analysis to address the ambiguities identified by the inter-rating process which led to differences of opinion – Advanced Triangulation Analysis.

Data Sources Included in Inter-rater Coding	Inter-rater Code	Kappa Agreement Value
DS4-DS7	BrainQuest Design (<i>Parent</i>)	0.72
	Emotional Behaviour – Joy + Pride/Confidence/Self-efficacy (<i>Parent</i>)	0.70
	PA (<i>Parent</i>)	0.72
	Social Behaviour (<i>Parent</i>)	0.62
	Social Behaviour – <i>Competition</i>	0.49
	Social Behaviour – <i>Conversation</i>	0.63

	Social Behaviour - <i>Cooperation, Pride, & Encouragement</i>	0.72
	EF (<i>Parent</i>)	0.67
	EF - <i>Cognitive Flexibility</i>	0.40
	EF - <i>Inhibitory Control</i>	0.53
	EF - <i>Planning & Strategizing</i>	0.72
	EF - <i>Working Memory</i>	0.27

Table 17: Inter-rater Kappa Values **Advanced Triangulation Analysis** – The

failure of some social and EF codes to meet inter-rater Kappa agreement values, highlighted the need for additional analysis rigour. Hence, the data sources involved in the qualitative analysis were triangulated with game logs (DS1), cognitive assessment data (DS2), and physical ability data (DS3) to address the ambiguities of the observations and interviews (DS4-DS7). Ambiguous incidences coded from one data source now required corroboration or further information from at least one additional source. E.g., if an observation stated, “*Child A is unable to stop themselves from catching a rustler*”, it then required an interview comment supporting the observation (e.g. “*I found it hard to resist catching the rustlers even though it meant breaking the rules*”) and/or data log evidence to understand task choice and pinpoint mistakes (Child A, Game 2, Number of rule breaks involving rustlers = 5).

This approach produced a finer grained picture of case study individual experiences but was infeasible to implement on a larger scale (i.e. for all participants) as part of the full coding and inter-rater reliability process due to the complexity of data logs, analysis method and subsequently the additional analysis time required. Such was the complexity; it could not be coded in Nvivo and was instead created as a series of stories for each case study participant in Microsoft Word under each code.

Nevertheless, the results of the advanced triangulation were validated by one of the inter-raters. Unlike in the initial inter-rater reliability process, the rater did not construct their own stories. However, using the stories generated by the main researcher and with access to referenced source files, the rater could accept or reject each story presented based on the evidence presented. Consequently, this allowed reporting of some codes for case study children which had previously failed to pass the inter-rater reliability process. However, these were individual stories and could not be generalized to the wider population without

the same level of analysis rigour. Furthermore, only the *EF* codes and the ‘*Social Behaviour – Competition*’ code were aided by the triangulation of additional data sources. The ‘*Social Behaviour – Conversation*’ code, meanwhile, received no additional benefit from further analysis as it could not be further informed by interviews or data logs. Table 18 describes the scope of inclusion for each code – Green indicates inclusion; red indicates exclusion.

Code	General Results	Case study Results
BrainQuest Design (<i>Parent</i>)		
Emotional Behaviour – Joy + Pride/Confidence/Self-efficacy (<i>Parent</i>)		
PA (<i>Parent</i>)		
Social Behaviour – <i>Competition</i>		
Social Behaviour – <i>Conversation</i>		
Social Behaviour - <i>Cooperation, Pride, & Encouragement</i>		
EF - <i>Cognitive Flexibility</i>		
EF - <i>Inhibitory Control</i>		
EF - <i>Planning & Strategizing</i>		
EF - <i>Working Memory</i>		

Table 18: Accepted & Rejected Codes

6.3 Results

This section begins by reporting the inferential statistical results of all 28 participants (both case study and non-case study) involved in the 5-week evaluation with respect cognitive assessment and BrainQuest performance. Following this, a featured case study is presented to provide an in-depth account of the user experience and the pathways of Diamond’s model, in addition to the conclusions from the total 9 case studies. A further 5 case studies examples can be found in Appendix B. Finally, the results for the wider sample of 28 participants are presented, to provide a holistic picture of user experiences and are framed according to the research questions.

6.3.1 General Quantitative Results

This part of the chapter details the statistical results of the BrainQuest evaluation, including BADS-C performance and changes following training as well as correlations between the in-game performance measures and cognitive and physical ability. Note, the results of the paired t-tests, though adjusted for multiple comparisons, should be interpreted with caution given the lack of study power and the relative dubiety concerning the implications of novelty on BADS-C retesting.

6.3.1.1 BADS-C Performance

It is prudent to compare the test-retest performance of the BrainQuest evaluation participants (Tables 20-21, 28 children aged 11-12 years) with the established BADS-C norms (Table 19, 25 children aged 8-14 years) to understand how the results compare with populations whom have not undertaken cognitive training. The scores presented are age-scaled, allowing comparison of test performance across a broader age range.

There were some initial similarities between the test-retest results reported in the BADS-C norms and the results observed in the BrainQuest evaluation. E.g., the significance of test-retest correlations in Key Search, Zoo Map 1, and 6E tests. However, the strength of these correlations varied. In BrainQuest, the 6E test recorded a strong and significant test-retest correlation but the BADS-C norms recorded only a weak but significant correlation. This implies that in the BrainQuest study, as children's scores increased on the pre-test, the same children's scores increased on the post-test, and this occurred more often than in the norms. In other words, 6E appeared to be much more reliable than the BADS-C norms led us to believe. Nevertheless, the opposite was true of the Key Search which was less reliable in BrainQuest.

The greatest disparity between the norms and the BrainQuest evaluation concerned the difference in pre-to post-test means – established by conducting a series of paired t-tests. For example, the norms reported significant improvements in Playing Cards and 6E test means but neither were found in the BrainQuest evaluation. In fact, there were no significant improvements on any tests apart from on the Water Test ($t(27) = 5.388, p < .001, \text{Cohen's } d = 1.018$) which recorded a very large effect size. Unfortunately, there is no norm available for comparison on the Water Test.

Though the difference in all subtest means, apart from the Water Test, did not reach significance, the mean scores on all subtests increased from pre-test to post-test and all but 5 children recorded improved or maintained total age-scaled scores. While it was useful to perform these calculations from a feasibility perspective, their stark contrast to the BADS-C norms illustrate the need for caution when interpreting the results of studies lacking in power.

BADS-C Published Test-Retest Norms						
	Time 1 mean scaled score (SD)	Time 2 mean scaled score (SD)	p*	Correlation	p	Sample Size
Playing Cards	8.76 (2.89)	11.16 (1.18)	0.004	-0.238	0.252	25
Water Test	Correlation and t cannot be calculated as all children were marked at ceiling at time two					
Key Search	11.00 (2.87)	11.68 (3.01)	0.071	0.814	<0.001	25
Zoo Map 1	10.72 (3.31)	11.32 (2.91)	0.304	0.585	0.002	25
Zoo Map 2	9.92 (3.34)	10.56 (2.72)	0.389	0.289	0.161	25
6E	10.28 (2.64)	11.8 (1.94)	0.006	0.436	0.030	25
* differences in mean between first and second time test, using paired t-tests						

Table 19: BADS-C Test-Retest Reliability (Emslie et al., 2003, p. 23)

BrainQuest Evaluation – BADS-C Pre & Post Test						
	Pre-test mean scaled score (SD)	Post-test mean scaled score (SD)	p*	Correlation	p	Sample Size
Playing Cards	5.14 (3.43)	5.79 (3.50)	0.392	0.364	0.057	28
Water Test	7.58 (3.41)	11.50 (2.52)	<0.001	0.181	0.357	28
Key Search	9.18 (3.22)	10.04 (2.46)	0.131	0.500	0.007	28
Zoo Map 1	9.25 (2.76)	9.93 (3.48)	0.270	0.500	0.006	28
Zoo Map 2	8.75 (4.50)	10.14 (3.39)	0.207	0.024	0.902	28
6E	8.50 (3.12)	9.25 (2.82)	0.055	0.784	<0.001	28
Age-scaled Total	48.39 (10.50)	56.64 (8.31)	<0.001	0.474	0.011	28

* differences in mean between first and second time test, using paired t-tests

Note – Bonferroni correction for multiple comparisons applied (alpha = 0.007)

Table 20: BrainQuest Evaluation - BADS-C Pre & Post Test

BrainQuest Evaluation – BADS-C Pre & Post Test: Paired T-test Results									
	Mean Diff	Std. Dev Diff	Std. Error Mean Diff	Lower	Upper	t	Df	Sig. (2-tailed)	Cohen's d
Pre-test Playing Cards – Post-test Playing Cards	0.643	3.917	0.739	-0.873	2.158	0.870	27	0.392	0.164
Pre-test Water Test – Post-test Water Test	3.929	3.858	0.729	-2.433	5.425	5.388	27	<0.001	1.018
Pre-test Key Search – Post-test Key Search	0.857	2.915	0.551	-0.273	1.987	1.556	27	0.131	0.294
Pre-test Zoo Map 1 – Post-test Zoo Map 1	0.679	3.186	0.602	-0.557	1.914	1.127	27	0.270	0.213
Pre-test Zoo Map 2 – Post-test Zoo Map 2	1.393	5.698	1.077	-0.817	3.602	1.293	27	0.207	0.244
Pre-test 6E – Post-test 6E	0.750	1.974	0.373	-0.016	1.526	2.010	27	0.055	0.380
Pre-test Age Scaled Total – Post-test Age Scaled Total	8.250	9.831	1.858	4.438	12.062	4.441	27	<0.001	0.839
Note – Bonferroni correction for multiple comparisons applied (alpha = 0.007)									

Table 21: BrainQuest Evaluation - BADS-C Pre & Post Test: Paired T-test Results

6.3.1.2 BrainQuest Performance Correlations

Detailed correlations were required to understand the relationship between EF, physical ability and BrainQuest performance – these are detailed in Table 22. 4 BrainQuest ‘performance measures’ are introduced:

1. Trophies per game (Trophies/Game) – the number of trophies represents the number of times the hero could follow the task ordering rules correctly per game
2. Hero points per game (Hero Points/Game) – as there were absences, some children played the game more than others so hero points per game (rather than session) is an even more accurate representation of performance
3. Rustler points per game (Rustler Points/Game) – as there were absences, some children played the game more than others so rustler points per game (rather than session) is an even more accurate representation of performance
4. Rustler shuttle runs per game (Shuttle Runs/Game) – as rustler points do not purely correspond to PA (e.g. you earn 20 points for completing a shuttle run with an animal but only 10 without an animal), shuttle runs was an alternative measure used to measure the number of shuttle runs completed alone

As the 6E test influenced BrainQuest's design, it was reasonable to assume that it might correlate with game performance measures – specifically the hero role measures. This assertion held true to some extent and there were significant and moderate correlations between 6E pre-test scores and 2 BrainQuest hero performance measures (Trophies/Game and Hero Points/Game), as well as a significant and moderate correlation between 6E post-test scores and the Trophies/Game performance measure. This suggests that the desired overlap between executive skills used to undertake the 6E and those used to play BrainQuest did, indeed, exist. However, the correlation was not perfect, implying there were notable differences between the two tasks.

There were also some unexpected correlations. Rustler performance appeared to correlate just as much as hero performance with the BADS-C. Firstly, there were significant and moderate correlations between pre-test 6E scores and 2 rustler performance measures (Shuttle Runs/Game and Rustler Points/Game), as well as a significant but weak correlation between post-test 6E and Shuttle Runs/Game. Furthermore, there were notably significant and moderate correlations between the pre-test Key Search and 2 rustler performance measures (Shuttle Runs/Game and Rustler Points/Games), though neither correlation remained at post-test. These results suggest the rustler role had greater EF involvement than previously envisaged.

The rustler role performance measures also correlated with a physical ability measure, which was anticipated given the emphasis on PA in that role – including shuttle runs and sprints to escape the hero. There was a significant and moderate correlation between mile time rank and Shuttle Runs/Game, as well as a significant but weak correlation between mile time rank

and Rustler Points/Game. On the contrary, there was no relationship between physical ability measures and hero performance measures. Further, there was no relationship between rustler performance and beep test ability even though beep test and mile time rank shared a significant and strong correlation. This further emphasises that the rustler role performance was not simply predicted by physical ability alone.

The different BrainQuest performance measures themselves shared some relationships. There was a significant and moderate correlation between Trophies/Game and Rustler/Runs, as well as a significant but weak correlation between Hero Points/Game and Rustler/Runs. This suggested that those who performed better in the hero roles also made more runs while playing as the rustler. The measures of rustler performance shared a significant and strong correlation, implying that those who made more runs earned more points. This is obvious but, in fact, suggests that it was number of runs and not the successful or unsuccessful capture of animals which had the greatest impact on points totals. In other words, in rustler roles, PA was rewarded more than animal capture strategy.

Measure			BrainQuest Performance				PA Data (Pre-intervention)	
			Trophies / Game	Hero Points / Game	Rustler Points / Game	Shuttle Runs / Game	Mile Time Rank	Beep Test
BrainQuest Performance Measures	Trophies / Game	Correlation:	-	.608	.356	.513	.150	.239
		P-Value:	-	<.001*	.063	.005*	.447	.272
		Sample Size:	-	28	28	28	28	23
	Hero Points / Game	Correlation:	.608	-	.328	.394	.179	.189
		P-Value:	<.001*	-	.089	.038*	.361	.387
		Sample Size:	28	-	28	28	28	23
	Rustler Points / Game	Correlation:	.356	.328	-	.886	.377	.098
		P-Value:	.063	.089	-	<.001*	.048*	.657
		Sample Size:	28	28	-	28	28	23
	Shuttle Runs / Game	Correlation:	.513	.394	.886	-	.420	.189
		P-Value:	.005*	.038*	<.001*	-	.026*	.388
		Sample Size:	28	28	28	-	28	23

BADS-C Pre-test	Playing Cards	Correlation:	.305	.063	.148	.072	.020	.056
		P-Value:	.115	.749	.453	.717	.919	.798
		Sample Size:	28	28	28	28	28	23
	Water Test	Correlation:	.353	.196	.127	.078	.297	.289
		P-Value:	.066	.318	.518	.694	.124	.182
		Sample Size:	28	28	28	28	28	23
	Key Search	Correlation:	.036	.027	.519	.516	.403	.238
		P-Value:	.854	.891	<.005*	<.005*	.034*	.274
		Sample Size:	28	28	28	28	28	23
	Zoo Map Part 1	Correlation:	.272	.351	.191	.129	.080	.171
		P-Value:	.161	.067	.329	.514	.684	.436
		Sample Size:	28	28	28	28	28	23
	Zoo Map Part 2	Correlation:	.081	.077	.252	.297	.656	.105
		P-Value:	.682	.698	.196	.124	.740	.633
		Sample Size:	28	28	28	28	28	23
	6E Test	Correlation:	.461	.445	.429	.516	.065	.115
		P-Value:	.014*	.018*	.023*	<.005*	.742	.600
		Sample Size:	28	28	28	28	28	23

	Age-scaled Score	Correlation:	.468	.292	.438	.522	.184	.213
		P-Value:	.012*	.132	.020*	<.005*	.350	.328
		Sample Size:	28	28	28	28	28	23
BADS-C Post-test	Playing Cards	Correlation:	.491	.171	.303	.416	.266	.184
		P-Value:	.008*	.383	.117	.028*	.171	.401
		Sample Size:	28	28	28	28	28	23
	Water Test	Correlation:	.016	.044	.036	.023	.132	.156
		P-Value:	.936	.823	.856	.909	.503	.477
		Sample Size:	28	28	28	28	28	23
	Key Search	Correlation:	.283	.138	.112	.089	.043	.068
		P-Value:	.145	.484	.571	.652	.827	.757
		Sample Size:	28	28	28	28	28	23
	Zoo Map Part 1	Correlation:	.189	.379	.090	.092	.066	.050
		P-Value:	.334	.046*	.649	.641	.738	.855
		Sample Size:	28	28	28	28	38	23
	Zoo Map Part 2	Correlation:	.067	.082	.305	.187	.310	.261
		P-Value:	.736	.678	.115	.340	.109	.228
		Sample Size:	28	28	28	28	28	23

	6E Test	Correlation:	.464	.347	.286	.380	.039	.129
		P-Value:	.013*	.071	.140	.046*	.843	.558
		Sample Size:	28	28	28	28	28	23
	Age-scaled Score	Correlation:	.328	.328	.430	.439	.225	.127
		P-Value:	.088	.088	.022*	.020*	.249	.565
		Sample Size:	28	28	28	28	28	23
PA Data (Pre-intervention)	Mile Rank	Correlation:	.150	.179	.377	.420	-	.767
		P-Value:	.447	.361	.048*	.026*	-	<.001
		Sample Size:	28	28	28	28	-	23
	Beep Test	Correlation:	.239	.189	.098	.189	.767	-
		P-Value:	.272	.387	.657	.388	<.001	-
		Sample Size:	23	23	23	23	23	-

Table 22: BrainQuest Performance Correlations

6.3.2 Case Study Results

Section 6.3.2 describes the user experience of the case study children using evidence from the advanced triangulation process of all data sources (DS1-DS7). This includes one detailed case study account and summarised conclusions for the remaining case studies. Additional case study examples can be found in Appendix B.

6.3.2.1 Interpretation

6.3.2.1.1 Case Study Analysis Criteria

As stated previously, the participants targeted for individual case study inclusion were a diverse group in terms of executive ability, gender, and physical ability. Single participants were considered as single cases and contributed to identifying behaviour trends to be contrasted with the findings of the wider study population.

Though there were 9 case study participants (6 planned and 3 emergent; 5 girls, 4 boys), given the depth of detail (and, therefore, length) dedicated to each case, only the examples of 6 are presented in this thesis (one featured in this Section, the others in Appendix B). The cases presented reflect a range of performance abilities (2 low, 2 moderate, and 2 high cases of EF ability), gender balance (3 boys, 3 girls), and a balance between emergent and pre-defined cases (2 emergent, 4 pre-defined). Notwithstanding, the case study conclusions presented in Section 6.3.2.3 (p. 229) includes the results of all 9 case studies to provide additional clarity.

6.3.2.1.2 Interpreting Strategies

The main researcher identified strategies manually by analysing the case study data logs and recording task choice patterns. The main researcher then applied a letter and a description of each pattern to form the strategies presented in Table 24. Finally, the log files again were again passed over and the user's task choices were compared against the strategy table.

Rule Refresh	Points Refresh	Difficulty Levels Refresh															
Remember the following BrainQuest task ordering rules: Task ordering rule 1: <i>Change task type each time</i> Task ordering rule 2: <i>Attempt all 6 tasks at least once</i>	<p>Hero Points:</p> <p>Combo Bonus = IF (Correct Choice = Combo Bonus +1), ELSE (Combo Bonus = 0)</p> <p>Completed Task Points = 10 x Combo Bonus</p> <p>Total Task Points = Completed Task Points + Task Ordering Rules Bonus (100 points)</p> <p>Rustler Points:</p> <p>Rustler Points = 10 points per shuttle + 10 points per animal delivered</p>	<table border="1"> <thead> <tr> <th>Level Number</th> <th>Level Name</th> <th>Support Tools</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>Rookie</td> <td>Task Shading + Task History</td> </tr> <tr> <td>2</td> <td>Professional</td> <td>Task History</td> </tr> <tr> <td>3</td> <td>World Class</td> <td>Nothing</td> </tr> <tr> <td>4</td> <td>Legendary</td> <td>Task Randomizer</td> </tr> </tbody> </table>	Level Number	Level Name	Support Tools	1	Rookie	Task Shading + Task History	2	Professional	Task History	3	World Class	Nothing	4	Legendary	Task Randomizer
Level Number	Level Name	Support Tools															
1	Rookie	Task Shading + Task History															
2	Professional	Task History															
3	World Class	Nothing															
4	Legendary	Task Randomizer															

Table 23: Recap of rules, scoring, and difficulty

Strategies were defined in order of complexity in Table 24. Note that although some strategies are more complex than others, there is a contextual factor as to when certain strategies are most useful. Hence, users will sometimes mix strategies (using a maintenance strategy). The strategies uncovered from log file analysis were categorized below. The letters associated with each strategy are used throughout this chapter.

Strategy	Complexity Level	Strategy Description	Strategy Explanation
A	None	Uninterpretable or no strategy	The user makes no attempt to follow either task ordering rule.
B	None	Grouping tasks of the same type together	The user groups tasks of the same type together breaking task ordering rule 1.

C	Low	Simple task type change each time	The user changes task type each time but task selections may be random and they may not complete rule 2.
D	Low	Task type = n-2 throughout * n = current task number	The user maintains the same task type on every second selection throughout and they may not complete rule 2.
E	Moderate	Task type = n-2 until all subtypes complete * n = current task number	The user maintains the same task type on every second selection throughout and attempts a previously unimplemented task of the 6 subtypes in between times.
F	High	2 or more consecutive cycles comprising 3 different types	The user completes 2 or more cycles, each comprising 3 different task types to complete rule 2 without breaking rule 1.
G	Very High	Grouping animals together for 2 or more consecutive cycles of 3 tasks	This strategy builds upon F but for each cycle of 3 the user is consistent in their choice of animal.
H	Very High	Undertaking task types in a repeatable order for 2 or more consecutive cycles	This strategy builds upon F but for each cycle of 3 the user is consistent in the order in which they pick tasks e.g. return, save, stop.
I	Very High	Selecting tasks top to bottom for 2 or more consecutive cycles	This strategy builds upon F, G, and H but the user uses the interface to guide choices e.g. return cow, stop cow rustler, save cow, return sheep, stop sheep rustler, save sheep.
J	Maintenance + High	Changing to a more simplistic strategy after completing all	After completing rule 2 using a moderate or high-level strategy, the user may change to a low-level strategy which allows them to

		6 task types - in other words, making rule 1 a priority	concentrate on attending to rule 1. This is an efficient strategy as it relinquishes having to hold both rules in WM.
K	Maintenance + Moderate	Stopping additional tasks to preserve trophy	After completing rule 2 using, the user may stop undertaking any further tasks to leave no chance of breaking rule 1. This strategy is likely to end in success but drastically limits the number of hero points available.

Table 24: Strategy Definitions

6.3.2.1.3 Interpreting Physical Activity

Although data was gathered regarding the number of shuttle runs and points undertaken by participants in the role of the rustler, this may not directly correspond to a complete representation of their PA. The following issues remain unresolved at this stage:

- Equality of PA – number of runs does not explain the intensity of the PA undertaken. Shuttle runs may have been undertaken at a walking, jogging, running or sprinting pace and each of these speeds are associated with different amounts of MVPA. Furthermore, they may impact the number of shuttle runs made during a game as more intense PA may require a longer recovery time. Equally, some shuttle runs may take a longer time to complete due to the duration of a chase scenario – though children were encouraged to stay on a predefined shuttle run route, in the heat of the chase running beyond these boundaries was commonplace.
- An unforeseen strategic component to the rustler role may have also impacted PA as the rustler attempts to time runs to gain as many points as possible. The result of this is that during some games more points can be achieved with fewer shuttle runs.
- Rustler points may also be affected by other factors, such as the hero neglecting the rustler pens.

6.3.2.1.4 Analysis Variables

The analysis variables referenced throughout this chapter are defined below:

Analysis Variable	Definition
BADS-C Pre-test Rank	The rank on the BADS-C EF testing battery pre-BrainQuest training
BADS-C Post-test Rank	The rank on the BADS-C EF testing battery post-BrainQuest training
6E Pre-test Rank	The rank on the 6E subtest of the BADS-C EF testing battery pre-BrainQuest training
6E Post-test Rank	The rank on the 6E subtest of the BADS-C EF testing battery post-BrainQuest training
Mile Rank	The rank in order of the time taken for all 28 children to run a mile without stopping OR if they stopped before the mile, the number of minutes for which they could run for before stopping
Bleep Test Rank	The rank in order of the highest score upon the Bleep Test
Hero Points	The number of points achieved in the role of the hero in one game
Rustler Points	The number of points achieved in the role of the rustler in one game
Shuttle Runs	The number of shuttle runs completed in the rustler role in one game (approx. 30 metres each – 2 sides of the game space)
Trophy Score	The score concerning following of the task ordering rules. It directly corresponds to the 6E test 'Profile Score'.

	2 points are awarded for each of the 6 tasks attempted (max 12). 1 point is deducted for a mistake made on each task type (max 3).
Trophy/Game Rank	The rank in order of most BrainQuest trophies won per game in the role of hero – each trophy won represents the correct following of the task ordering rules
Hero Points/Game	The rank to most BrainQuest points achieved per game in the role of hero – higher points per game reflect a balance between an ability to complete many tasks and follow the rules
Shuttle Runs/Game	The rank in order of the greatest number of shuttle runs per game completed during the rustler role
Rustler Points/Game	The rank to most BrainQuest points achieved per game in the role of rustler – higher points per game reflect number of rustler runs undertaken as well as bonus points for returning animals successfully

Table 25: Definitions of Analysis Variables

6.3.2.2 Featured Case Study: Melvin

6.3.2.2.1 Overview

Melvin performed well on the BADS-C EF testing battery as well as the 6E subtest. His physical ability was the best in the class and he was the best all-round BrainQuest player, ranked 1st on Trophy/Game and Hero Points/Game and 2nd on Rustler Points/Game, Shuttle Runs/Game measures. He was very competitive and wanted to be the best in the class. Thus, he put great effort into earning points and was highly motivated to undertake as many games as possible. His teachers also noticed an improvement in his behavior following the study, something which he had previously had problems with.

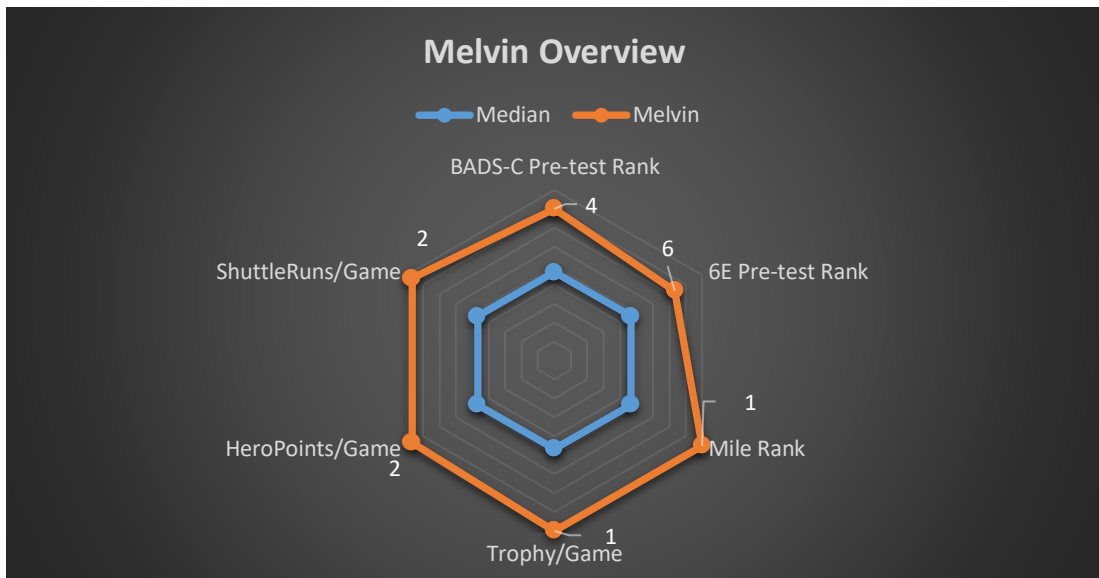


Figure 46: Melvin Overview

6.3.2.2.2 BADS-C Performance

High BADS-C performance, High 6E performance – Melvin recorded the 4th highest overall BADS-C score and 6th highest 6E score. In the pre-test 6E test, he followed the task ordering rules correctly without making any mistakes and recorded 12/12 for the profile score and 2/6 additional points for developing a strategy. Melvin’s strategy was to change color each time according to the subtask number i.e. all part 1s before part 2s.

Decreased 6E performance – On post-test 6E his profile score remained the same but there was no discernible strategy deployed and, therefore, his score decreased to 12.

6.3.2.2.3 BrainQuest Performance

6.3.2.2.3.1 Cognitive Training Performance

High BrainQuest EF performance – Melvin was the standout success throughout the 7 sessions and won a trophy on all but 1 occasion. He completed all difficulty levels and was ranked 1st for Trophy/Game and Hero Points/Game, as well as ranked 2nd for Rustler Points/Game and Shuttle Runs/Game.

Near-perfect trophy record – Melvin followed the task ordering rules correctly on the BrainQuest Test Game (Figure 47) but despite this he was unable to initially repeat his

success at Game 1 even though it was on an easier difficulty level. Following this, however, Melvin maintained an upward trajectory and successively completed different difficulty levels. Melvin completed Legendary by Game 5 and completed it again on each of his 3 remaining games. Thus, Melvin successfully completed the game 8 of his total 9 attempts.

Consistently high Hero Points – Aside from Game 1, Melvin’s Hero Point (Figure 47) scores remained high throughout, though there were notable peaks at Game 2 and the final 2 games of the study. However, it was not until he had earned all the trophies and set a point target of 10,000 that he started posting Hero Point scores on a consistently increasing trajectory. It is worth noting from Game 3 onwards, Melvin had assumed an unassailable lead at the top of the leaderboard. Thus, it was unclear whether he was motivated to maximize points in every game or play it safe to ensure a trophy win.

Increasing efficiency and the need for more challenge– The data also showed improvements in Melvin’s efficiency following repeated exposure to previously mastered difficulty levels. In Game 2 whereupon reattempting Rookie difficulty he more than doubled his score from the previous game. Also after Game 6 and on subsequent plays of Legendary difficulty, Melvin increased his score by more than 300 points on each occasion. This emphasises why it is important to incrementally change task demands and is characteristic of improvements in specific processes.

Yet Melvin’s 10,000 points target and the absence of further trophies to win, may have invigorated his efforts. This is discussed further in Section 6.3.2.2.3.2 (p. 221) but regardless of the cause, we can conclude Melvin needed additional levels of challenge - when asked as to what improvements could be made to BrainQuest, he advocated more game levels because he found it “*quite quick*” to complete.

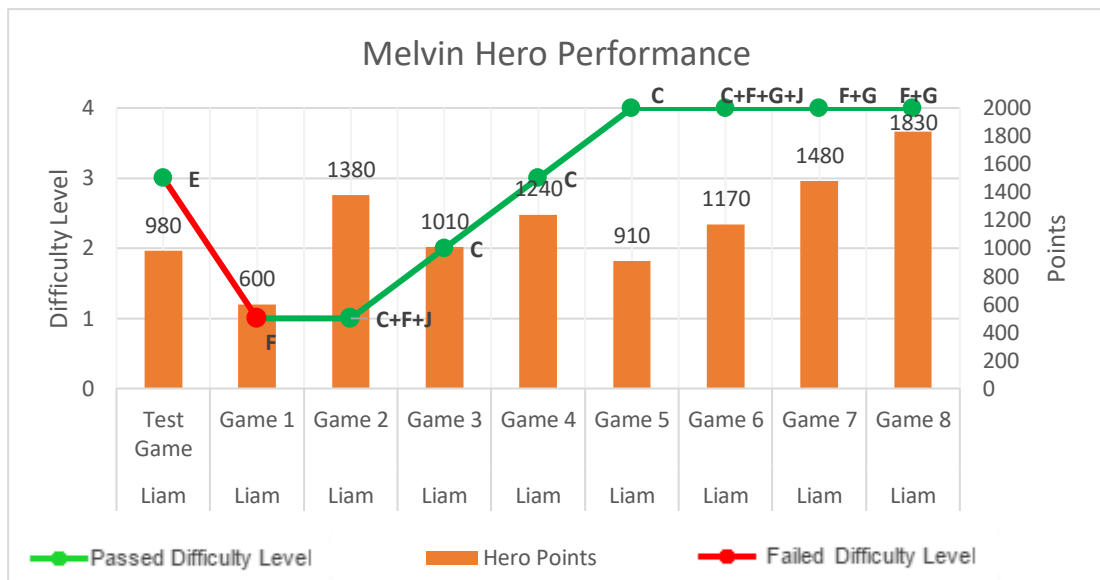


Figure 47: Melvin Hero Performance - Strategy Line

6.3.2.2.3.2 Strategy Evolution

Early complex strategies – Contrary to many other case studies, Melvin developed a strategy as early as the Test Game (Figure 48). However, the strategy he deployed was different to that which he utilized in the 6E pre-test where he split tasks up according to subtask number. In the Test Game, he successfully used strategy E - selected the same task every second choice with a different task in-between times until every different task type was completed.

In Game 1, he changed to strategy F and undertook 2 or more consecutive cycles of 3 different task types. Although this is a more efficient strategy (it allows you to follow task order rule 1 in a smaller number of steps, while following rule 2), Melvin was unsuccessful as he did not complete all the different task types. As this was his first time on Rookie difficulty, perhaps he got confused by the task shading tool, which only helps with following Rule 2. The post-test interviews support this hypothesis of confusion as Melvin states that initially he was unsure as to what to do.

Changing strategy complexity after completion of 1 task ordering rule – Despite the problems in Game 1, Melvin utilized the same strategy successfully in Game 2 and correctly did a task of each type in 2 consecutive cycles of 3 before changing strategy (J) to one less complex – simply changing to a random task of a different type each time. Consequently, Melvin's hero point's total increased substantially. Changing strategy to one of a simpler nature may suggest that either a cognitive challenge, obstructing one from implementing a

pre-defined strategy or that Melvin's cognitive ability was so capable, he could simply remember previously completed tasks. Melvin's interview suggests the latter theory to be true as he stated that even on BrainQuest's most challenging levels, he'd "*just look out*" for the correct task to do – and he never failed.

Adopting a less complex strategy due to a lack of challenge – From Game 3 until Game 5, Melvin adopted a less complex (or no pre-defined) strategy – simply changing task type each time – as he successfully progressed from Professional to Legendary difficulty levels he maintained solid point scores but his scores never reached the heights of Game 2. Despite this, Melvin appeared to find the game relatively easy as he never even bothered to use the task history tool at Professional difficulty. In Game 4, Melvin's point scores dropped to the lowest point since failing to successfully complete Rookie difficulty level in Game 1.

Resumption of a complex strategy to maximize points or refinement of processes – In Game 6 Melvin returned to the same complex strategy he used in Game 2 (C, F, J) but this time Melvin also grouped tasks within the cycle strategy by animal e.g. cow tasks first, followed by sheep tasks. It may be that following games where Melvin experienced a dip in performance, he responded by deploying a more complex strategy in the following game.

In the final 2 games of the study, Melvin continued to choose different tasks in cycles of 3 and again grouped animals together. However, different from Games 2 and 6 where following the completion of the 6 different task types he reverted to a simpler strategy, in Game 7 and 8 he maintained the complex strategy until the end of the game. Note, Melvin did not stick to a repeatable order for every cycle, instead, he interchanged between animals in groups of 3.

The data logs drew parallels with Melvin's interview. He acknowledged his lack of strategic complexity up until the Legendary difficulty level, in congruence with the simplistic task changing (C) between Games 3 and 5 followed by more complex strategies apparent from Games 6-8. As stated, there were 2 likely reasons for this – increased efficiency resulted from a conscious effort to maximise points or was due to repeated exposure to the same set of demands and, therefore, the automaticity of specific processes.

Melvin maintained that he did not need to use the task support tools on Rookie and Professional levels, nor the post-game feedback often and could remember "*most (tasks) on the top of my head*". Furthermore, he stated that on Legendary he developed a complex strategy which involved grouping by different animals:

“I would usually do...return cow, stop cow rustler, save cow, then I would go to the top right and do return sheep, stop sheep rustler, and save sheep.” – Melvin, Interview

When the interface randomized the thumbnails, Melvin would “*just look out*” for the correct task following his strategic order. Hence, Melvin appeared to be making a conscious effort to maximize his points.

Dissimilarly, the order of Melvin’s task choices in his final 2 games are nearly identical with the biggest difference being that in the final game he had time to complete an additional 2 tasks. Thus, this would suggest increasing the speed of a learned order. It appeared to be a bit of both – extra effort and an increasingly refined process.

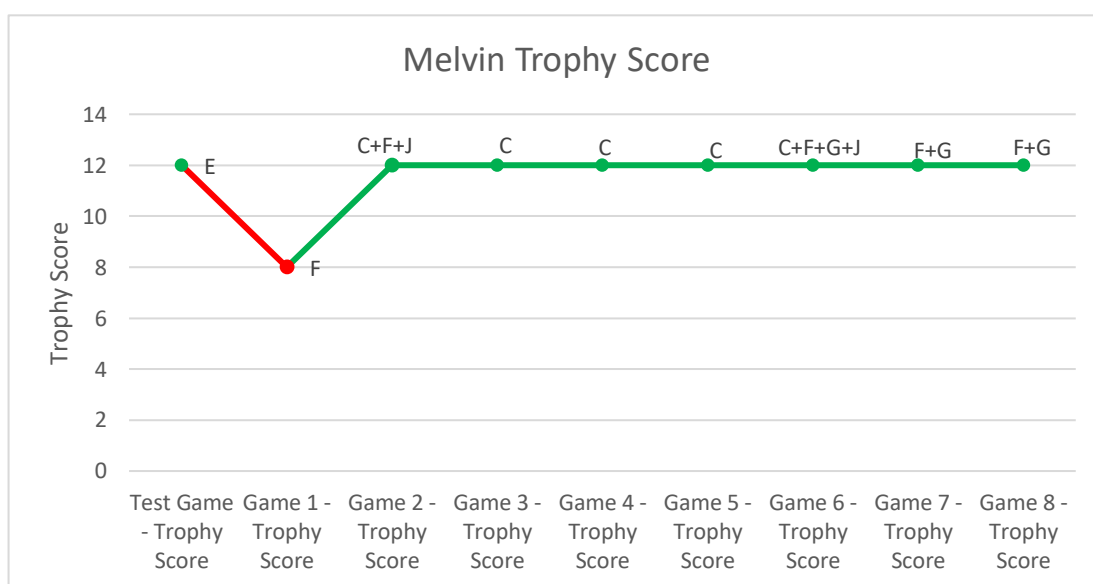


Figure 48: Melvin Trophy Score

6.3.2.2.4 Physical Activity

High physical ability, high BrainQuest performance – Melvin’s physical ability ranked top of the class according to the mile time and beep test measures provided by the PE teacher. The data logs reflected this in his BrainQuest performance where he was ranked 2nd on both Rustler Points/Games and Shuttle Runs/Games measures.

Maintaining PA throughout – Melvin’s Rustler Points and Shuttle Runs followed a volatile path (Figure 49 & Figure 50), spiking at Games 6 and 7 before a decline to pre-spike levels but always staying far above the class average. Melvin maintained a mean of 140.7 points (SD=30.5) and 11.9 runs (SD=2.8), well above the class mean – 53.4 and 6.4, respectively.

Melvin intimated that his PA declined towards the end of the study because nobody was close to rivalling him for total points:

“on like the last two [rustler] games, I sort of like just walked because I was already winning” – Melvin, Interview

However, though there was a steady decline between Games 11-13, his final effort returned to his own mean.

Moderately perceived exertion but observed vigorous PA – In Melvin’s post-intervention interview he stated BrainQuest to be a 5 on the fatigue scale (where 1 is not tiring and 10 is exhausting) but he did say that fatigue in the game varied depending on *“how many times you had to do it”* in reference to the rustler role. When asked what part of the game he found particularly tiring, he responded:

“if you’re like sheep rustler and there are no sheep in the hero’s pen, you’d have to keep doing tonnes of laps right round” – Melvin, Interview

Despite this, the observations indicated Melvin’s engagement in moderate to vigorous PA throughout the study, particularly during hero-rustler interactions – often describing him as *“running”*.

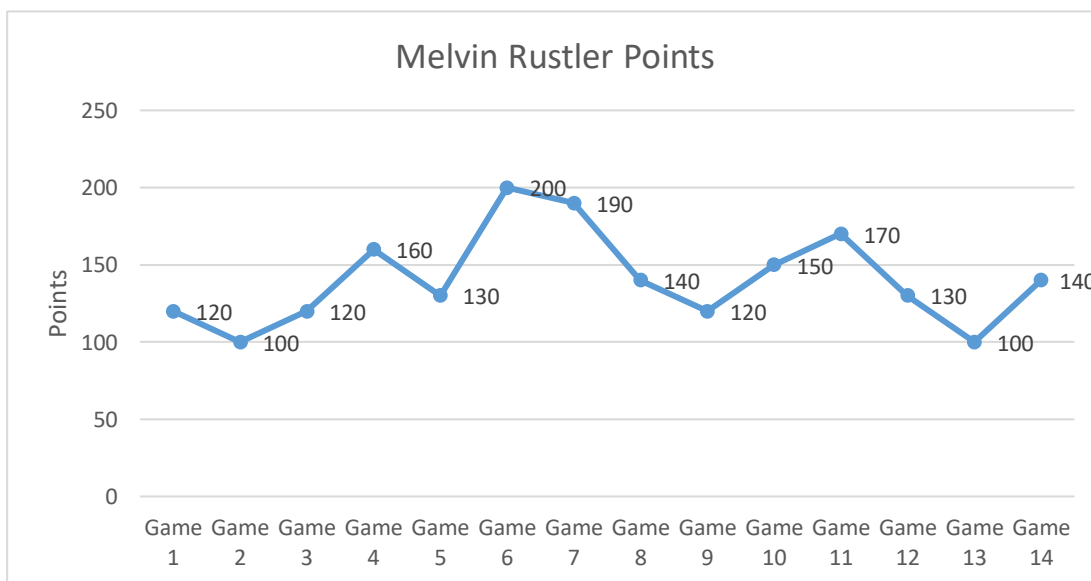


Figure 49: Melvin Rustler Points

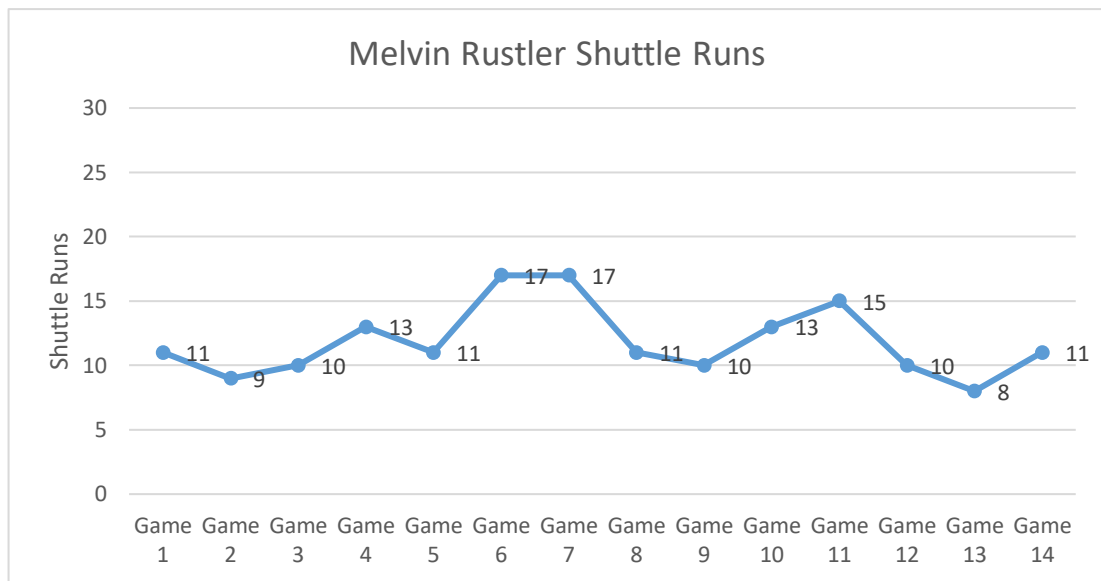


Figure 50: Melvin Rustler Shuttle Runs

6.3.2.2.5 Joy + Pride/Confidence/Self-efficacy

Motivation to play additional games – Melvin’s data logs suggested high motivation towards wanting to play the game – he maintained a 100% attendance record, played in the hero role a joint class record of 9 times (class mean = 6.9), and played as a rustler for the joint second highest number of 17 times (class mean = 12.3). Hence, there were some sessions where Melvin played in each role more than once – during sessions where there were absences. The observations noted Melvin begging the main researcher to play twice on more than one occasion.

Investment in leaderboard and pride in performance – Melvin was driven primarily by his goal of topping the leaderboard and earning points. This was supported by the observations where he was recorded broadcasting his points scores to other players and the researchers, keeping tabs on the leaderboard and potential rivals, and setting himself points goals – towards the final sessions of the study he set a goal of 10,000 points which he surpassed. In Melvin’s interview, he cited his points score as his proudest achievement during the study.

Trophies as motivational hook – Melvin also valued trophies and was observed broadcasting his trophy achievements to other children and the researchers. Indeed, it may have been the trophy system which was the catalyst for his initial motivation for play as he stated that his attitude towards the game:

“started to change a lot more with the trophy system, when I found out” – Melvin, Interview

Increasing BrainQuest self-efficacy – Like many of his peers, Melvin also found the game difficult to understand at first:

“at first we were all sort of running about not knowing what to do. Now we know what to do” – Melvin, Interview

However, his self-efficacy towards the activity grew and he stated feeling as if he improved with progressive games, something which made him feel *“happy”* because he *“actually listened to the game”*.

Increasing enjoyment – BrainQuest also shattered Melvin’s pre-conceptions of serious gaming and he stated:

“at the start, I just thought ‘it’s someone coming in to do something not too fun’ but when I started to do it, it ended up getting really fun and I wanted to keep on doing it” – Melvin, Interview

In one word, Melvin described BrainQuest experience as being *“exhilarating”*.

6.3.2.2.6 Social Experience

Enjoying sharing success stories with others – As noted, Melvin gained a lot of satisfaction from achieving the points and leaderboard goals he set himself throughout the study but he also appeared to enjoy the social consequences of his success. The observations documented Melvin engaging in jovial but competitive conversations with other players regarding the leaderboard and trophies as well as during hero-rustler interactions. For example, chases between Melvin and another boy went far beyond the confines of the play space and Melvin humorously teased his opponent by withholding cattle after being caught. Melvin also enjoyed telling others of his achievements and many seemed to scarcely believe the extent of his success.

Building relationships and cooperating – Melvin appeared to form some genuine relationships with other children in the study despite his previous social issues, outlined by

his teachers before the study. Melvin said he not only enjoyed socializing with individuals beyond his immediate friend group but also worked cooperatively with them:

“it was quite fun because some people that you wouldn’t usually play with, you would actually end up cooperating with them and finding out that it is actually quite fun” – Melvin, Interview

Melvin stated that following the intervention his relationship with some of the other children in the class had changed for the better and he had started *“to play with them a little bit more”* than previously.

Melvin cooperated with others by asking them to upkeep numbers of cattle in each pen and by helping less able players to understand game rules properly. However, there were also selfish reasons for helping others. E.g., to maintain the game’s challenge which Melvin admitted would be absent if *“nobody else knows how to play it”*.

Improved behaviour beyond BrainQuest – In the interview with the class and PE teacher, they highlighted an improvement in Melvin’s behaviour beyond the scope of the study but had emerged at the same time as the BrainQuest sessions but they may have been alternative reasons for the positive change:

“We’ve put a lot of work in with Melvin recently and I don’t know if it has just coincided at the right time (touch wood) but I’ve not had any problems outside. He’s not behaved impeccably in the playground but he’s walked away before he’s lost it.”
– Class Teacher, Interview

“And he’s out in the playground again” – PE Teacher, Interview

“And he’s out in the playground again which he wasn’t before and he made the choice to write his rules for going out in the playground which before he was like ‘no I’m not doing it, I’ll stay in’. So we’ve put time in and he’s done other thing but whether it’s just a coincidence...” – Class Teacher, Interview

6.3.2.2.7 Melvin Summary

Contributions towards RQ1 – Indirect Pathways Summary	Contributions towards RQ2 – Direct Pathways Summary
<p>Joy + Pride/Confidence/Self-efficacy</p> <ul style="list-style-type: none"> • Set a goal of topping leaderboard • Expressed pride in his point achievement • Broadcasted results to his peers • Found the game initially hard to understand 	<p>Pre-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 4th • Achieved 6E score of 14 • Able to follow both task ordering rules 1 and 2

<ul style="list-style-type: none"> • Felt more confident regarding the rules by the end • Enjoyed the game more at the end • Described BrainQuest experience as “<i>exhilarating</i>” 	<ul style="list-style-type: none"> • Deployed strategy – equivalent to BrainQuest strategies F and G
<p>PA</p> <ul style="list-style-type: none"> • Mile Rank: 1st • Bleep Test: 1st • Rustler Shuttle Run Rank: 2nd • Mean Rustler Shuttle Runs: 11.9 • Shuttle runs peaked in Games 6 and 7/14 • Number of rustler runs varied throughout but maintained above the class average in all games • Number of runs dropped below his own mean in the final 3 games of the study but had troughed at similar numbers at other points in the study • Fatigue scale: 5/10 • Found BrainQuest tiring during the rustler role after continuously doing shuttle runs 	<p>Post-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 6th • Overall age scaled score improved but not as much as some of his peers • Achieved 6E score of 12 • Able to follow both task ordering rules 1 and 2 • No strategy deployed <p>BrainQuest Performance Evolution</p> <ul style="list-style-type: none"> • Complex strategies were developed early but complexity varied throughout the study, though there were complex strategies used towards the end • It seemed strategies were only implemented to become more efficient following completion of a difficulty level • Seemed able to implement task ordering rules using low complexity strategies • No use of task history tool • Deployed strategies of low, moderate, high and very high complexity • Maintenance strategies used • Deployed 5 different feasible strategies • Deployed 6 different strategy combinations • Highest Difficulty Level Completed: 4 • Trophy/Game: 8/9 • Highest Hero Points Score: 1830 • Difficulty Level (Win/Lose) <ul style="list-style-type: none"> ○ Rookie: 1/1 ○ Professional: 1/0 ○ World Class: 1/0 ○ Legendary: 4/0
<p>Social Experience</p> <ul style="list-style-type: none"> • Cooperative <ul style="list-style-type: none"> ○ Melvin helped others with the game rules ○ Melvin wanted to help people to preserve the game’s challenge • Competitive <ul style="list-style-type: none"> ○ Melvin and opponents appeared to be competitive with regards to their achievements and he loved to show off his point scores and trophies ○ Melvin chased beyond the game boundaries 	

<ul style="list-style-type: none"> ○ Melvin teased his opponents by withholding cattle ● Relationship Change <ul style="list-style-type: none"> ○ Melvin felt BrainQuest enabled him to engage and have fun with individuals he wouldn't normally play with 	
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Table 26: Melvin Summary

6.3.2.3 Case Study Conclusions

Table 27 summarises many of the trends and conclusions to be drawn from all case studies, many of which can be found in Appendix B. The conclusions identified are used later in this chapter to both contrast and corroborate with the general results of the 28 participants (case and non-case study) to address the research questions.

ID	Contributing Research Question	Conclusion	Evidence	Cases Presenting
CC1	RQ1: Engagement	Trophies and the leaderboard were used as a form of goal setting.	4 children used trophies as a goal	Alexa, Leonard, Patrick, Stevie
			3 children used leaderboard as goal	Rachel, Angelina, Melvin
CC2	RQ1: Engagement	The sounds and graphics were a popular aspect of the game	5 children reported enjoying the sounds and animations that appeared at various points throughout the game, and for 2 of these children, they were their favourite aspect of the phone app	Leonard, Alexa, Natalia, Patrick, Rachel
CC3	RQ1: Engagement	Some children expression themselves through a unique style of play.	2 children projected a cunning persona during gameplay	Patrick, Leonard

CC4	RQ1: Engagement, Social Interaction	Trophies and the leaderboard had social outcomes.	7 children conversed with other players regarding their achievements	Alexa, Patrick, Leonard, Melvin, Stevie, Rosie, Rachel
			Stevie wanted the main researcher to add a Legendary trophy to his account on the event he was not able to achieve one	Stevie
CC5	RQ1: Engagement, Pride / Confidence / Self-Efficacy	Trophies and the leaderboard were a source of pride for the children.	7 children stated feeling pride in achievements during interview	Rachel, Patrick, Leonard, Natalia, Angelina, Melvin, Stevie
			6 children were proud of earning trophies	Alexa, Leonard, Natalia, Patrick, Stevie, Angelina
			2 children were proud of their leaderboard performance	Angelina, Melvin
			3 children were proud of their overcoming difficulty levels	Stevie, Patrick
CC6	RQ1: Pride / Confidence / Self-efficacy RQ1: PA	Many case study children enjoyed, gained confidence, or took pride in their PA achievements.	Patrick felt like all the running had helped him lose some weight	Patrick
			Alexa felt the game had <i>“helped her with her running”</i>	Alexa
			Rachel stated that she <i>“enjoyed the running”</i> in the game	Rachel

			Angelina felt the running involved in the game made the experience more enjoyable	Angelina
			Rosie said that playing the game made her feel “ <i>proud</i> ” of her running	Rosie
CC7	RQ1: Pride / Confidence / Self-efficacy RQ2: BQ Challenge	The game was initially hard to understand but case studies felt more competent with respect to the game rules with time.	4 children found the game hard to understand initially	Alexa, Rachel, Patrick, Leonard
			4 children felt more confident in their ability to follow the rules by the end	Alexa, Rachel, Patrick, Leonard
CC8	RQ1: Engagement RQ1: PA	There did not appear to be novelty effects associated with PA or user engagement	6 children stated enjoying the game more towards the end of the study than at the start	Angelina, Melvin, Stevie, Natalia, Rachel, Alexa
			3 children enjoyed the game the same amount from start to finish	Alexa, Leonard, Patrick
			The rustler Shuttle Runs for 5 children remained at the same or above their own mean by the final game of the study	Melvin, Alexa, Rachel, Angelina, Natalia
CC9	RQ1: PA	The game appeared to encourage PA for even the least physically able children but it was unclear as to whether this could be sustained for the long term	Leonard and Patrick, two children with poor physical ability, enjoyed hero-rustler chases more than any other activity	Leonard, Patrick
			Patrick was ranked bottom of the class for his mile time but his Rustler Shuttle Runs per game score was ranked 18th	Patrick

			Patrick ran his most during hero/rustler interactions	Patrick
			Following BrainQuest, Leonard's teachers had noticed an improvement in his physical ability – he was now able to run a mile	Leonard
			Leonard and Patrick fell below the class mean of Rustler Shuttle Runs	Leonard, Patrick
			Both Leonard and Patrick's number of Rustler Shuttle Runs fell below their respective means towards the end of the study	Leonard, Patrick
			Leonard didn't want to run if there was not the prospect of returning any cattle	Leonard
CC1 0	RQ1: Social Interaction RQ1: PA	The 'Stop the Rustler' task and the continuous Rustler Shuttle Runs were the most tiring aspects of the game but the game could have been more exerting.	The game was rated a mean of 4.4 on the fatigue rating (1 not tiring, 10 exhausting) by the case study children	Rachel, Patrick, Leonard, Natalia, Angelina, Melvin, Stevie, Rosie
			Leonard and Angelina stated finding the game tiring following continuous Rustler Shuttle Runs	Leonard, Angelina
			According to Stevie, the level of PA difficulty depended upon the opponent	Stevie
CC1 1	RQ1: Social Interaction	Motivation to play for some was simply the opportunity to interact with other people.	2 children were motivated by running around with classmates	Rosie, Natalia

CC1 2	RQ1: Social Interaction	Cooperation during gameplay was less prevalent but it still occurred	Rachel and Angelina appeared to cooperate with each other in hero and rustler roles to maximise each other's scores	Angelina, Rachel
			2 children were observed verbally encouraging their peers during games	Patrick, Alexa
CC1 3	RQ1: Social Interaction RQ2: BQ Challenge	There was cooperation in learning the game rules, procedures and strategies	Case study group 1 were all observed/reported helping each other with learning the game rules and sharing tips	Alexa, Patrick, Rachel
			Case study group 2 were all observed/reported helping each other with learning the game rules and sharing tips	Leonard, Natalia, Angelina
			The emergent case studies were all observed/reported helping other children with rules and sharing tips	Melvin, Stevie, Rosie
CC1 4	RQ1: Social Interaction	There was some evidence of changing attitudes towards other but it appeared that not all accounts of relationship change were reciprocated	Alexa believed her relationship with Patrick had slightly improved	Alexa
			Melvin thought it was fun to play and interact with class mates he wouldn't normally play with	Melvin
			Natalia and Leonard appeared to form a good relationship and Leonard shared strategies with Natalia and no other player	Natalia, Leonard
			Natalia particularly enjoyed interacting with the other members of the group	Natalia
			Patrick did not believe his relationship with Alexa or Rachel had improved	Patrick
			Leonard did not believe his relationship with the other	Leonard

			players in the groups had changed	
CC1 5	RQ1: Social Interaction	The children yearned for greater diversity in their social interactions	2 of the pre-defined case study children, opportunities to play beyond their set groups and with individuals who they regarded friends, resulted in an observed enhanced enjoyment in the game	Leonard, Patrick
CC1 6	RQ1: Social Interaction RQ2: BQ Challenge	The hero-rustler role appeared to test behavioural regulatory skills	There were 2 direct accusations of cheating with players seeking arbitration from observers	Alexa, Patrick Rosie, Stevie
			7 case study children were involved in arguments because of hero-rustler chases	Alexa, Patrick Rosie, Stevie, Leonard, Natalia, Rachel
			4 case study children were involved in violations of game boundaries during hero-rustler chases	Leonard, Natalia, Melvin, Stevie
CC1 7	RQ2: BQ Challenge	Data logs suggested the hero role was challenging for most children as Hero Points peaked relatively early in the study before decline or plateau.	5 children failed to complete the game on all difficulty levels	Alexa, Rachel, Patrick, Leonard, Rosie
			Only 1 child's Hero Points peaked at the end of the study	Melvin
			7 children's Hero Points peaked before game 3	Alexa, Patrick, Rosie, Stevie, Leonard, Natalia, Rachel

CC1 8	RQ2: BQ Challenge	Self-reported challenge did not correspond to objective performance.	5 children stated finding there to be a difference in challenge between the different difficulty levels	Alexa, Natalia, Angelina, Rachel, Stevie
			4 children stated the game's challenge not to have changed throughout but only 1 child completed all levels	Melvin, Rosie, Leonard, Patrick
CC1 9	RQ2: BQ Challenge	The task history tool was used by most children but to variable extents.	6 children made use of the task history tool during gameplay	Rachel, Patrick, Leonard, Natalia, Angelina, Stevie
			2 children made light use of the task history (<5 times in one game)	Rachel, Patrick
			2 children made moderate use of the task history (<9 times in one game)	Leonard, Stevie
			2 children made heavy use of the task history (>=9 times in one game)	Natalia, Angelina
CC2 0	RQ2: BQ Challenge	Case study children who found a difference felt the biggest change in difficulty was when the support tools were removed or when the thumbnails were randomized.	3 children found the biggest increase in difficulty to be World Class to Legendary when the thumbnails were randomized	Natalia, Angelina, Alexa
			2 children found the biggest increase in difficulty to be Professional to World Class when the task history tool was removed	Rachel, Stevie
CC2 1	RQ2: BQ Challenge	For those experiencing challenge, it appeared to manifest itself in difficulty in	5 children found it hard at points during game play to remember which task to choose next	Natalia, Stevie, Angelina,

		remembering previously chosen tasks while choosing a new one.		Alexa, Leonard
CC2 2	RQ2: BQ Challenge	Most children could deploy strategies of high and very high complexity but only a smaller number could implement advanced combinations utilizing a maintenance strategy.	5 children could perform combination strategies - changing strategy (maintenance strategies) to make it easier to follow the rules	Alexa, Natalia, Angelina, Melvin, Stevie
			8 children deployed strategies of very high complexity	Alexa, Rachel, Patrick, Leonard, Natalia, Angelina, Melvin, Stevie
			8 Children deployed strategies of high complexity	Alexa, Rachel, Patrick, Leonard, Natalia, Angelina, Melvin, Stevie
			5 Children deployed strategies of moderate complexity	Natalia, Angelina, Melvin, Stevie, Rosie
			8 deployed strategies of low complexity	Alexa, Rachel, Patrick, Natalia, Angelina, Melvin, Stevie, Rosie

CC2 3	RQ2: BQ Challenge	Social factors impact performance by influencing task and strategies.	1 child was observed changing her strategy and even breaking the task ordering rules to cooperate with other players	Rachel
			For 1 child, adopting a 'stealth' style of play allowing for greater flexibility in catching rustlers coincided with a decrease in strategy complexity	Patrick
			2 children adopted or modified a strategy to enable for more frequent catching of rustlers	Natalia, Angelina
			1 child adjusted her task choices to time catching the rustlers efficiently	Rosie
			1 child repeatedly broke the task ordering rules to catch another player	Leonard
CC2 4	RQ2: BQ Challenge	BrainQuest forced children to generate new strategies rather than rely on the same strategy throughout the study.	4.3 was the mean number of unique strategy combinations developed during study	Alexa, Rachel, Patrick, Leonard, Natalia, Angelina, Stevie, Rosie
CC2 5	RQ2: BQ Challenge	The initial novelty was perhaps the biggest challenge but the variable difficulty appeared to maintain the challenge to some extent throughout the study.	The mean number of games failed by the case studies who attempted difficulty: <ul style="list-style-type: none"> • Rookie: 0.9 • Professional: 0.9 • World Class: 0.3 • Legendary: 0.8 	Alexa, Rachel, Patrick, Leonard, Natalia, Angelina, Stevie, Rosie
			3 of the 4 children to attempt Legendary, failed the difficulty at least once	Angelina, Natalia, Stevie

CC2 6	RQ2: Transfer	Post-test 6E performance increased for 4 children but in 3 cases there was no change and in 2 cases decreased.	6E performance improved from pre-post test	Rachel, Natalia, Stevie, Rosie
			Decrease in 6E performance from pre-post test	Leonard, Melvin
			No change in 6E performance from pre-post test	Alexa, Patrick, Angelina (Angelina at ceiling)
CC2 7	RQ2: Transfer	3 children's attempt to follow the task ordering rules improved at the post-test and no children's rule adherence got worse from pre-test.	Following 6E rules improved from pre-post	Patrick, Natalia, Stevie
CC2 8	RQ2: Transfer	Strategizing on the 6E following BrainQuest improved for 3 children but for 3 others, BrainQuest strategizing did not transfer to 6E.	6E strategizing complexity increased from pre-post test	Natalia, Stevie, Rosie
			Able to strategize in both BrainQuest and pre-test 6E	Melvin, Angelina, Natalia, Leonard, Rosie
			Able to strategize in both BrainQuest and post-test 6E	Leonard, Alexa, Natalia, Angelina, Stevie
			Able to strategize in BrainQuest but not in post-6E test	Rachel, Patrick, Melvin

Table 27: Case Study Conclusions

6.3.3 General Qualitative Results

6.3.3.1 RQ1 – indirect executive functions

To what extent does the game support the pathways to EF improvement identified by the Diamond pathways: joy, social belonging, physical fitness and pride/confidence/self-efficacy?

As discussed in Chapter Two (Section 3.3, p. 78), joy is a phenomenon which may be understood by motivational theories such as Self-Determination Theory (Ryan & Deci, 2000) and Lepper and Malone's Framework (Lepper & Malone, 1987). Joy can be derived from creating engaging experiences but may also overlap with the social, physical, and confidence pathways also described in this chapter. Consequently, the joy derived from social play is described under 'Social Behaviour' (Section 6.3.3.1.2, p. 243), while joy as a product of general user engagement is described under 'Emotional Behaviour' (Section 6.3.3.1.1, p. 239).

Another category related to maintaining user engagement, creating feelings of competence and fostering self-efficacy, is the concept of challenge and the support tools used to scaffold variable difficulty. However, both categories are presented within RQ2 due to their hypothesized intrinsic relationship with EF.

6.3.3.1.1 Emotional Behaviour (Joy + Pride/Confidence/Self-Efficacy)

Emotional behaviour was split into several sub-categories: one category addresses *pride/confidence/self-efficacy directly, while engagement collates the results of many design decisions taken to contribute to the phenomenon of joy and a sustained desire for play.*

6.3.3.1.1.1 Engagement

General Opinions – In general, the children appeared to enjoy their experience with BrainQuest and the children's general opinions of the game were very positive, particularly towards the end of the study: *"come play this game, it's epic"* Jax, *General Observations*. This was echoed by the class teacher's comments:

"I think it has been very enjoyable. There's been a lot of motivation, there's been a lot of buzz about it and they've been enthusiastic about the leaderboard and who's

got what trophy and they've looked forward to each session" – Class Teacher, Interview

Notwithstanding, though there were 439 references to children expressing positive emotions towards or during the game, there were aspects of the game which were detrimental to user engagement and there were 175 references to negative emotions – these are discussed later in the chapter.

Engagement Evolution – The session review notes illustrated the level of user engagement. In 3 sessions, multiple children requested to play the game for more than the scheduled 3 games per session by filling in for absent children. On one occasion an argument ensued between 3 children Melvin, Monty, and Ellen:

"A lot of kids were begging me to allow them to play BrainQuest in both sessions due to the absentees. Melvin, Martin, and Ellen got into an argument over it and I asked to play rock paper scissors in order to decide" – Observer, Session Review

However, it should be noted that many children who asked to play in subsequent sessions were those invested in either the leaderboard or trophy system and this is consistent with the power of goal-setting to capture user engagement. The class and PE teachers felt engagement followed a pattern of peaks and troughs:

"I think in weeks 2 or 3, their enthusiasm dipped a wee bit and I was working with you and I had some kids that were quite happy to stay with me and not to come through [referring to the parallel activity undertaken by half the class while they waited for their turn to play BrainQuest], but on the last week the enthusiasm went right up again, and I don't know if that is to do with the challenge of the game?" – PE Teacher, Interview

This observation may be valid as there was a dip in the level of challenge (Section 6.3.3.2.1, p. 247) during weeks 2 and 3 when many children encountered World Class difficulty. On the contrary, this contrasted with the accounts of other children who suggested either enjoying the game more with time or enjoying the game equally from start to finish (CC8, Section 6.3.2.3, p. 229). Thus, perhaps motivation fluctuated between individuals. Nonetheless, it appears that a novelty effect did not emerge at least for the number of sessions within the study.

Fantasy – The fantasy-enhancing sounds and graphics seemed an important game aspect for some children and there were instances where observers were approached to troubleshoot problems when they did not appear:

"John asked me to get the sound effects on because his phone was on mute. He was happy when his phone started to bah" – Observer, Session Review

Nevertheless, there were occasions where the meaning of the sounds and animations were confusing, specifically the rustler fail noise – which occurred following a return to one’s pen without animals. Hence, they may require future redevelopment.

Role Balance – The balance between the hero and rustler roles appeared to hinder user engagement. There were 4 observed occurrences of children expressing their frustration while playing as the rustler when the hero pens were empty and there was nothing for them to steal.

“Patrick is complaining that there are a lot of sheep in his pen so she’s not returning sheep back to her pen” – Observer, Case Study Observations

Bugs – Game bugs were also an intermittent issue, particularly in early sessions (outlined in Section 6.3.3.3, p. 255) but only some had observably detrimental effects on user engagement. The most common grievance concerned errors affecting point scores or trophies performances, and logging bugs requiring games to be restarted – there were 24 referenced complaints.

“Rachel says she lost 30 points and is unhappy” – Observer, Case Study Observations

The main researcher mitigated the effects of points/trophy bugs by retrospectively using the database logging to distribute unattributed points or trophies to children affected. Furthermore, for the logging crash bugs remaining, 4 these issues were resolved by session 4 and this led to a drastic reduction in negative emotions.

6.3.3.1.1.2 Learnability

Appropriateness – BrainQuest appeared at an appropriate ability level for the target age group. 9 case study children interviewed accurately described the fundamental task ordering rules of the game. However, general observations indicated a learning curve associated with the rule, task procedure, and technology mastery (CC25 – Section 6.3.2.3, p. 229), which extended beyond the scope of the tutorial sessions. The observation notes suggested difficulties in grasping the rules for a minority of children persisted until Session 3 as 5 children approached observers for reassurance.

Misunderstanding Rustler Role – Rustler roles also caused misunderstandings and 4 arose regarding: the rules of hero/rustler interactions, how to earn points from rustler shuttle runs, the correct paths to take during shuttle runs, and confusing hero and rustler roles.

Nevertheless, on some occasions, it was unclear whether the children misunderstood the rustler game rules and procedures or choose to ignore them because of an inability to inhibit a more desirable behaviour.

Learning – From session 4 until the end of the study, the number of queries regarding the game rules rapidly decreased as noted by the main observer:

“Really good effort from the first group of kids today, didn’t need any help to get set up” – Observer, General Observations

By the end of the study, 25 children had progressed past Rookie difficulty level and, therefore, had implemented the task ordering rules at least once. Hence, during early sessions, an additional layer of challenge appeared present.

6.3.3.1.1.3 Pride/Confidence/Self-efficacy

Leaderboard/Trophy Pride – Participants appeared to derive pride from winning trophies and performing well on the leaderboard. In sessions 3, 4, and 5 there were 28 occurrences of children approaching observers to relay their achievements and coincided with many children winning their first trophies according to the data logs. However, in the remaining sessions emphasis changed from communicating pride to the observers, to communicating pride to their peers:

“Before, during, and after each of the game sessions, there was a lot of social interaction between the kids while looking at each other’s phones - at the leaderboard and trophy cabinets.” – Observer, General Observations

Hence, it appears in-game achievements supported feelings of competence and may have been the catalyst for social interaction – consistent with the design guidelines.

Goal Setting – The trophies and leaderboard also seemed to be used as methods of goal setting (CC1, CC5 – Section 6.3.2.3, p. 229). However, there was limited data to understand how these goals changed over time or following completion, suggesting the observation period was not long enough to capture goal-setting evolution. E.g., most participants had not won all trophies by the final study session and, thus, may still have been invested in this long-term goal – a possible explanation for the absence of engagement novelty decline. Nevertheless, 2 children completed trophy goals before the final session and this hinted at possible future user behaviour as they behaved in two different ways, either (1) selecting a new goal or (2) in the case of trophies, collecting as many as possible:

“Ellen and Melvin had run out of trophies to earn. Melvin’s focus shifted to beating a personal point’s target that he had set himself, of 10000 points which achieved and then celebrated wildly with joy – jumping up and down! Ellen was happy just to keep winning Legendary trophies, letting me know of how many were now in her trophy cabinet.” – Observer, General Observations

Yet there were instances where failing to attain a goal led to feelings of diminished confidence. The observation notes report one child, who failed to achieve a trophy because he broke the task ordering rules on his final task, subsequently going on strike and refusing to play for the session remainder. This suggests the reward system eventually became too predictable and additional goals, such as achievements and rewards, are required.

Notwithstanding, BrainQuest provided alternative targets to some extent. Some children, who initially expressed a desire to achieve one goal, later claimed it to be of little interest and instead favoured another goal. E.g., several children initially communicated an interest in the leaderboard before changing to trophy goals as their initial goal became increasingly unachievable.

Other Sources of Pride - PA was also a source of pride, confidence, and self-efficacy (CC6 – Section 6.3.2.3, p. 229), while mastery of game rules also created feelings of self-efficacy (CC7 – Section 6.3.2.3, p. 229). Finally, some children derived pride from their actions and ways in which they expressed themselves, e.g. Jax, who became known for his rustling abilities (rustler points were recorded in the ‘score centre’ menu of the game). Jax scored the most rustler points of any other child and opted to play more rustler games than anybody else in his pursuit of being the best:

“I scored 350 points and I already quit” – Jax, Observation Notes.

The prevalence of self-expression suggests BrainQuest facilitated user autonomy but may also highlight the need to officially reward rustler activities as well as individual playing styles.

6.3.3.1.2 Social Behaviour

The concept of relatedness shares an intrinsic relationship with joy, hence, there is an overlap between ‘emotional behaviour’ and ‘social behaviour’ codes as well as specific design aspects of the ‘BrainQuest design’ code.

Hero-Rustler Interactions – As expected from analysing the social behaviour, the elements of BrainQuest involving interaction with other children were found to be the most engaging aspects of the game across the entire data set (CC11 – Section 6.3.2.3, p. 229):

“What have you thought of BrainQuest over the last few weeks?” – Main Researcher, Observation Notes

“Good! The funniest bit is when Richard tries to chase me, that’s fun” – Bradly, Observation Notes

Children dedicated extra time and prioritized hero-rustler interactions, even if it negatively impacted achieving their long-term goal. There are 5 occurrences of observers having to tell pairs of players involved in a chase which ventured beyond their game boundaries, to return to their play spaces. It also appeared that player task choice was impacted by the prospect of engaging with other players (CC23 – Section 6.3.2.3, p. 229).

According to the design requirements, social interaction provides value for engagement and hot EF skills if it involves emotional regulation. BrainQuest appears to evoke a wide spectrum of emotion – there were 23 instances in the observation notes of children ‘laughing’ or ‘smiling’ during hero-rustler interactions. There were also several occasions where players adjusted the timing of their runs to coincide with the activities of an opponent or tried to provoke the opposition into chases because it was the most enjoyable activity – archetypal of ‘cognitively engaging PA’ (Chapter Two, Section 2.4.1, p. 57). This suggests the need to increase opportunities for direct social interaction in the other tasks beyond the ‘stop rustler’ but part of the fun may have been the element of ‘schadenfreude’ involved in impacting upon one’s opponent. Leonard, expressed his pleasure at being able to antagonize other players:

“When you tag someone, they get really mad and it’s funny. They don’t get mad at you, they just sort of laugh it off, it’s funny just to watch them lose the thing that they were trying to get” – Leonard, Interview

The data also suggested the inability to control intense emotions during hero-rustler interactions. There were 3 examples in the observation notes where arbitration from observers was required following arguments concerning hero-rustler interactions. In other occasions, an individual’s experience, mood or even approach to the game could be manipulated depending upon whom they were playing with. E.g., Maxwell was observed putting in a greater amount of effort while playing with his friends, Patrick stated he would have enjoyed the game more had he been playing with friends, and Ellen “*jumped for joy*” when she learned she was in a group with some friends. There were occurrences of children asking to play with their friends in the observation notes for nearly every session. This

assertion is emphasised by the comments of Ellen, who wanted a “*massive game*” which would have allowed for play with a greater variety of individuals.

Relationship Change – There were instances where relationships may have benefited from interacting with one another (CC14 – Section 6.3.2.3, p. 229), such as one relationship described by the PE and class teacher following the study:

“Have you noticed any social changes in the classroom in general or between certain individuals, such as new friendships or changes in the way the children communicate with each other over the course of the last 7 weeks?” – Main Researcher, Teacher Interview

“Victoria was finding life really tough in all of my lessons, not just when she was working with you. She was finding playing with people and against people very difficult. Towards the end (of BQ project), that week where she had a really good time in your lesson in the last week she has been excellent, so whether that is a result of this or a result of something else I don’t know but she definitely, in the last 2 or 3 weeks been much better and it kind of started off that last week when things went well in that lesson.” – PE Teacher, Teacher Interview

“Patrick is another one who I noticed did really well on your test but Patrick has been for years a bit ostracised by the rest of the class and again in the gym hall lessons where he’s had to play with people and against people, he’s been much more involved with the boys and girls and he’s got changed separately in a different room to all the rest of the boys for the whole of P7 but in the last couple of weeks he’s asked if he could go back in there and just get changed with them because he’s got no problems. So that has been 2 big coincidences that’s happened in these weeks and whether or not it is because he’s done really well in this.” – PE Teacher, Teacher Interview

“When we were out with the parents, he was really good at explaining to everybody and involving everybody in his group. He’s been ostracised by a lot of the class, but a lot of it has been self-inflicted and there is definitely a difference and he’s developed a wider circle of friends I would say outside. Maybe not playing the most appropriate games but if you ignore the wrestling, he’s playing with more people.” – Class Teacher, Teacher Interview

Social Consequences of Trophies, Leaderboard, and Level – Consistent with the design guidelines, the trophy and leaderboard eventually led to social interaction. There were 12 instances in the general observations and session reviews of groups of children comparing points and the leaderboard. Trophies also held a high social value and there were many incidents involving users conversing with each other and comparing trophy cabinets. There were 8 occurrences of trophy comparison conversations between specific children reported in the general observations and session reviews:

“Pedro has won a Legendary trophy and Bradly is envious but Leonard is impressed” – Main Researcher, General Observations

“He’s jammy” – Bradly, General Observations

“Just do every task, just keep going” – Richard, General Observations

“See Pedro went hero first so he’d get a trophy, I knew it” – Bradley, General Observations

“I’m only on Professional, I need to up my game” – Leonard, General Observation

This assertion was supported by Stevie who asked an observer to credit his account with a Legendary trophy in the event he failed to achieve a trophy.

The difficulty levels appeared to carry social kudos. There were 3 incidences of children discussing their current difficulty level and 3 children asked if they could skip ahead to higher difficulty levels before completing easier levels. On one occasion, Victoria, was removed from the session by the PE teacher after a tantrum because she was asked to first pass Rookie before levelling up:

“I don’t want to be just a Rookie”- Victoria, General Observations

Later in the study, however, Victoria had a change of heart regarding the Rookie level, at least publicly. She declared to an observer and the other players in her group:

“I like being a Rookie because it reminds me of club penguin and there is this cool guy called Rookie with a big hat and it spins round” – Victoria, General Observations

Cooperation - From the case study conclusions CC13 and CC12, cooperation was prevalent in the teaching of the game rules, game set up and sharing advice. Though less common, cooperation also appeared to occur during gameplay and within the wider data set and there were 3 instances where participants encouraged their peers. There was only one instance of tactical cooperation during gameplay (detailed in Angelina’s case study) and involved cooperation between a group of 3 girls in different roles, helping each other to maximise points. Hence, the lack of cooperative gameplay is likely to have limited one source of cognitively engaging PA and suggests the need for creating further opportunities in future design evaluations.

6.3.3.1.3 Physical Activity

Intensity – The game seemed to endorse a range of PA intensities (from low intensity walking to vigorous intensity sprinting) but varied between different games and individuals. A frequency analysis of the words used in DS4-DS7 found the word ‘running’ (or derivatives ‘run’ or ‘runs’) to be the 16th most frequently used word, 397 times, and the most frequent description of movement or PA. ‘Chasing’ (or derivatives) was the next most

frequently used word describing movement – 88 times. In contrast, the word walking (or derivatives) was used to describe participants 81 times in the study. This suggests that running was the most common form of PA undertaken but qualitative analysis alone is unable to draw any concrete conclusions concerning the levels of MVPA attained.

Notwithstanding, the PE teacher, who observed many of the sessions and even played the game with another colleague, provided an account of BrainQuest’s physical challenge which appears to support the presence of vigorous PA interspersed by lower intensity activity:

“They literally had to run as fast as they could and if you watch the kids play BrainQuest and I played it with the deputy head Bruce Murray last week so you know I was absolutely gutted because I was running as fast as I possibly could and it’s that thing again, it’s short bursts of physical activity and recovery as you get your breath back and I think anything that encourages vigorous activity is a good thing. I don’t know what happens afterwards because I always spill them back into Lynne’s class but that’s definitely a good offshoot of the game that it promotes very vigorous physical activity interspersed by bouts of recover.” – PE Teacher, Interview

Encouraging Low Physical Ability Individuals – There was a moderate correlation ($r=0.42$; $p<=0.05$) between mile time ranking and rustler shuttle runs per game, suggesting that a physical ability was important but not a total predictor of shuttle run performance and the likely PA exerted. However, there was no data to capture hero PA as there is no fixed distance covered per task. Furthermore, though there was a mean of 6.4 rustler shuttle runs per game, there is again no way of being able to draw any conclusions as to the intensity ‘shuttle runs’ were undertaken e.g. a user may have walked rather than ran during each ‘shuttle run’.

6.3.3.2 RQ2 – direct executive function

What evidence is there to suggest that the children experience EF challenge and improvement through playing BrainQuest?

Although many of the indirect pathways discussed in RQ1 are likely to have involved the challenge of a diverse range of EFs, this subsection presents the qualitative evidence and some additional descriptive quantitative data supporting the direct challenge of EF.

6.3.3.2.1 BrainQuest Challenge

Data Log Analysis (DS3) – The difficulty level system appeared to maintain the game challenge, though it was unclear to what extent this challenge maintained at the cusp of

ability. The initial challenge seemed the hardest – the mean number of failed games per participant were: 1.6 on Rookie, 1.0 on Professional, 0.2 on World Class, and 0.6 on Legendary difficulty. A loss percentage – the percentage of total games that were lost, is also applied to the difficulty levels: 63.6% on Rookie, 52.7% on Professional, 16.7% on World Class, and 50% on Legendary difficulty. In addition, only 10 children attempted Legendary difficulty level and 7 failed at least once. Hence, though the level of challenge may not have been maintained at the same intensity throughout each difficulty level, it remained to some degree throughout the entire study. Notwithstanding, the level of challenge appeared to increase on Legendary with the introduction of the task randomizer tool. This assertion regarding the level of challenge from World Class to Legendary was supported by the comments made by some of the children:

“I think there was once I forgot what ones I had done. It was when you swapped about the stuff, I kept thinking that it was like the normal one.” – Stevie, Interview

As discussed in the case study conclusion CC28 (Section 6.3.2.3, p. 229), most case study children could formulate and deploy low and high complexity strategies during the study. However, the case study children were not always able to implement their strategies successfully.

	Session 2 end	Session 3 end	Session 4 end	Session 5 end	Session 6 end	Session 7 end
Rookie	92.9%	67.9%	39.3%	21.4%	7.1%	10.7%
Professional	0%	14.3%	35.7%	42.9%	35.7%	14.3%
World Class	0%	0%	10.7%	10.7%	17.9%	21.4%
Legendary	0%	0%	0%	10.7%	21.4%	21.4%
Completed All Levels	0%	0%	0%	0%	0%	32.1%

Table 28: Difficulty Level Progression by Session

Table 28 shows how the children progressed through the levels of the game at each session. Session 1 (the ‘Test Game’) is not included because it was a practice session. It shows the % of children who finished each session on each difficulty level. Note that the totals do not sum to 100% because children who were absent at a session are not included in the total for that

session. By the end of the project, there was a wide variance in performance: 10.7% of the children were unable to progress past the first level, while 32.1% had managed to get to the most difficult level. This suggests that BrainQuest is playable by users with a wide range of ability levels but those at the lower end of the ability spectrum may benefit from extra support.

The change in game scores over time are shown in Figure 51. The graph shows the average number of points per session played by users in the role of hero over sessions 1 to 7. The graph demonstrates that scores improved over time but not linearly and that there was some variance in performance between players. There was a dip in performance between sessions 3 and 4, and there is a marked improvement between sessions 6 and 7. The performance drop can be explained by the withdrawal of game scaffolding between levels 1 and 2 (as shown in Table 28, around one-third of the children had reached level 2 by the end of Session 3). Observations suggest that the increase in points in session 7 is possibly due to users performing at higher levels who were now competent enough to take advantage of the combo bonuses which reward the user with multipliers of points for streaks of tasks performed without breaking the rules. This suggests the need for additional difficulty levels to cater to higher ability levels children.

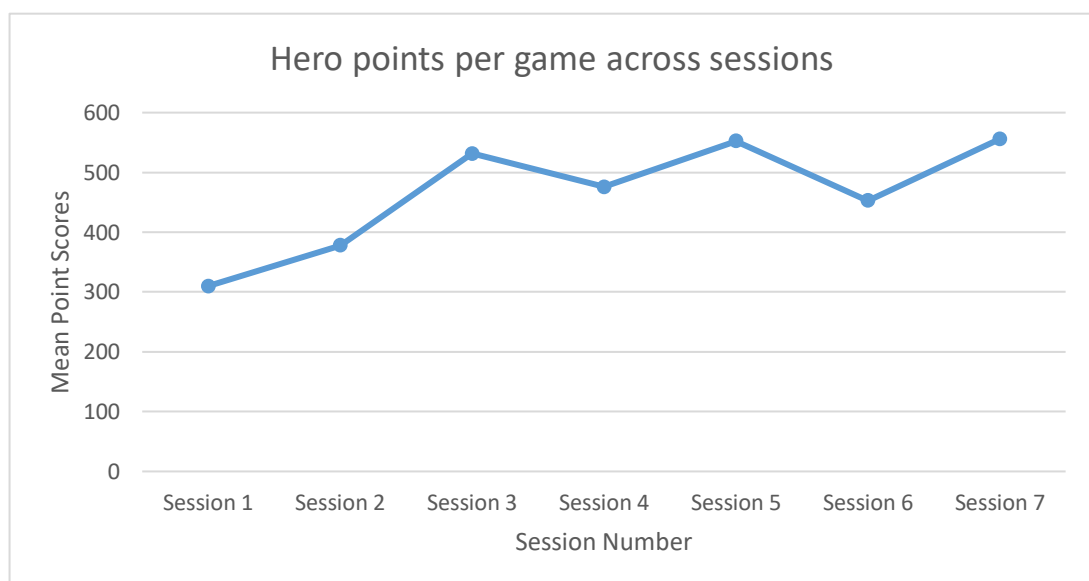


Figure 51: Hero points per game across sessions

Observation and Interview Analysis (DS4-DS7) – Referencing case study conclusion

CC18 (Section 6.3.2.3, p. 229), 5 case study children felt there was difference in challenge between the individual difficulty levels:

“On some of the ones [difficulty levels] where you could slide over and you could see what ones you could get, on the other ones it’s quite hard because you have to remember what ones you have done and what ones you haven’t” Stevie, Interview

Despite this, there was no consensus regarding the biggest challenge increase – 3 children reported World Class to be the biggest step up, contradicting the data, while 2 children found Legendary to be the biggest increase. It is worth noting, however, some of the case study children never reached World Class or Legendary difficulty and would not have experienced additional challenges.

Challenge went beyond the initial difficulty of learning the game rules, procedures, and technology (Learnability, Section 6.3.3.1.1.2, p. 241). For some, it appeared hard to remember previously completed tasks while attempting to pick a new task which conformed to the rules. There were several observations of children physically slowing down or stopping completely and taking time between the completion of one task and the start of a new one – hinting at the presence of cognitive challenge in choosing the next task, yet equivocal. Fortunately, case study conclusion CC21 (Section 6.3.2.3, p. 229) supports the assertion that the challenge was cognitive and may suggest difficulties relating to WM while making comparisons between a potential task, previous choices, and the task ordering rules.

Equally, challenge depended on individuals and some case study children could not discern any difference in challenge between levels (CC18 – Section 6.3.2.3, p. 229). Furthermore, 2 participants within the wider sample enquired as to whether any additional difficulty levels could be added before the end of the study. Melvin, who stated there to be no difficulty difference, was the first participant to complete the highest difficulty level and accelerated through the difficulty levels in continuous succession. Therefore, his appeared to be a genuine account of challenge but for others who claimed not to have been challenged, the data logs offered some contradiction – 2 of the 4 case studies making such claims did not advance to the final difficulty level.

6.3.3.2.2 Support Tools

Linked to both challenge and self-efficacy were the BrainQuest support tools. As the game is designed around increasing the difficulty of the EF challenge through support (and then subsequent withdrawal of support) from software tools (task shading tool and task history tool), it is useful to examine how these were used by the children.

The qualitative data across the entire data set suggested the children found the support tools useful but the task history tool appeared to be the most successful. This is supported by case study conclusions CC17 and CC19 (Section 6.3.2.3, p. 229), as 7 case study children stated using the task history tool. 6 children used it for reassurance while playing BrainQuest but this took different forms, requiring different degrees of support. For some, the task history was needed to help them choose the next task but for others the tool was used during the post-game feedback screen to review their performances. Moreover, 2 case study children used the task history tool > 9 times in each applicable game and for one individual, the tool was their favourite thing about the app. To the contrary, there were some problems with the task history tool. Two case study children reported not using it and some children who did use it encountered issues. Over the study sessions, general observations note 4 children requiring the tool to be further explained to them by a researcher. 4 children appeared confused regarding how to use the tool or had claimed to have forgotten about the tool at some point during game play. Hence, it may be a useful tool but it must be upgraded to be easier to understand and more apparent to users.

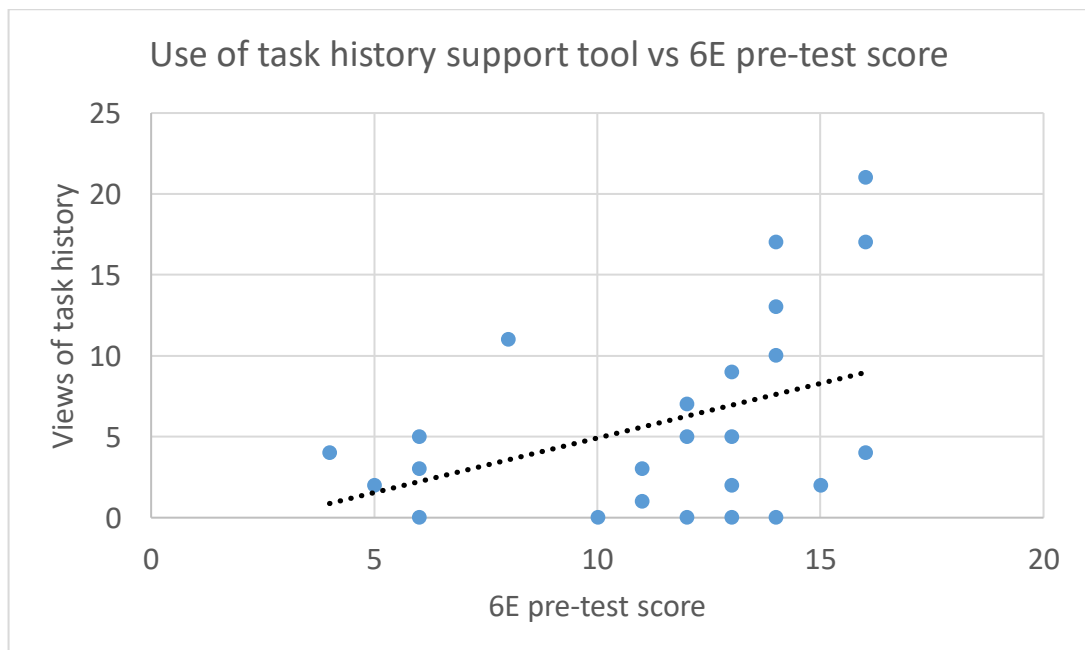


Figure 52: Use of task history vs 6E ability

According to additional data provided by the log files, users played a mean of 4.1 games in the role of hero where the tool was available ($SD = 1.1$). During these games, there were wide variations concerning the frequency of tool use (Mean = 5.3 views, $SD = 5.9$). A total of 5 children made no use of this feature. Tool use is plotted against initial 6E test scores in Figure 52. There was a moderate correlation between pre-test score and use of this support tool ($r = 0.41$) with a tendency for children with higher initial 6E scores to view the history more often. This could be explained by the fact that one of the skills measured by the 6E test is performance monitoring (Emslie et al., 2003) which implies that children who score well on this are better able to self-regulate by reflecting on their past performance.

7 case study children reported using the task shading tool but this may be of less significance because unlike the task history tool, which is an optional extra screen, the task shading tool is part of the task choice interface itself, therefore, inescapable. Supporting this, 2 case studies stated not using the task shading tool and another 2 case studies found the task shading tool to be too simplistic and they didn't require it:

"I think that would be really, really useful for if you are just starting but some people that know how to play it...I think that those people don't really need it" – Patrick, Interview.

Despite this, 3 children felt that the task shading tool would be useful for players beginning playing BrainQuest.

6.3.3.2.3 General Evidence of EF During Gameplay

As the EF codes required analysis to the level of advanced triangulation across data sources (DS1-DS7), the only concrete outcomes are provided by the case studies.

Working Memory – BrainQuest was designed to challenge WM by users having to store, manipulate and update task ordering rules, previously completed tasks, potential task choices, spatial and visual information about the game environment, previously successful strategies, and opponent information. Case study conclusion CC21 suggests the efficacy of the designed challenge. There were 5 examples from the interviews of case study children reporting memory challenges during particular difficulty levels and these could be triangulated with decreases in performance in data logs – when required to select a new task they struggled to “remember” which task they should pick next. In such games, these

children posted lower point scores and number of attempted tasks suggesting an increase in the amount of time spent while making decisions, and in other cases even mistakes.

Irrespective of the transfer to the 6E test, transfer of EFs to the real world is more important and although it was not the focus of the study, questions regarding transferral of BrainQuest performance to the real world were put to the class and PE teachers following the study. The class teachers hinted at potential benefits in concentration beyond the scope of the study:

“We always do our reading comprehension on a Thursday afterwards and I’ve found that they’ve been really switched on, which is great because I’m preparing for the testing but they’ve been really into what we’re doing and it’s not anything hugely exciting, just closed procedure things looking at different types of words and word endings and all the clues you can use and I’ve found they’ve been really focused and really switched on” – Class Teacher, Interview

“More than what they usually are?” – Main Researcher, Interview

“For that kind of activity I’d say” – Class Teacher, Interview

Inhibitory Control – The data analysis was unable to draw any conclusions regarding IC of attention because it was impossible to triangulate user direction of attention from observations alone following the failure of the video recording. Consequently, only IC of actions and emotions could be reported following triangulation of data logs, observations, and interviews.

The case studies (CC16) suggested the hero-rustler role as a challenge of inhibitory skills and there were 7 instances of case study children failing to regulate their emotions and becoming embroiled in arguments requiring observer arbitration. There was also a social influence on task choices and some children failed to follow the rules when presented with the temptation of chasing opponents – failure to inhibit actions.

Notwithstanding, the teachers described improvements in emotional regulation beyond the classroom – Victoria’s emotional regulation improvements are described in Section 6.3.3.1.2 (p. 243), while Melvin’s are outlined in his case study (Section 6.3.2, p. 213). Though these are the opinions of two teachers, it justifies the need for future exploration into any potential real-world benefits of BrainQuest.

Planning/Strategizing – Though there may have been some challenges to WM and IC in isolation, they were mostly challenged within the context of planning/strategizing to follow the task ordering rules. Some key findings from the case studies:

- Most case studies could generate a range of strategies which varied in complexity (CC22)
- BrainQuest forced the generation new strategies rather than allowing the repeated implementation of the same strategy in all games by changing the interface demands – 4.3 was the mean number of unique strategies generated by the case studies (CC24)
- Social factors were an influence on strategies deployed and affected task choice – 5 case study instances (CC23)
- Improvements in strategizing scores were seen on the BADS-C post-test following BrainQuest for 3 case studies, with one child deploying the same strategy which he had developed in BrainQuest but 3 other case studies failed to improve (CC28)

CC24 is particularly relevant to the novelty problem associated with many challenges of EF as well as the problems with many CTGs. BrainQuest appears to require the user to repeatedly invent novel strategies, rather than just refine or increase the speed of specific processes or increase the span of items to remember.

CC23 highlighted the influence of social factors on strategizing task choice. For example, the desire to implement stop rustler tasks appeared to lead to rule breaks, changes in strategy, and the adoption of more flexible and less structured strategies. However, it also endorsed the generation of additional strategies to govern playing style. E.g., Patrick developed a “*stealth*” style of play which involved deception of rustlers by “*pretending to do another task*”. Furthermore, Leonard timed his runs to coincide with specific opponents and hid animals from opponents to make them think his pen was empty. These results may be indicative of an emotionally affective hot EF factor on strategizing during BrainQuest gameplay.

Further suggesting the impact of hot EF on strategizing was the prevalence of cheating during gameplay, particularly during rustler roles. There were 3 games noted in the observations where rustlers continually ran through the middle of play spaces rather than around the perimeter (after having previously been corrected by observers) to trick the hero. Other ways of cheating included: rustlers collecting animals from the middle, rustlers running into other game spaces to escape, rustlers trying to hack buttons on the interface to allow them to earn extra points without having collected any animals. Fortunately, cheaters were held to account by other members of the group and reported to observers, yet scheming to achieve competitive advantage may suggest the rustler role be more cognitively engaging than first anticipated.

6.3.3.3 Software Issues

The types of bug encountered are listed in Table 29 in order of most to least serious:

Severity	Bug	Description	Occurrences	Fixes
High	Logging error bug	Occasional app crashes caused by uncaught logging exception	Occurred 9 times from Sessions 1-3	Long term – fixed from Session 4
Medium	Trophy bug	Attributed Rookie trophies to some children following their first rustler game and required the main researcher to reset trophy cabinets to display correctly allocated trophies	Occurred 5 times	Short term - main researcher reset trophy cabinets to display correctly allocated trophies Long term – fixed from Session 2
Medium	World class difficulty bug	Failure to award trophies for flawless performances caused by call to outdated method in source code	Occurred 2 times	Short term - Main researcher reset trophy cabinets to display correctly allocated trophies Long term – fixed from Session 3
Medium	Rustler points bug	Intermittent failure to allocate rustler points during some games encountering this	Affected 10% of participants per session from Sessions 1-3	Short term – a minimum number of points based on the number of shuttle runs recorded in the

		bug following each session		database compensated users following each session Long term – Fixed from session 4
Low	NFC software bug	Spontaneous inability to scan NFC tags native to Sony smartphones	Occurred 15 times	Short term - Fixed instantly by resetting the NFC system but a reoccurring issue

Table 29: Software Bugs

6.4 Study Discussion

6.4.1 Overview

This section presents the preliminary discussion of the 5-week school-based BrainQuest evaluation. This preliminary discussion revisits the research questions highlighted during this chapter, while the primary discussion of BrainQuest’s wider implications is reserved for Chapter Seven.

6.4.2 Learnability

BrainQuest appeared to be suitable for the clear majority of children in the target age group as all case studies could explain the game rules and 90% of children could follow the task ordering rules correctly at least once by the end of the study but there were signs that the children required a lot of support to be able to play the game in initial sessions. 3 children (10%) failed to pass even the first difficulty level. As the children had already received 3 additional tutorial sessions prior to the first data collection session, this suggests that any real-world implementation of the game may have to provide a lower floor in terms of beginner difficulty and facilitating the understanding the task ordering rules.

Furthermore, the additional misunderstandings caused by the rustler role may emphasise the difficulties of mastering two distinct and complex roles and their associated rules. Perhaps a future version of the game would also benefit from both heroes and rustlers having the same set of rules to undertake and limiting distinctions in character to within the in-game fantasy itself. Heroes and rustlers could undertake the same activities but the outcomes of their actions have different repercussions upon the game's interface.

6.4.3 Improving Support Tools

Given that 10% of the children did not get past level 1 in the game, BrainQuest would benefit from additional support tools to cater for children at the lower end of the ability spectrum.

Quantitative analysis suggested a disparity in how often the task history tool is viewed, with children with initially high EF viewing it more and users of the tool stating it would be useful for others to use. However, the results suggest that this support tool could be improved for those who felt their ability did not require its use or for those who forgot to use it. E.g., the task history could appear at the end of every game to prompt reflection on performance, rather than relying on the user to open it for themselves. An intermediate step between level 1 and the current level 2 might be to pop up a prompt immediately after every error to explain what the correct action should have been. Furthermore, several children had problems in understanding the feedback being presented to them, suggesting the need for data to be more clearly explained to the user and perhaps include a more detailed form of constructive feedback, rather than just green and red colours to indicate correct and incorrect tasks.

6.4.4 Indirect Pathways to EF Improvement

BrainQuest was usable and all participants reported enjoyment and fun from their experience with the game and especially trophy, leaderboard, difficulty levels, and sound/animation features. There is qualitative evidence from observations and interview that the nine case study children (who started the project with a range of EF abilities) had positive experiences relating to **fun and enjoyment** and **self-efficacy, pride, and confidence** – the indirect routes to EF which are proposed by Diamond (2013).

BrainQuest was designed to be a social experience and facilitate opportunities to foster **social belonging and support**, another indirect pathway of Diamond's model. BrainQuest appears to have been successful at involving this pathway, with observational evidence of cooperation and encouragement between individuals during the game. Not only did children cooperate with respect to learning how to play the game and the rules, but more commonly they shared strategic advice, encouraged and praised each other, and occasionally even disregarded the competitive design of the hero/rustler interaction with heroes and rustlers helping each other to earn points. In between games and following the sessions, children flocked together in groups to compare their achievements and discuss the game – consistent with the idea of building community. Additionally, there was some evidence of relationship change within and beyond the boundaries of the study, with self-reported and teacher-reported accounts of positive relationship changes between specific children and their peers. However, in some instances, the accounts of relationship change were unilateral and not reciprocated by another party.

Activities involving the hero/rustler interactions were the most important contributor to the provision of **fun and enjoyable** gameplay. In fact, these scenarios evoked these feelings in all children at every session and for many appeared to be an irresistible distraction at the expense of following task ordering rules – adding a challenge of emotional regulation (hot EF), in accordance with the design guidelines. Despite this, the hero/rustler interaction did have drawbacks which included being a source of arguments and misunderstandings and many children stated to have preferred to play with their friends. This suggested that the game may need to provide a greater variety and less constrained social interactions, giving children the option to interact with players within the context of a shared activity but not forcing them into confrontational situations.

The inclusion of trophies and leaderboards was another contributor to game enjoyment and bolstered long-term goal setting alternatives which was reflected in the limited, if any, novelty effects upon user engagement. However, there appeared to be the need to diversify and extend the choice of goals and sources of pride available to the user to foster long-term engagement and provide opportunities for further individual self-expression. The leaderboards, trophies, and even titles of the different difficulty levels provided further positive social consequences and were the catalyst for conversations between participants, as well as opportunities to connect with others regarding a shared activity.

Though trophies and leaderboards were sources of pride for many children, BrainQuest enabled individual self-expression through providing multiple roles; performance metrics;

and not constraining users to follow task ordering rules against their will, which allowed for niche goals to be set. Several individuals set goals for themselves, which emerged as another source of pride but should be officially recognized through the expansion of the reward system in future evolutions of the game.

Physical activity also emerged as a contributor to the enjoyment of the BrainQuest experience and increased feelings of self-efficacy or pride towards running for some children. Running was the most commonly used term to describe the PA undertaken in the game and, consistent with the design of the game, the chases were deemed by most children to be the most intense PA involved in the game. Moreover, coupled with the prevalence of strategizing and emotional regulation during gameplay, as well as the difficulties in learning the technology itself requiring coordination with real-world movement, BrainQuest appears to sponsor a form of ‘cognitively engaging PA’ (Diamond, 2015; Diamond, 2012; Best, 2010) – an EF promoting strategy itself. The significant and moderate/weak correlations between rustler role performance measures and mile time rank also suggested PA was a factor, though not a predictor, of some aspects of BrainQuest ability. Nevertheless, it remained unclear as to the intensity or total time spent in MVPA – something which must be addressed by accelerometer captured data. Additionally, perhaps too little emphasis was placed on rewarding PA in the game and this may have contributed to the disengagement or lack of effort of some children during these roles.

One small issue which affected user engagement and enjoyment of the game in early sessions were the game bugs. While these bugs rarely had a serious impact upon the playability of the game and were almost entirely fixed by the third game session, it does raise some important points for future cognitive training developers. Game reliability is a powerful force upon user enjoyment and marketable CTGs must be subjected to rigorous testing as consumers may be less forgiving and patient than the participants in this study.

6.4.5 Direct Pathways to EF Improvement

The quantitative and qualitative results both compliment and contrast with each other about BrainQuest’s ability to challenge and subsequently improve EF. Thus, consensus is required in several areas affecting BrainQuest’s direct pathway to EF. Firstly, relating to the observed correlation inconsistency between BrainQuest performance measures and BADS-C performance. Secondly, regarding BrainQuest’s observed level of EF challenge during

gameplay. Finally, concerning the efficacy of training following the lack of statistical evidence for universal BADS-C subtest improvement.

Making sense of correlations – As stated, there were moderate correlations between 6E performance (at pre- and post-test) and hero role performance measures which may validate BrainQuest’s challenge of similar EF skills. In other words, playing BrainQuest required the user to exercise some of the same EFs challenged by the 6E. But why are the correlations only moderate rather than strong or even perfect? And why does only the 6E correlate with hero performance measures?

These results illustrate the complexity of EF. BrainQuest performance may not correlate perfectly with the 6E nor any other BADS-C subtest because of the disparity between their context and content. Put simply, BrainQuest may challenge a greater number of EFs than any single subtest, and in a real-world rather than lab environment. BrainQuest performance integrates both hot and cool EFs in gameplay which may not translate directly from the paper-based cognitive assessments. Further illustrating this is the fact that the subtests themselves mostly fail to correlate with each other – in our dataset at pre-test, only the Playing Cards test significantly and moderately correlated with Zoo Map 2. There were no correlations at post-test. Hence, even assessments which supposedly overlap in EF skills fail in this regard and are likely the results of task impurity.

Each subtest challenges a specific combination of cognitive skills which together produce an end result – the sum of its parts. However, though these tasks share certain cognitive skills (e.g. working memory, inhibitory control, strategizing – like the 6E and BrainQuest), performance is usually compared with respect to end results and not isolated skills. This is the correct procedure because it reflects real-world functioning (we usually use multiple combinations of skills together) but also explains why tasks involving similar skills can produce grossly different outcomes. This is quintessential of the task impurity problem.

The BrainQuest rustler role also shared relationships with 6E and Key Search subtests. In general, this would indicate that the rustler role, though assumed to involve EF albeit without utilizing 6E task structure and rules, was far more EF-active than anticipated. There is no explicitly defined WM challenge (remembering task ordering rules for comparison possible task choices), no required inhibition of tempting task choices, and no scheduling of different task types within the time-limit. However, there are other EF challenges. For example, the strategic challenge of timing runs to maximize chances of evading capture, hot emotional regulation when interacting with the hero and other rustlers, switching between sustained and selective attention to track other player movements and concentrate on stealing animals,

cognitive flexibility to seize opportunities, and the motor cognitive coordination challenges of coordinating real-world and on-screen events. Some of these cognitive skills, i.e. the switching between sustained and selective attention as well as the cognitive flexibility, are involved in the 6E and may account for the correlation. However, the correlation with the pre-test Key Search is less clear given that it's not shared by the hero.

Finally, the correlations between BrainQuest performance measures and certain BADS-C subtests changed, to some extent, from pre-test to post-test – 4 BrainQuest performance measures correlated with the 6E at pre-test but only 2 correlated at post-test. Meanwhile, the rustler performance measure which correlated with Key Search pre-test did not correlate at post-test. There were also arbitrary correlations between performance measures and Playing Cards and Zoo Map 1 tests present at post-test which were not present at pre-test. The inconsistency of correlations coupled with the fact that no subtest managed to achieve perfect re-test reliability, may be indicative of a subtle change in the skills required by the BADS-C as novelty erodes. In other words, the tests themselves may become less sensitive to executive skills.

Direct EF challenge during gameplay – As the correlation between BrainQuest performance measures and BADS-C pre-test performance supports the theorized EF challenges involved in the game, it is important to understand how the challenge evolved throughout the evaluation and the extent task novelty was refreshed and sustained.

Only 9 children completed all difficulty levels so it appears there was at least some success in sustaining the game's challenge. The game also seemed to distinguish between different ability levels because the participants' final difficulty level achieved was spread across the game levels at the end of the project – e.g. rather than all participants reaching the highest level or all unable to progress beyond the first level.

However, as previously stated, to maintain the maximum challenge of EF, task novelty must be preserved to reduce automaticity and to keep the task at the cusp of one's ability. BrainQuest's capability of doing this, by altering task demands through variable difficulty levels, remains somewhat unclear. Self-reporting of the difficulty levels painted a varied picture. All participants reported BrainQuest getting easier over time and this may mean that the original novelty encountered during the learning of initial rules and technology was never sufficiently recaptured, despite the increasing difficulty. Conversely, the users who did report that the game was challenging from the perspective of the evolving rules cited the changes deployed at more advanced levels as the source of difficulty. This suggests the preservation of challenge beyond the scope of initial game learning. Therefore, there appears

to be multiple challenges involved in the game: (1) initial game rule (including the task ordering rules and the rules of play) and technology learning, (2) the variable challenge manipulated by the designer to disrupt pre-learned strategies for following the rules. The implications of the multiple, distinct challenges are discussed in greater detail in Chapter Seven but currently we are only concerned with understanding the variable challenge.

With regards to preserving challenge through the variable difficulty level, it would appear differences in challenge between each difficulty were not equal. Rookie and Professional difficulty levels had high rates of failure (failures/games played) but the number of failures substantially decreased by World Class level. Though this may be consistent with the initial rule and technology challenge narrative, following World Class difficulty, the level of challenge appeared again to increase at Legendary level. This implies the successful disruption of pre-learned user plans for following the task ordering rules. If this is the case, why was World Class difficulty level easier to complete?

Perhaps the ease of World Class difficulty was due to only minor changes in the task demands (simply removing the task history tool) in comparison to other difficulty transitions. The Rookie to Professional transition changes the way the interface presents tasks to the user through the shading tool, while World Class to Legendary does the same thing through the task randomizer. In contrast, the task history tool used in Professional is not intrinsically linked to the task selection screen and is a separately selectable screen, meaning that the children who did not use it were essentially attempting World Class difficulty. This further justifies the need for substantial changes in task demands to preserve challenge but also indicates that to do this in an incremental and consistent manner (congruent with motivational theories), technology designers must first understand the ways the technology is used – specifically, the interface in the case of BrainQuest.

The qualitative analysis of the case studies also supports the idea an evolving challenge in BrainQuest. This is demonstrated by the generation of novel and variable strategies by players to follow the task ordering rules as well as handling the social component of the game. These strategies varied in complexity and suitability depending on the difficulty level. Users were required to regularly re-plan and develop new strategies to overcome new difficulty levels, thereby, suggesting the maintenance of a novel challenge. This is critical to sustaining improvements in EF and is an aspect missing from many CTGs which seek to manipulate difficulty through decontextualized cognitive challenges, like list lengths and speed of processing.

In many cases, multiple strategies were employed, emphasising the dynamicity of BrainQuest in providing opportunities to utilize EF skills in response to an evolving challenge and avoid enabling users to simply refine a specific set of processes. Moreover, deploying multiple strategies, task ordering strategies and social strategies – e.g. hero/rustler interactions – during a single game is far more complex than that of the equivalent strategizing required on paper based 6E test and include the presence of both hot and cool EF. Hence, this may be one reason why only a limited number of case studies improved upon their strategizing ability during the post-test 6E – the context disparity may not be conducive for easy or near transfer. Alternatively, as displayed by one case study child, some children of high ability could follow task ordering rules without the need to deploy any strategies to assist their WM. Hence, with respect to the 6E test, it is unclear how strategies are affected by repeated measures rather than a new and novel activity – or an activity like BrainQuest which presents an evolving challenge. Consequently, future evaluations should concentrate upon when strategies are formed and how children decide upon what strategies to use, as well as providing an assessment of strategizing ability in the real-world situations.

The game also presents a third challenge (3) to emotional and regulatory skills during the hero-rustler social interactions and the case studies highlight the power of such challenges to affect both the ability to undertake strategies correctly and the choice of strategy itself. Despite this, whether increases in in-game performance relate to any benefits in the real world is an open question. The teachers who work with the children every day as well as one case study child suggested an improvement in relationships with peers and ability to regulate emotion for some specific participants following the study. Despite this, any concrete conclusions about benefits to real-world functioning and behaviour requires additional study. Future research should attempt to corroborate individual accounts with detailed qualitative data from parents and other sources in addition to real-world assessment questionnaires and, crucially, objective measures of real-world benefit such as test scores.

Addressing lack of universal BADS-C improvements – Though there were modest positive increases in all post-test BADS-C sub-test performance means, only the Water Test reached significance. This is perhaps surprising, given the significant retest improvements on Playing Cards and 6E tests in the BADS-C norms, despite no EF training intervention being applied. It would be reasonable to expect the test-retest statistics for the 6E to reach significance, if not greater significance in the BrainQuest evaluation than in the BADS-C norms, given the integration of 6E rules in BrainQuest’s design. However, there are several plausible explanations.

From a methodological standpoint, the lack of study power in both the published norms and the BrainQuest evaluation likely contributed to statistical inconsistency. As stated in Chapter Two (Section 2.3.3.3.2, p. 45), performing inferential statistics on small sample sizes can skew results both favourably and unfavourably. Furthermore, there were performance increases in all BADS-C subtests in the BrainQuest evaluation but the absence of statistical significance. However, this does not conclude the absence of an effect but simply means that we could not be >95% sure that the null hypothesis ('BrainQuest training does not improve BADS-C subtest performance') should be rejected for this sample. The same may not be true of another, better powered sample.

As suggested, novelty may also have been a factor on post-test performance. The BADS-C manual states, "*BADS-C tests are not novel when they are given for a second time*". Hence, the skills used in solving the various BADS-C challenges may subtly change when administering the test for the second time – perhaps no longer using purely executive skills. This novelty factor may have affected the BADS-C norm results more than the BrainQuest evaluation due to differences in duration between tests. E.g. the BADS-C norms quoted a 3-4-week duration between repeated testing, whereas in the BrainQuest evaluation there was a slightly longer 6-week period (Monday of Week 1 to Monday of Week 7).

Nevertheless, the lack of novelty may still have affected the BrainQuest evaluation – specifically the Water Test. It would be unwise to applaud the significant increases in this subtest as being a direct consequence of BrainQuest training. There are no BADS-C norms for comparison on this subtest so it is unclear whether these results are normal. The results themselves are almost unbelievable. An effect size of > 1 and a post-test mean which implies that participant average scores exceeded 9 marks (on a test marked out of 10), makes practice effects a plausible explanation. The Water Test is undoubtedly the most novel subtest within BADS-C and children may have remembered previous solutions, retrospectively planned a solution following pre-testing, and discussed suitable solutions with peers. Finally, there remains the question of transfer. The Water Test did not correlate with BrainQuest performance measures unlike the 6E which had a theoretical basis for skill overlap. Therefore, any significant improvements on the Water Test would be an example of far transfer; unlikely given that such gains were not observed on a theoretically related test (i.e. 6E). This issue is further examined in Chapter Seven (Section 7.3.2, p. 282).

An alternative explanation for the absence of significant improvements is training duration. The intervention may have not included enough training time to substantiate performance increases. The total mean number of games played (including hero and rustler roles) was

18.64. Considering each game was 5 minutes in length, each player averaged 93.2 minutes of actual in-play training time. This excludes the valuable time spent interacting between games but this is more likely to require hot EF skills anyway. 93.2 minutes is a fraction of the training time implemented by previous studies. The Lumosity RCT (Hardy et al., 2015) engaged their training group in a minimum of 15 minutes per session, 5 days a week, for 10 weeks – thus, the minimum training time totalled 750 minutes.

6.5 Summary

The results of the 5-week ‘feasibility’ evaluation of BrainQuest detailed in this chapter present a complex picture of efficacy. There is a great deal of general qualitative and some quantitative evidence to support BrainQuest’s hypothesized direct challenge of executive skills during gameplay. For example, the performance correlations observed between BrainQuest and cognitive assessments as well as the longitudinal observations of the 5-week evaluation. The latter also indicates BrainQuest has characteristics which indirectly support EF – the involvement of PA, encouraging positive social interactions, support for self-efficacy/pride/confidence, and fostering engagement. Furthermore, many of the case-study accounts of BrainQuest inspire further confidence in the game’s efficacy – particularly the qualitative evidence of strategy generation, an evolving and multi-faceted challenge for WM and IC skills (hot and cool), and the ability of the game to capture users’ engagement.

However, while BrainQuest may present a challenge of executive skills, it remains unclear whether it significantly improves general EF abilities. Most improvements observed from pre-test to post-test did not reach statistical significance even in the most closely related cognitive test and these results contradicted previous cognitive assessment norms.

Nevertheless, the lack of statistical power involved in both the BrainQuest evaluation and established norms, may have negatively impacted the results observed. Similarly, the test-retest suitability of the BADS-C is dubious at best.

Though, the contrast between the results is to be expected for a complex game undergoing initial feasibility evaluation, it is clear that substantial additional study is required before the game’s capabilities can be fully understood. For now, the results remain promising if not yet ‘game changing’.

7. Discussion

This chapter hosts the main discussion for the work presented in this thesis. It begins with a summary of the findings from the 5-week BrainQuest evaluation within the context of the Diamond (2012) model. The chapter then builds upon the preliminary discussion at the end of Chapter Six (Section 6.4, p. 256) by contemplating the broader implications of the findings for the field of cognitive training, as well as appraising the suitability of the deployed methodology. Next, reflection is drawn on previous stages of the BrainQuest journey by considering the design decisions as well as the relationship between BrainQuest and many of design requirements. Though limitations of the research are acknowledged throughout this chapter, it ends by identifying some technical and logistical lessons learned.

7.1 Reflections Upon Findings and Impact

7.1.1 Reviewing Findings within Diamond (2012) Model

The influence of Diamond's 2012 model of EF pathways in BrainQuest's design and its underpinning of the research questions justifies review following the evaluation results. This section presents a summary of how the final BrainQuest system implemented the defined pathways as well as how it can inform future CTG research.

7.1.1.1 Review of Finding for Each Pathway

BrainQuest's contribution towards fulfilling each pathway within the model requires review. There is evidence to suggest that BrainQuest in its current form positively impacts all pathways, consistent with requirement R1 and Diamond's (2012) model. However, the extent of its contribution must be further determined through additional study.

There is evidence to support the challenge of EFs, including high-level EFs involving several subcomponents, during BrainQuest gameplay. The evaluation findings are summarised in Table 30.

Pathway Type	Pathway Name	Findings
Builds EF Directly	General	<ul style="list-style-type: none"> Multiple BrainQuest performance measures significantly and moderately correlated with BADS-C performance, most notably on the 6E and Key Search subtests – the former having been an inspiration on BrainQuest’s structure and the envisaged EF skills targeted Though performance means increased in all 6 BADS-C subtests at post-test, only the Water Test reached statistical significance 6E improvements did not reach statistical significance
Builds EF Directly	Planning/Strategizing – <i>adapt to changed circumstances</i>	<ul style="list-style-type: none"> All case study children reported having to plan and strategize in the game. All case study children generated more than one strategy during the study and strategies often changed when attempting new difficulty levels involving changed user interface demands – thus, strategizing was novel rather than an incrementally refined process. Strategies varied in complexity and were influenced by changes in difficulty level, goal, previous success, and social factors. 6E post-test performance improved for 4 case studies, including 1 child who applied a BrainQuest generated strategy. 6E post-test performance remained the same as pre-test for 3 children and for 2 it got worse.
Builds EF Directly	Inhibitory Control – <i>remain disciplined</i>	<ul style="list-style-type: none"> BrainQuest appeared to create situations consistent with hot EF, involving the regulation of emotion in social interactions. Case study children identified situations in which they broke the rules to undertake a more appealing task or to interact with a specific individual – a challenge of hot IC. Players broke rules governing movement and task procedures during chases with peers – indicating a disciplinary challenge.
Builds EF Directly	Working Memory – <i>hold and manipulate</i>	<ul style="list-style-type: none"> Case study children reported having to hold and manipulate sequences of previously implemented tasks

	<i>complex sequences in WM</i>	<p>in mind while attempting to choose a new rule-adhering task.</p> <ul style="list-style-type: none"> • Case study children reported challenge in selecting tasks at specific difficulty levels, particularly the first and final difficulty levels – indicating the preservation of challenge to some extent. • For many case study children, increases in difficulty had an opposite effect upon points, further indicating challenge preservation. • 6 case study children made use of (and some were reliant on) the task history tool, suggesting the necessity of support in overcoming a challenge to WM skills. • Most children were unable to successfully complete every BrainQuest level before the end of the study, meaning that many were unable to accurately follow the task ordering rules in every game – indicating challenge.
Build EF Indirectly	Social Belonging	<ul style="list-style-type: none"> • Cooperation was fostered by learning game rules and exchanging strategic advice – interactions appeared to transcend friendship groups. • There were only limited instances of in-play cooperation and coordination of strategies. • Social community appeared to be fostered by the leaderboard and trophy systems, creating opportunities for children to communicate with each other. • BrainQuest enabled children of different physical and cognitive ability levels to play together for many sessions without any negative consequences. • Some limited evidence to suggest positive changes in social relationships beyond the scope of the study.
Build EF Indirectly	Joy	<ul style="list-style-type: none"> • All 9 case study children reported BrainQuest to be a fun and enjoyable experience, while general observations suggest this extended to the entire data set with positive recorded sentiments far outweighing negatives. • Interest in the game appeared to be maintained throughout the study with no perceivable novelty effects.

		<ul style="list-style-type: none"> • In nearly every session several children of mixed ability campaigned to play additional BrainQuest games. • Aspects of the game which involved social interactions seemed to most enjoyable, particularly the playground game style chases. • Achieving self-set goals created by the reward system was also a source of joy. • The sounds and graphics involved in the game were also deemed enjoyable.
Build EF Indirectly	Pride/Confidence/Self-Efficacy	<ul style="list-style-type: none"> • Users appeared to experience pride and confidence through progress towards their goals – in every session children publicly broadcasted achievements. • 7 case study children stated feeling “<i>pride</i>” in their trophy or leaderboard achievements. • Most case study children and the teachers also reported feelings of increased self-efficacy – towards physical ability, strategizing ability, and general mastery of the game.
Build EF Indirectly	PA	<ul style="list-style-type: none"> • Coupled with the evidence of EF and social skills and technology learning, BrainQuest characterized ‘cognitively engaging PA’. • Case study reports and observations suggest variable physical intensities within the game but most descriptions are consistent MVPA associated forms of PA. • Most case study children reported PA as positively contributing to the experience. • Observation notes most commonly described movement as “<i>running</i>”. • Physical ability was a factor in rustler success (low correlation between Mile Time and Rustler Points/Game ratio) but did not predict hero role success (no correlation with Trophy/Game or Hero Points/Game ratios)

Table 30: Findings Summary

7.1.1.2 Changes to Diamond (2012) Model

BrainQuest highlights how CTGs can be used to address the ‘indirect pathways’ of Diamond’s model as well as the ‘direct pathway’ traditionally attempted in CTGs. However, the structure and relationships of the indirect pathways may need to be redefined as, currently, the model is analogous to providing a list of ingredients rather than a recipe.

The category of ‘Increases Joy’ (Diamond, 2012) is somewhat ambiguous. There are several more common descriptions of the phenomenon being described – namely, creating a motivating and engaging activity, which will lead to greater programme adherence. Considering motivational theory paradigms, like SDT (Ryan & Deci, 2000; Deci & Ryan, 1985a), creating ‘joy’ is a product of competence, relatedness, and autonomy. Such an interpretation would, therefore, imply that joy is also a product of social belonging and confidence/pride/self-efficacy pathways. Autonomy (Ryan & Deci, 2000; Deci & Ryan, 1985a) is not present within the model and this is partly why its inclusion in BrainQuest is more limited. However, its greater role in future designs is one of the game changes outlined in Section 7.8 (p. 298). Alternatively, other models such as Lepper and Malone (1987) describe similar compositions of joy. Hence, the model would benefit from the integration of such theories.

‘Social belonging and support’ (Diamond, 2012) may be able to create feelings of competence and relatedness (Ryan & Deci, 2000; Deci & Ryan, 1985a) but as we know, situations requiring general regulation of emotions are also able to challenge our hot EF abilities (Kerr & Zelazo, 2004). Surely then, a variety of social situations both cooperative and potentially competitive may contribute to EF, rather than just socially supportive scenarios. Hence, perhaps a general social pathway would be more appropriate and best described as a ‘direct’ pathway to building EFs. Possibly the ‘directly builds EFs’ pathway should also be fractioned into hot and cool EFs to emphasise the importance of including both in any EF training interventions.

The ‘improves fitness’ (Diamond, 2012) pathway could also be made clearer by including a more specific description of the type and intensity of PA required to do this. Perhaps this could be changed to ‘contributing towards MVPA’. Also, cognitively engaging PA has been championed by some authors (Diamond, 2015; 2013; Best, 2010) as an even more effective means of contributing to cognition, meriting its inclusion in the model. Again, there is a debate to be had as to whether any PA pathway should be classed as indirect or direct in the way it builds EF. Moreover, the literature suggests the inclusion of social interactions during

PA are another means of providing cognitively engaging PA and the model should reflect this.

The model could benefit from including additional outcomes which relate to the indirect pathways, such as for social interaction (i.e. outcome = wider friendship group) and PA (i.e. outcome = improved team sports performance) outcomes. Furthermore, there are benefits to researchers by including suitable evaluation methodologies for each pathway in the model, such as the qualitative methods used in the BrainQuest evaluation.

7.1.2 Efficacy vs Effectiveness

Following the appeals of authors such as Melby-Lervåg et al. (2016), Mishra et al. (2016), and Moreau & Conway (2014) for fundamental CTG redesign, it was important to validate the novel approach taken by BrainQuest. Before contemplating the game's effectiveness, its efficacy had to first be established. Understanding whether BrainQuest presents a rigorous challenge to its hypothesized executive skills and contributing pathways (PA, social interaction, engagement, and self-efficacy) was essential before ascertaining potential real-world impact. Furthermore, echoing Morra & Borrella (2015), it had to be considered if BrainQuest could test the envisaged cognitive skills consistently over time rather than training users to become efficient at performing contextually specific processes. Hence, the likelihood of expecting skill transfer to different contexts.

This was required because some cognitive training studies have assumed the efficacy of their games prematurely, taking for granted the gamification of cognitive tests and WM tasks (i.e. N-Back, complex span) will consistently require the same skills with multiple exposures. This has resulted in a lack of far transfer. Though it is likely that gamified cognitive tests do challenge a similar set of executive skills, some have questioned (Mishra et al., 2016; Simons, 2016) whether they can present a sustained challenge over time, critical to ensuring both repeated improvements and the long-term engagement required to do so.

7.1.3 Adding Depth to Breadth

The work presented in this thesis underlines the promise of collaboration between its contributing disciplines: cognitive psychology; PA; and serious game design, for addressing mental and physical health through computer games. The results of BrainQuest's evaluation may be able to inform future cognitive training and exergame design. However, there is a

trade-off between the breadth and depth of the work presented. Though the findings support BrainQuest's promise as a vehicle for implementing Diamond's 2012 model, there remains the need to understand the true extent of effectiveness for each model pathway.

Establishing a deep understanding of the effectiveness of each pathway, especially the direct EF challenge pathway, will require additional study using more rigorous experimental designs. For example, greater study power, a wider range of cognitive assessments, methods less susceptible to practice effects, and activity-matched control groups. The work presented in this thesis offers many exploratory outcomes to guide future research. This chapter highlights many of these outcomes and makes suggestions for future work to be implemented by additional game developments and empirical evaluation.

7.2 Reviewing BrainQuest's EF Challenge

As discussed in Chapter Six (Section 6.4.5, p. 259), the challenge presented by BrainQuest was three-fold: (1) initial game rule and technology learning, (2) the variable challenge manipulated by the designer to disrupt pre-learned strategies for following the rules, (3) social challenge.

This section explores the challenges presented in BrainQuest in more detail and discusses the game's ability to preserve novelty, induce EF improvements, as well as attempting to ascertain alternative explanations for these improvements.

7.2.1 Initial Game Rule and Technology Challenge

During the UCD phase, the main researcher sought to utilize challenges (2) and (3) while minimizing challenge (1) from a usability perspective. Moreover, the iterative design process attempted to identify areas which could improve the usability of the game, including the game's task ordering rules and how to undertake each activity using the technology.

However, the evaluation of BrainQuest highlighted that difficulties in understanding the game rules and the technology persisted during initial study sessions and may have been one of the most challenging aspects of the game. Although case study accounts and general data suggest challenge can be preserved by disrupting previously successful task choice strategies (2) and social challenges (3), it is difficult to conclude whether challenge maintained EF skills at the cusp of a child's ability. Additionally, it would indicate the trajectory of

challenge did not increase linearly and relative to player skill as had been envisaged at the design phase. It appeared that some difficulty levels were substantially less challenging than others, and the initial difficulty levels were likely influenced by an additional novelty of (1) rules and technology.

The challenge of (1) initial game rules (task ordering rules and rules of play) and technology may have contributed to an inconsistent trajectory of challenge. Though these challenges

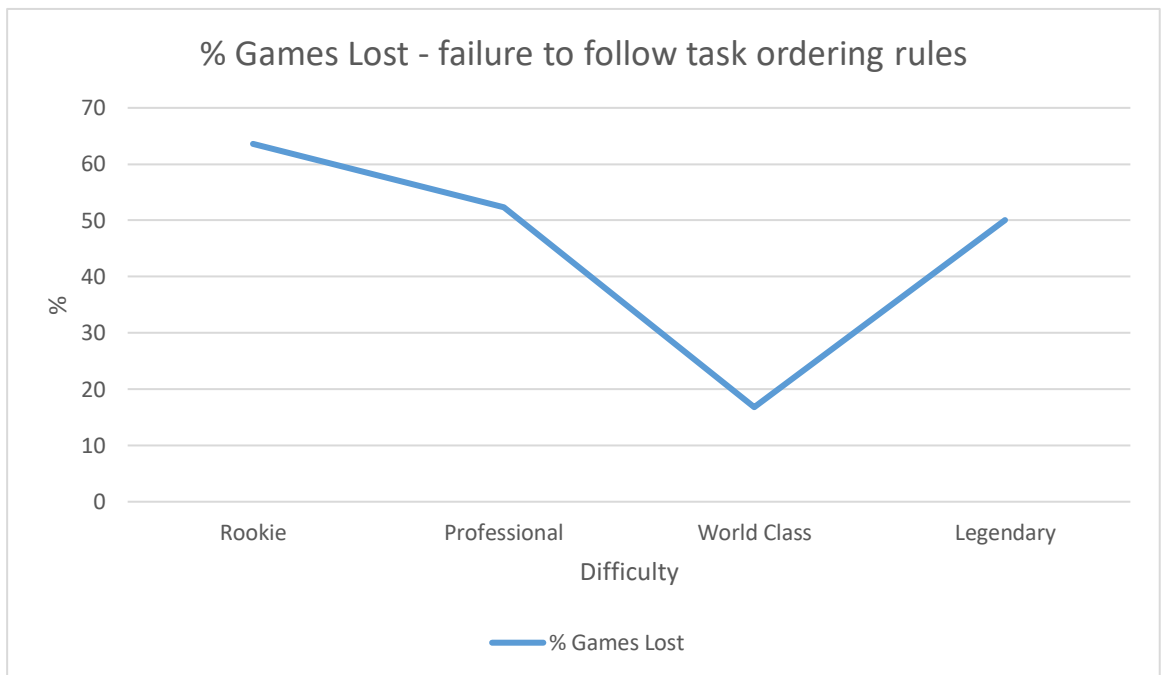


Figure 53: % Games lost on each difficulty

were most prevalent in early games and, unlike the interface, were not subject to changing demands, they were among the most novel aspects of the game. In addition, children in the study stated enjoying the game more as their understanding of the rules and procedures grew and some even derived pride from being able to understand the rules better. Consequently, understanding the rules and technology may be one of the challenges most likely to support feelings of competence.

It is also a crucial issue relating to task novelty. In the current BrainQuest version, following the mastery of the rules and technology, these aspects of the game never become novel again – as the rules remain the same throughout the game, as does the way in which one interacts with most aspects of the technology (excluding the task choice screen of the user interface). Therefore, this aspect of the game is a refined process rather than a test of underlying

cognitive skills. Future evolutions of the game should consider harnessing aspects of rule and technology understanding as an iterative cognitive challenge which demands should be incrementally changed like the task choice screen user interface to further preserve novelty.

Most relevant for change would be both the task ordering rules and the procedures governing the activity itself, which could be manipulated to create additionally novel and unforeseen challenges for children of high ability and a lower starting difficulty for less advanced players. E.g., advanced players who progress through the difficulty levels quickly may benefit from additional activities to be undertaken, new objectives to complete, and an increase in the task ordering rule complexity. On the contrary, less able children may benefit from initially simplified rule sets and further support tools. Furthermore, a separate issue is that of the different user roles, which each require complex sets of rules. Given the extent of the cognitive dimension of the rustler role, perhaps it would make sense to initially homogenize the user roles – giving the user a single set of complex rules and procedures to remember before introducing new examples.

Technology manipulation requires a little more finesse as (Rigby & Ryan, 2010) and the technology's controls should not distract from the experience (R24). In BrainQuest, though the user interface manipulation using the task tab shading and randomization actively attempted to support/obstruct the user's decision making, only the pictures of each activity were manipulated and not the game controls. Although making the controls harder is a risky strategy to manipulate challenge, making the user interface more easily learnable may be plausible for future iterations e.g. in game tutorials and walk through modes. This is generalizable to any serious game in the real world where technology experts are not present to troubleshoot or explain rules, where teachers are not confident in their understanding, or where children are in control of their own learning.

7.2.2 Planning and Strategizing Challenge

The evolution of strategies generated by the children and the plans deployed to undertake them are one of the most valuable contributions of the research presented in this thesis. These findings vindicate the BrainQuest's design as encouraging the generation of novel solutions to a changing problem, rather than simply facilitating trained efficiency of a single solution (repeated and contextually-specific cognitive processes) – the historical CTG pitfalls alluded to by authors such as Simons (2016), Morra & Borrella (2015) and Redick (2013).

As stated, the occurrences of strategy change coupled with the increase in failures on Legendary difficulty, as well as the reliance of many users on support tools, provides evidence for BrainQuest's ability to maintain novelty through an evolving challenge. For example, the strategies deployed by individuals often changed when attempting a new difficulty level or following failures, while becoming more complex and efficient following the implementation of a successful strategy.

However, were strategies increasingly complex and efficient for some children because of general improvements in strategizing ability or was it because they had simply become accustomed to the demands of the activity, thereby diminishing the novel challenge? In other words, how do we know novelty persisted? The key to this question may be points performance (the number of correct tasks undertaken). Had it been the former theory, one might expect points to remain consistent with previous attempts and indicate the maintenance of challenge, whereas the latter theory may be compatible with sizeable or incremental points increases. Most case study children were consistent with the former theory, while one high achieving child was consistent with the latter. Hence, the cause of increasing strategic sophistication may not be generalizable to the entire data set and this emphasises the need for future assessment of the skills challenged in BrainQuest beyond the scope of the game.

In future iterations of BrainQuest, further increasing the novelty of challenges may be beneficial. Though the demands of the task with respect to the user-interface and pre-learned strategies were incrementally changed, the rules remained the same throughout. As stated, future iterations should consider including incremental rule change or additional problems to solve to further refresh the novelty of the task. The greater the novelty of the task presented, the more valuable the evidence for changes in planning and strategizing abilities.

One shortcoming, is that strategies had to be defined manually during the analysis phase of the study and could only be determined for case studies. In keeping with the design requirement R5, it would be beneficial to automate the characterisation of strategies in real time to provide a more detailed snapshot of individual performance, the suitability of the deployed strategy for the current difficulty level/situation, to provide more informative feedback to the user, and as a basis for unique and additional rewards. Furthermore, being able to automatically discern strategies could be the basis for setting an appropriate level of challenge for players to maintain them at the cusp of their ability. E.g., one child in the BrainQuest study easily completed the different difficulty levels without the need for a complex strategy, suggesting that he was not being challenged enough. An automated

strategy analysis tool could be able to understand this and suggest a relevant difficulty level which the player would find difficult. Thus, it could make BrainQuest's challenge more closely tailorable to individual ability levels.

7.2.3 Social Challenge

Children stated challenge depending upon whom they were playing against which alludes to the dynamicity of that aspect of the game and its potential to create additional novel situations as well as the PA discussed later in the chapter. In addition, the social aspect of the game added a hot EF aspect to strategizing which authors, such as De Luca & Leventer (2008) and Kerr & Zelazo (2004), suggest is more representative of the real world. Some children were observed modifying a strategy while adhering to the task ordering rules to catch rustlers, while others broke the task ordering rules to do so. As noted in the design guidelines, the social challenge, likely to require a deal of IC and regulation of emotion, is very difficult for children of the user age group and able to promote character development.

In addition to influencing task ordering strategies, social challenges may have even been the catalyst for additional opponent-specific strategizing. E.g., adopting variable playing styles depending on the opponent faced and their characteristics. Coping with an opponent with greater physical ability may require additional strategy, such as keeping track of their movements and timing runs to one's advantage i.e. while a rustler is stationary and attempting to steal cattle rather than a moving target. There were some limited examples of such behaviour but there were no explicit accounts of opponent-specific strategizing. However, future analysis of such behaviour would be useful for further study because it relates to the literature. Such behaviour adds an additional dimension to the cognitive skills involved in the game as it requires the use of long-term memory (storing and retrieving characteristics of opponents) in addition to the existing short-term memory (task ordering rule) and attentional control (multiple competing stimuli) challenges. In the literature, Unsworth et al. (2014) suggested all 3 distinct processes were critical mediators of fluid intelligence. Hence, if prevalent, this would support BrainQuest's challenge of high-level cognitive skills.

Unfortunately, there is no automated mechanism for capturing social challenges in real time and they could only be noted by observation. For those who modified their strategies to catch a rustler, there may have been situations where opting to do such a task may have been beneficial, such as stopping a nearby rustler. Therefore, an automated way of being able to

track player proximities and speeds may help to identify appropriate situations to catch rustlers and interrupt a strategy. Alternatively, an automated system may be able to look at frequencies of chosen tasks to see how often a user chooses to interact with others and whether they do so in contravention of the task ordering rules.

Moreover, inspired by the work of Green et al. (2012, 2015) and the cognitive challenges of action video games (R11), BrainQuest incorporated a dynamic task (Stop Rustler). This included multiple moving objects in addition to static animals and props, thus, requiring switching between sustained and selective attention. Unfortunately, the observational methods alone were unable to draw consensus upon the patterns nor ability of attention displayed by users. However, automated measures using technology may be able to help understand or even measure attention, utilizing eye tracking technology to capture what the user is focusing on – their environment, opposing players, props or the mobile phone screen, and for how long.

Nevertheless, it may be impossible for an automated system to understand, reward or punish user behaviour during challenges of emotional regulation because the nature of emotions may only be captured through triangulating real-time observations and user self-reflections. Hence, generalizable to other CTGs: though it may be possible to challenge hot EF, measuring performance is fraught with obstacles. Retrospectively, this may be the reason why many CTGs avoid hot EF altogether.

7.3 Assessment of EF in BrainQuest

7.3.1 Suitability of Methodology

7.3.1.1 Advantages of Process vs Outcome

The mixed methods, longitudinal approach used to triangulate multiple data sources captured the challenge and evolution of EF skills in previously unseen detail with respect to CTG studies. Several studies (i.e. Hardy et al. 2015; Anguera et al., 2013; Jaeggi et al., 2008) provide experimental designs with emphasis on statistical analysis of cognitive assessments, allowing for concrete conclusions to be drawn regarding CTG effectiveness.. However, focusing on outcome measures allows little insight into the process of change during training.

Instead, focusing on the process of change may help to understand relationships between CTGs and their cognitive challenges, explain outcomes, and skill transfer likelihood. If there

is no evidence of far transfer (as in nearly every CTG study to date) observed following training, we can reflect on the process by triangulating multiple data sources to consider why this is – i.e. context or content specificities, a change in the skills trained during the intervention, unforeseen challenges. Equally, positive evidence of far transfer can be understood – i.e. contributions of the game design and social challenges or how skills emerge. Hence, the process is critical to understanding the contribution of CTGs and explaining phenomena rather than arbitrary reporting of cognitive assessment performance under the assumption such outcomes impact real-world functioning.

In complex and novel projects like BrainQuest, understanding training processes are fundamental to assessing the feasibility of the approach. BrainQuest integrated multiple EF training methods (PA, social, motivational design) – and the efficacy of each pathway and the user experience could not be assumed without observation. Hence, evaluating the process allowed consideration of the strengths and weaknesses of the design and the suitability of each of Diamond’s pathways which may influence future game refinements and evaluation methodology. Consequently, methodologies such as the one described in this thesis may be more suitable than traditional approaches for the exploratory study of CTGs.

7.3.1.2 Qualitative Difficulties

Much like the difficulty in untangling individual EF subcomponents using quantitative measures alone, the intrinsic relationship of EF subcomponents was also hard to unpick by qualitative approaches. The observations were littered with situations in which participants stood still, glued to the phone interface in-between task choices, yet it was impossible to know whether EF was being challenged during these situations, let alone what the challenge(s) were. Did it signal a problem with WM in remembering the previously implemented task? Was the user able to remember previous tasks but was, in fact, planning the most efficient series of tasks to implement next? Was more than one skill being tested at once? Notwithstanding, there are potential solutions to such problems, such as using reviewing video footage with user commentary to allow the nature of observations to be defined.

While the ability to use a mixed methods approach to triangulate data from different sources can help to understand which EF(s) are being used, given the intrinsic nature and impurity of EF in real-world domains, it is likely many EFs are being utilized at once in any given situation. It is likely, particularly with higher order EFs like planning and strategizing, that

there is lower level involvement of WM and attention. Similarly, the close relationship between WM and attention (under the umbrella of IC), means that observation one is likely to involve the other (Diamond, 2013). Hence, while user commentary may characterize EF activity, isolating contributing EFs and understanding the relationships between them may be impossible without neuroimaging.

Like several studies referenced in the literature review which measure a variety of EF aspects but may only find significant effects with respect to certain aspects of EF (e.g. Hardy et al., 2015; Anguera et al., 2013), the study presented in this thesis concentrates most closely on planning/strategizing ability (referred to as ‘strategizing’ throughout). This is not to suggest that planning/strategizing is the only EF skill challenged by BrainQuest given the role of lower level EFs in these skills – planning/strategizing involves WM and attention. Instead, it is the construct which we have most evidence to evaluate through the triangulation of data sources and it is not isolated, meaning it may more closely resemble real-world ability. In addition, there are some conclusions regarding how BrainQuest may provide WM and IC challenge including and beyond planning and strategizing situations.

Conclusions regarding WM and IC could only be drawn through triangulation between qualitative data sources and the data logs for the case studies. Unfortunately, this level of detail was infeasible to be reported over the entire data set as it requires complex and time-consuming comparisons. Consequently, without having as a fine-grained a level of detail, the raters found it difficult to interpret events in the same way. Exacerbating the problem of inter-rater reliability were semantic differences and different coding styles. E.g., where one rater may have coded a full sentence, another may have coded a phrase. Hence, a lesson for future researchers is not only to develop a coding scheme but to also develop a common coding methodology.

Another shortcoming is that qualitative analysis does not extend beyond the scope of BrainQuest itself and attempt to draw conclusions regarding any transfer of the skills challenged in the game to real-world functioning. However, this is an issue of effectiveness and, therefore, beyond the scope of the feasibility goals of the 5-week evaluation.

7.3.1.3 Quantitative Caution

Though the mixed methods approach, making use of both quantitative and qualitative data enabled a more detailed analysis of BrainQuest’s feasibility, there remain drawbacks with the statistics employed. Firstly, as highlighted by the work of Robertson & Kaptein (2016)

presented in Chapter Two (Section 2.3.3.3, p. 43), one should be circumspect regarding reported performance changes of underpowered samples. The BrainQuest evaluation was itself underpowered due to this being an explorative study to understand feasibility and the results significantly contrasted with the equally underpowered BADS-C reported norms. Thus, highlighting the impact underpowered samples can have on results. Future studies seeking to evaluate outcome measures will need to recruit more participants.

Future studies which place greater importance on analysis of outcome measures will also require a suitable control. Redick (2013) and Shipstead et al. (2012) are among the authors who outlined the problems of CTG study control groups to be mitigated. Though important, it is not enough for control groups to be active rather than non-contact, they must also be well matched in terms of their cognitive challenge. Potential control activities would likely change depending on the research questions. E.g., to compare the effective cognitive effects, BrainQuest could be compared to alternative activities able to present a plausible training placebo or even other training methodologies. Furthermore, given the complexity of the BrainQuest model and the importance of user engagement, there is an argument for collecting more than just cognitive assessment outcome measures. E.g. comparison of the engagement value of the digital version of the game as opposed to a non-digital alternative (like the UCD session in Chapter Five).

7.3.1.4 BADS-C Suitability

In the literature review, several qualities of the BADS-C were highlighted as reasons for its involvement in the BrainQuest research project. To recap, the assessment battery is heavily influenced by some of the key EF models which have also inspired BrainQuest, like the Central Executive (1974) and the Supervisory Attentional System (1982). With respect to BrainQuest's design, BADS-C provided a series of subtests which seek to preserve the interconnected nature of EFs rather than attempting to isolate any one function. This is illustrated in Table 31, which presents the visible overlap between executive skills. In theory, this makes BADS-C subtests ecologically valid and representative of real-world functioning and this was a key attraction of integrating the structure and rules of the 6E test into BrainQuest's design. It seemed reasonable to use the BADS-C in the BrainQuest evaluation, given the similarities with the 6E. Doing so enabled validation of the challenge of EF skills in BrainQuest, as well as tentative contemplation of training transfer to both near (6E) and far (other BADS-C subtests) environments. However, as discussed in Section 7.3.2 (p. 283), assumptions of transfer scope may have been more complex than originally imagined.

Moreover, the BADS-C was deemed a suitable cognitive test as it was geared towards children and testers could also gather structured qualitative data to provide accounts of how children attempted the different subtests. This last part proved important in the case study results of the BrainQuest evaluation as it allowed comparison between how the children approached the 6E and their approach to the game.

All things considered, the reasons for using the BADS-C were justified to validate BrainQuest's EF challenge within the context of the feasibility study presented. However, future studies should consider the use of more reliable cognitive tests, such as the CANTAB battery (CANTAB, 2017) which, unlike the BADS-C, is less susceptible to the obvious practice effects encountered in the BrainQuest evaluation. Nevertheless, more reliable tests tend to limit novelty and are, according to authors like Kenworthy et al. (2008), Burgess et al. (2006), and White et al. (2009), 'constrained' rather than 'open-ended'. Thus, they lack the same ecological validity. Nevertheless, by triangulation of multiple measures of EF, a more representative picture of real-world functioning is achievable.

The BADS-C's subtests overlap in terms of the executive skills used and provided multiple means of measuring certain EF constructs – something Makin (2016) and Redick (2013) state to be conspicuously absent in many CTG studies. However, it also highlighted that the task impurity of multiple measures may lead to inconsistent results. In Table 31, the 6E and Zoo Map 2 both involve flexibility and perseveration as well as using feedback. However, BrainQuest performance measures only correlated with the 6E test. Further, the 6E test and Zoo Map 2 scores did not correlate with each other either despite theoretically involving similar processes.

Finally, as an aside, the makers of BADS-C should consider re-establishing new test-retest norms with a larger sample, following some of the stark contrasts between their norms and the results reported in this thesis. They may also wish to understand whether repeated administration of the BADS-C can ever be feasibly implemented while providing an accurate portrayal of EF skills. Can they recommend a minimum duration between administrations or does the BADS-C never fully recapture its novelty? This dubiety is cause for concern when attempting to draw meaningful statistical inferences regarding EF performance changes and the reason why future BrainQuest studies will likely use different testing batteries.

	Flexibility and Perseveration	Novel Problem Solving	Sequencing	Using Feedback	Planning	Impulsivity	Following Instructions
Playing Cards	*						
Water Test	*	*	*	*			
Key Search Test		*		*	*	*	
Zoo Map 1		*	*	*	*	*	
Zoo Map 2	*			*		*	*
6E	*			*	*		

Table 31: EF Skills and Subtests from BADS-C Manual

7.3.2 Transfer

As stated earlier, the focus of the study was on the efficacy of BrainQuest and understanding whether gameplay could sustain EF challenge in the way it was intended. Hence, only capturing some limited picture of potential transfer of improvements to other tasks, was deemed appropriate for the work presented in this thesis. Nonetheless, the transferal of skills is a fundamental issue of CTGs and, therefore, any early findings merit proper discussion.

Previously discussed in Chapter Six, the statistical relationship between BrainQuest and the BADS-C was mixed. BrainQuest appears to pose a challenge to executive skills, as highlighted by the significant and moderate correlations between 6E and Key Test performance and multiple game performance measures. However, it is unclear if BrainQuest can improve underlying, generalizable EF abilities. Though there were improvements at post-test for all BADS-C subtests, performance only reached statistical significance for the Water Test. Furthermore, the BADS-C norms noted significant retest performance increases in both the 6E and Rule Shift Card despite no training intervention being applied. The lack of significant 6E performance gains was surprising, given its close relationship with the structure and rules of BrainQuest.

This subsection seeks to understand the disparity between BrainQuest and the 6E test performance and account for the limited transfer observed.

7.3.3.1 Comparison with 6E Test

The biggest difference between BrainQuest and the 6E is the requirement of hot EF in the game. Hot EF, specifically emotional regulation, is most notable in hero-rustler interactions. E.g., heroes who are unable to inhibit the desire to chase and catch opponents are more likely to break the task ordering rules. Similarly, when surrendering stolen animals, rustlers may have to suppress their irritation at having been denied extra points. The results support this by the prevalence of arguments regarding whether the rustler was caught. Furthermore, the social implications of motivational phenomena (i.e. the leaderboard, trophies, or self-constructed social goals) were only present in BrainQuest and may have influenced a user's approach.

There are also user interface differences – the way task choice is presented to the user which may affect their approach to each activity. E.g., in BrainQuest, following the completion of an instance of one task, the user is returned to the task choice screen where they are again presented with the range of 6 possible task choice alternative thumbnails. In the 6E, by contrast, the choices of different tasks always remain visible as the task types are placed horizontally on the desk and they may do as many instances as they like of one task in succession before changing task type. This difference in task demands may also change the way they approach the 6E test in comparison to BrainQuest and can even allow for additional strategies e.g. doing an equal number of instances of each task type.

In addition, there are a greater number of procedural rules in BrainQuest compared to the 6E test. E.g. there are multiple procedures involved within one instance of a task, each including additional rules regarding how to carry out each procedure: i.e. to return a cow, the user must (1) pick up a cow from the play space and scan the tag, (2) return to the hero cow pen and scan the pen to open it, (3) place the cow in the pen. In addition, there is another set of rules for the rustler role to remember, with respect to the user interface (i.e. there are a range of alternative buttons to press depending upon whether the hero pen is full or empty, and a button to press if caught by the hero) as well as the rules governing movement and interaction (i.e. run around the outside of the play space and run in a single direction). Players may also have to work with items from long-term memory, such as previously successful strategies or opponent characteristics. Thus, understanding the rules of BrainQuest is potentially a much greater task and the challenge to WM in coordinating different information may be much more complex.

7.3.3.2 BrainQuest: Near or Far Transfer

As outlined in the literature review, the effectiveness of CTGs can be judged on their ability to provide the transfer of cognitive skills to situations beyond the scope of training. ‘Near transfer’ considers post-training performance on an untrained task involving the same skills as the training activity in a similar context (i.e. WM training leads to improvements on a WM test) (Simons, 2016). ‘Far transfer’ considers post-training performance on untrained tasks in a different context and/or different or more complex content (i.e. WM training leads to improvements on a fluid intelligence test) (Simons, 2016). However, transfer can often be hard to categorize by these definitions alone and what may initially be considered a similar context can be further removed than first thought. Hence, in practice sometimes a judgement call must be made.

Transfer between BrainQuest and the 6E appears, superficially, to be an example of near transfer – BrainQuest is designed to train many of the same EFs present in the 6E test and is integrated with the rules of the test itself. Many task choice strategies are applicable to both BrainQuest and the 6E. However, unlike gamified CTGs, the cognitive assessment rules and structure only form one aspect of BrainQuest. Instead, BrainQuest challenges additional EF skills, most notably hot EF inhibitory skills, motor control (due to the involvement of PA) and additional demands on WM. Furthermore, the context of BrainQuest is far removed. The activity is performed as a physically active game in the real world which involves social interaction and motivation factors. Therefore, any transfer observed between BrainQuest and the 6E may, in fact, be far and any transfer between BrainQuest and the other BADS-C subtests is undoubtedly far.

7.3.3.3 Explaining Transfer Observed

The correlation between BrainQuest performance measures and the 6E test, especially at pre-test, suggested the challenge of similar EF skills in the game. The qualitative data from the case studies gave reason to believe that the key EF impact of BrainQuest could be on planning/strategizing abilities of the participants as all case study participants generated many different plans of increasing complexity to follow task ordering rules. Compounding this was the fact that 4 of the 9 case studies were unable to strategize on the pre-test 6E test but developed strategies and plans in BrainQuest.

However, post-test 6E transfer was narrow, if present at all. There were improvements in 6E sample means but not enough to achieve statistical significance while the case studies did little to clarify why improvements were so limited. Only 3 children improved their 6E strategy scores from pre-test to post-test while 2 of these children had already strategized, though with less complexity, at pre-test. Meanwhile, 3 children recorded the same 6E 'strategy scores' from pre-to post-test, though one child was at the ceiling, and 3 children did not strategize at all despite being able to do so in BrainQuest. Only one of the children who improved their 6E strategy, Stevie, utilized a post-strategy which had been generated during BrainQuest play and not present in the pre-test 6E. This shows that direct transfer of strategy can be achieved but questions remain as to why for many case study children no transfer was observed, perhaps surprising given rule strategy was the closest aspect of BrainQuest to the 6E.

Firstly, it is hard to tell by the results of one task. As stated in the literature review, assessment of change in cognitive constructs should be correlated with multiple tests of the same construct due to the interconnected nature of EFs and cognition in general. Ability level may also have been a factor. As we saw in BrainQuest, some children were unable to complete all difficulty levels and the 6E test is comparable to World Class level of BrainQuest in terms of task ordering rule support. Hence, for children who were unable to complete or form successful strategies at this level, it may be unrealistic to expect them to be able to implement similar strategies on the 6E test at a comparable difficulty. Similarly, some children, including 5 case studies demonstrated the ability to follow the task ordering rules of BrainQuest at World Class difficulty or above. On the contrary, it could be that these children did not require a strategy because they felt themselves able to follow the rules without one.

It should also be noted that the emergence of strategies and complexity was observed over several sessions in BrainQuest whereas the 6E test was only performed twice and many weeks apart. Thus, the emergence of 6E strategies for some children may have been observed with additional attempts. However, does this then imply that children refine a specific set of processes in BrainQuest or is it that their underlying strategizing ability improves? A lack of transfer may indicate the former and this questions the sustainability of BrainQuest's novel challenge, at least with respect to the rules.

Alternatively, there may be a developmental component. It may be that children of this age do not possess the cognitive flexibility to recognize problems which may be solved by applying a previously successful strategy to a similar, if contextually different, problem.

Hence, they may attempt to solve the problem from scratch, which would benefit from increased strategizing ability but not necessarily be approached in a similar manner.

As discussed, BrainQuest was integrated with 6E task ordering rules rather than simply a gamified translation, there are many differences between the two, such as the dynamicity of BrainQuest tasks; the requirement of hot EF the game design theory at the core of the game; the difference in which alternative tasks are presented through the user interface; the time taken to complete one task; and the PA component. Hence, there is a significant disparity between the content of each activity.

The social implications (i.e. the leaderboard, trophies, or self-constructed social goals) of the game may have influenced strategizing performance. I.e., Melvin performed a complex strategy during his first game but following this simplified his strategy for a series of games, yet he accumulated more points than anyone else and completed all the difficulty levels. Only after completing all difficulty levels and setting a target of earning over 10,000 points, did he re-implement a series of complex strategies and broke personal point scoring records consecutively. By comparison, he could follow the task ordering rules correctly in BrainQuest at both pre-and post-test but did not implement any sort of strategy.

This observation raises some questions as to when strategizing is applicable. Do people strategize only in challenging situations or situations when they attempting to maximize performance? Such conclusions would be consistent with the types of situations typically associated with executive functioning. If the 6E does not challenge WM to the cusp of ability in selecting tasks and following the rules, a child may not need to formulate a strategy to follow the rules. Therefore, they would not be attributed any strategy points. However, being able to follow the rules without a strategy may not necessarily mean they are less competent. In some case studies, this may be one explanation for the absence of strategy transfer from BrainQuest to the post-test 6E.

Further study is required to ascertain the transfer of hot EF skills. Hot EF skills evoked by the game's social contexts could not be assessed by the BADS-C test. However, the variety of the social interactions involved, such as interacting with friends, rivals, and peers, may be one of the best opportunities for learning in the game. There is less contextual disparity between the social interactions involved in BrainQuest and those experienced by the children in other aspects of daily school life – playground games, communication in the classroom. As documented in this chapter, there was some limited evidence to support relationship change and behaviour change beyond the scope of the study for certain individuals but further study is needed to determine hot EF outcomes in greater detail.

In summary, BrainQuest appears to be further removed from the 6E than initially anticipated, a fact further highlighted by the existence of only a medium correlation between 6E and BrainQuest performance. Consequently, perhaps any transfer between BrainQuest and the 6E test is not an example of ‘near transfer’ at all but is, in fact, an example of ‘far transfer’. Thus, requiring subtly different combinations of EF skills.

7.4 BrainQuest: A Blueprint for Engaging User Experiences?

As informed by the design guidelines, to create more engaging experiences CTGs should move away from traditional methods of the pure gamification of cognitive assessments and embrace mainstream game design principles at the core of their design. This part of the chapter discusses the extent which BrainQuest did this.

7.4.1 Sustaining Engagement

As described in Chapter Six (Section 6.4, p. 256), BrainQuest did not appear to suffer from a noticeable engagement novelty factor, a particularly detrimental force upon serious games in general (Macvean & Robertson, 2013; 2012). Instead, most children even seemed to enjoy playing BrainQuest more at the end than at the start of the study. This may indicate the successful integration of motivational design principles in maintaining user engagement, consistent with design requirements R18 and R19. Alternatively, it may be that 8 game sessions were not enough time to uncover a decrease in engagement. E.g., within those 8 sessions, time constraints only enabled children to use BrainQuest for 30 minutes. This means that many children who set goals of winning all trophies may not have reached their goal by the end of the study and, therefore, it is unclear whether they would continue to play the game without any other goals to achieve.

On the topic of goal setting more generally, as stated in Section 7.4.2 (p. 288), trophies and leaderboards sponsored such phenomena. However, the results highlight that some children conceived their own goals or select less obvious goals, e.g. one child attempted to be the best rustler in the game. Consequently, in sustaining user engagement future versions of BrainQuest should provide a diverse range of goals from which the user may be able to choose and attempt to motivate the user by helping the user to track their progress. Such

goals may benefit from being intrinsic to the fantasy e.g. instead of setting a goal to ‘achieve most rustler points’, it may be more suitable to present one’s goal as a fantasy characteristic such as becoming ‘the deadliest rustler in the west’. In this respect, BrainQuest may have benefitted from the inclusion of greater narrative to enhance the fantasy and further integrate serious content.

Extending feedback is also crucial in supporting future goal-setting and the wider sustainment of engagement. In the study BrainQuest’s post-game task history tool allowed the user to reflect upon their correct and incorrect task choices but it likely did not go far enough in terms of detail nor in terms of encouragement. Nevertheless, there must be a distinction between support and advice within the game as advising the user to the point of telling them how to approach the challenge may be inconsistent with the requirement of task novelty (R17). Notwithstanding, careful explanation of errors and positive encouragement regarding performance is appropriate.

To summarize, it would be useful to observe a future iteration of BrainQuest, which includes an extension of feedback and goal-setting facilities, over a longer time period.

7.4.2 Success of Reward and Leaderboard Systems

The extrinsic reward elements were among the most enjoyable aspects of the game and appeared to facilitate goal setting which in turn promoted user engagement over the course of the study. Consequently, it would be easy to advocate extrinsic rewards use in all future CTGs and to justify their widespread use in the current crop of games. However, observing the way in which they were used in BrainQuest clarifies the environment in which extrinsic motivations may be most useful and even develop into more intrinsically motivational properties.

The extrinsic motivators in BrainQuest (the leaderboard and trophies) supported goal-setting, user engagement, and competence but, for many, they were important because they held a heavy social value. Nearly all case study children were seen telling others of their achievements and many discussions were observed between groups of children comparing trophy cabinets and leaderboards. They became a foundation of communication between children which transcended the boundaries of friendship groups and gender, therefore, providing a sense of relatedness. However, without the outlet of real-world face-to-face communication between peers, they may not have held the same value and would have been unable to facilitate the same sort of social interaction. Such observations draw parallels with

Bartle's taxonomy of player types, covered in Chapter Three (Section 3.3.5.2.3, p. 93). The BrainQuest players who value and doggedly pursue trophies and leaderboard goals closely resemble Bartle's 'achievers' in multiplayer games, choosing to measure themselves against others and taking pleasure in topping public ranking systems, as well as seeking mastery.

Therefore, lesson for designers is that seemingly extrinsic game design decisions such as reward systems and leaderboards, may not be successful without a social outlet. Neither gamified components nor extrinsic motivations are something to be avoided, consistent with requirement R20. However, game designers should be aware that they may be most effectively utilized as sources of user engagement when they support different player types or provide opportunities for competence, autonomy, and relatedness – the pillars of Self-Determination Theory (Ryan & Deci, 2000) and congruent with game design theory (R19). In a sense, BrainQuest may act as a suitable platform capable of amplifying any positive outcomes of gamified components because of the underlying game design principles deployed.

The parallels between motivational game design theories and EF-supportive techniques are undeniable to the extent that a lack of attention to game design may not just damage longevity of CTGs but, in fact, be render a game ineffectual from an EF perspective. Concepts such as incremental challenge at the cusp of ability, social challenge, fostering feelings of social belonging (i.e. cooperation), and promoting feelings of competence are synonymous with positive gaming experiences but also essential in building EF. This may go some way to explaining why some well-designed commercial video games, have also been positively associated with EF ability (Green & Seitz, 2015).

7.4.3 Harnessing Social Interaction

In general, making the game a mobile and social activity appeared to pay dividends with regards to user engagement, and BrainQuest appears to be congruent with requirements R6, R12, R15, R19, and R28. The results portray hero-rustler interactions as being some of the most enjoyable aspects of the game. Thus, for creating engaging CTGs, embracing social interaction is crucial.

In addition, from the perspective of Diamond's model, it is not only important for social interactions to occur but that their nature is of one which supports social belonging and a sense of community. In the study, there was a great deal of cooperation observed regarding the explanation of the task ordering rules as well as the general rules and procedures

governing the game. Children took it upon themselves to help other and teach less able peers, often beyond immediate friendship groups, and it could be argued that actions like these are examples of the social supports Diamond (2012) refers to. The definition of community is, *“the condition of sharing or having certain attitudes and interests in common,”* and the actions of children following games in the exchange of views, achievements, stories and advice regarding BrainQuest perfectly characterizes this.

Once, again we draw on Bartle’s player types. If Bartle’s taxonomy is correct, the reported pattern of intermittent socialization between games where players reflected on game experiences and exchanged stories, likely reflects the presence of many ‘socializer’ player types in the evaluation. Hence, this justifies the importance of promoting ‘relatedness’ within game design.

There are, however, some ways a sense of social belonging could be further enhanced in the game. For example, children mostly cooperated at times outside of gameplay apart from one in-play instance. Future iterations may benefit by creating more obvious opportunities to cooperate during play such as creating additional cooperative objectives and, therefore, creating shared interests and goals between children. This may also be useful to increase the cognitive engagement of PA involved in the game. Moreover, historical records of cooperation may emphasise shared achievements. This could be particularly useful in enabling relationship change, particularly beyond friendship groups.

Furthermore, an interesting proposal put forward by the children was the ability to create games of greater numbers, rather than just the 3 participants in each game of the current BrainQuest version. If the desired cognitive challenge of executive skills can be maintained, this could be useful in sustaining engagement and potentially for EF. Large group games are more akin to playground games and team sports, where cooperation is key to group success. Larger group games may also satisfy the desire of others to interact with friends but the game could help with directing interactions beyond friendship groups.

The current BrainQuest version included only 3 participants and 3 roles in each game for two reasons: (1) the roles translated from the original single-player vs AI prototype and included a sheep and a cow rustler as 2 of the 6 tasks (following 6E structure) to be completed by the hero, (2) smaller groups enabled easier observations from the perspective of the observers with respect to understanding the EF challenge of the game e.g. EF related observations with respect to following the rules could be concentrated upon one of the 3 children in the group. However, as we have seen, there may be an EF challenge involved in the rustler role too. Irrespectively, future versions of the game may benefit from a homogenization of roles. With

the introduction of more props, all players could play the role of a hero, by collecting, chasing, and stealing each other's cattle. While they may no longer be heroes nor rustlers, perhaps something in between might suffice.

Such a design change may be able to improve user engagement by increasing opportunities for social interaction which sometimes those in rustler roles were starved of in the study. It may also be able to generate greater feelings of autonomy from the user and allow them more freedom over their choices and movements, which seemed to be lacking for children in the rustler role during evaluation. E.g., some children complained about having to run for no cattle when hero pens were empty, while others were disappointed when they were not being chased by the hero often enough. With all roles now equal, it may provide an opportunity for children to bring their own style to the game and self-expression. Such individualism should also be acknowledged by the game through describing playing style to the user (i.e. to use the example of Patrick, a child who attempted to play in a 'stealthy manner' by sneaking up on opponents, the post-game feedback could describe him as a 'BrainQuest Ninja'), thus, helping the user to cultivate a fantasy persona. Relating back to Bartle's player types, perhaps the limits on autonomy imposed by the rules and procedures, stifled the emergence of additional player types beyond the observations of 'achievers' and 'socializers'.

It should be noted that such developments may require complex algorithms and integration of additional PA or networked data. Contrarily, such a change may diverge BrainQuest's rules from those of the 6E test but, as discussed, the game may also require additional rules to maintain challenge anyway. Thus, if the challenge of EF skills can be preserved, moving away from 6E rules is unlikely to be detrimental and, in fact, underlines why BrainQuest is not a gamified cognitive test.

Though there was some limited evidence to suggest the existence of relationship change because of BrainQuest play, similar accounts of such phenomena were not universal to all case study children. This may be because finding evidence of relationship change is, again, a measure of effectiveness, while the main evaluation in this thesis was concerned with efficacy. Before understanding whether BrainQuest can be the catalyst for relationship change and a positive long-term social impact in the real world, we needed first to assess how well the game can create opportunities for social interaction. Thus, future studies should be set up to include more sensitive measures of relationship change beyond the confines of BrainQuest – perhaps follow-up interviews, questionnaires, and even playground observations.

Future studies should also be careful to select the correct method for grouping children so as not to inadvertently manipulate artificial social interactions. In the study it was unclear whether children interacted with others beyond friendship groups because of any BrainQuest induced effects or because of the set groups imposed upon the children by the researchers. Hence, children may have engaged with other children beyond their friendship group out of a necessity for some form of social interaction rather than because they wanted to engage with these peers. On the contrary, children in the study who did not report any changes in relationship with other players may have done so because they were already friendly with group members. Thus, to understand relationship change, it is required to establish pre-existing relationships at pre-test and to make sure methodologies do not induce any bias.

Regardless of the effect upon relationship change, the defining of groups by ability level did not appear to have any negative consequences upon gameplay. This suggested BrainQuest is accessible to different ability levels and allows children of different abilities to play together in a way which may be difficult in other traditional sports. In addition to this, the discussed incidences of cooperation, highlight how mixed ability groups may be able to bolster cooperation. Further work is required to determine whether such results would be true when sorting groups by other measures of ability, such as physical ability.

7.5 Supporting Physical Activity

The emphasis on efficacy rather than effectiveness is also applied to the findings of PA involved in BrainQuest. Although BrainQuest could elicit the types of PA likely to be classed as MVPA – sprinting and running, the study was unable to contribute conclusions as to the extent of MVPA present within the study. However, children were only engaging in PA of some degree for 15 minutes per session (providing they played 1 hero game and 2 rustler games – each of a 5-minute duration, with a 5-minute intermission between games) which is unlikely to have a great impact upon MVPA. Nonetheless, the duration of play was constrained by school timetabling and many children expressed a desire to play in additional games in nearly every session – therefore, they may have played for greater lengths of time if left unchecked. Clearly then, future studies should aim to establish the extent of MVPA achievable in a BrainQuest session which is subject to less time constraint and further assess whether the game can promote real-world behaviour change towards more active lifestyles.

Although it is unclear whether the game can improve physical ability, the game certainly seems able engage children regardless of their physical ability level. Therefore, if the game

is a suitable medium for harnessing universal engagement, there should be an emphasis on understanding the best methods of translating this into measurable PA increases. There is also some evidence from the case studies that the game may have promoted self-efficacy towards PA as the accounts of some children and teachers convey pride and confidence in the PA undertaken.

Alternatively, real-world physical ability improvements may stipulate that such increases in confidence are matched by increases in physical challenge. All children agreed that physical challenge largely depended upon who their opponents were but, retrospectively, this may not have been the best method of challenge as it is not consistent with the pattern of incremental increase. Again, relating to the ideas for larger group BrainQuest games, like social engagement, PA engagement may benefit from having a wider pool of ability levels. This may allow those of lesser physical ability to chase those with similar ability, while providing them the opportunity to test their skills against more physically able players as their competence increases. Alternatively, PA challenge could be included within the variable difficulty system, e.g. challenging participants to sustain an average speed of movement.

One question, particularly important to the PE teacher we worked with during the study, was with respect to the benefits of BrainQuest compared to traditional PA. If traditional PA can provide EF improvement, what is the benefit of an exergame? Currently, BrainQuest may only have limited advantages of traditional physical activities. However, future versions of the game as well as additional research may be able to highlight the even greater potential of cognitive training exergames.

In its current form, as earlier stated, a primary advantage of BrainQuest, which is consistent with the exergame genre, is being able to capture user engagement in populations who otherwise may not enjoy or even avoid traditional physical activities because they lack self-efficacy. As a result, in being able to do so, games like BrainQuest might not only be able to provide a more enjoyable alternative to traditional physical activities (for some) but by improving self-efficacy and ability, games may be able to act as a gateway to traditional PA. Future cognitive training exergames may be able to accurately measure and track EF ability levels in a way which is not just a measure of game-specific performance but a valid representation of real-world executive functioning. Such games which can provide this data may be of great use to PE teachers, sports coaches, and children alike. Tracking of both physical and cognitive data may allow us to understand a child's strengths and weaknesses, how they are progressing over time, and how they may be best supported. Thus, future CTGs

may be able to go further than the current physical wellbeing apps in providing an understanding as to a child's overall wellbeing.

7.6 Implications for Teachers

Some of the comments made during the teacher interviews during the main evaluation suggested the potential of CTGs to support and inform educators. E.g., the teachers interviewed as part of the BrainQuest study stated noticing previously unrecognized potential of certain pupils. It should be noted, however, that contributions towards academic outcomes, PA targets, and physical education lessons are predicated on the outcomes of future effectiveness studies.

Future applications which can pay attention to both quantitative and qualitative data provided by the user may be able to help teachers tailor learning to individuals – levels of challenge or which skills need most practice. Teachers may be able to use CTGs to help children learn from contextually specific problems and apply them to real-world situations. An example might be a teacher reminding a child who is struggling to with time management of classwork about the strategy they successfully deployed in BrainQuest to complete a range of different tasks within an imposed time limit as quickly as possible. In this sense, integrating CTGs into EF-focused curricula could be particularly beneficial to the quality of teaching.

Integrating CTGs and exergames, as is attempted in BrainQuest, may also prove appealing for teachers in contributing to a range of targets. Games like BrainQuest may contribute towards PA directives as well as providing a fun and engaging activity which does not compromise the achievement of academic targets.

7.7 Logistical Lessons Learned

7.7.1 User-centred Design for Exergames

The UCD process was integral to BrainQuest's success and was received positively by all stakeholders but there remained room for improvement. During the UCD process, children undertook the role of informants: defining requirements, evaluating prototypes and contributing creatively to engagement design decisions but never EF challenge (handled by the researchers due to the subject's complexity). In retrospect, contributions could have been

extended to executive challenges, using mitigating language to extract information on challenging cognitive environments. E.g. “*situations where they struggled to remember*” or “*situations which required concentration*”. This could be explored in future developments.

The UCD process also produced insights for designers, such as using ‘non-technical’ prototypes to better understand the value of technology and how to model playground game activities and PA patterns. Without the non-technical version, the augmented NFC approach, involving social interaction and emphasising more intense PA, might never have arisen. Instead, we may have continued to refine the flawed GPS version of BrainQuest.

Gamestorming also proved useful for generating ideas and fantasy themes. The balance of idea generation activities, gathering data on specific design decisions but also granting the children creative freedom, worked well. In fact, every child in the creative game design task produced at least one design, while some produced up to 3. The session catered for different levels of confidence, allowing some to verbalize and publicly discuss their ideas but also enabled those with less confidence to contribute by posting ideas privately. However, the children involved in the Gamestorming session had prior experience with map-based exergames. This was helpful as a reference point for specific questions and describing experiences but likely constrained the creative exercise. Nevertheless, ‘all art is imitation’ and the children may have also been influenced by other gaming experiences too.

It was difficult to balance end-user and literature requirements. Regrettably, creative input became of secondary importance beyond the Gamestorming session as rule and interaction refinement were prioritized. Consequently, BrainQuest may have overlooked some additional user requirements emerging from later prototypes.

In previous UCD research, authors like Macvean & Robertson (2013; 2012) highlighted the importance of treating teachers as stakeholders in the process as well as children. The teachers hold influence over UCD success, particularly if several sessions are required because the teacher is in control of time taken out of critical classroom activities. Moreover, in the long term, it is teachers who must introduce new technologies into the classroom. Thus, their input is crucial to ensure technology benefits are realized (Macvean & Robertson, 2013; 2012). Fortunately, in BrainQuest’s development, there was only enthusiasm towards the project but this may be due to the prior experience of our partner teachers in participatory design. In other environments, researchers should prepare for having to reassure teachers of their value to the project.

One potential pitfall of UCD approaches concerns the generalizability of completed technologies to other age groups, geographical areas, and cultures. Would BrainQuest's fantasy theme developed with the Scottish children be appreciated in other countries? Likewise, the complexity of the game and the nature of the playground modelled tasks may be deemed too hard or too simple for other age ranges. Therefore, instead of modelling similar games around the user requirements of BrainQuest, researchers should consider undertaking their own UCD processes.

7.7.2 The School Context

Though BrainQuest integrated well into the school context in the 5-week evaluation, the study highlighted several issues to consider before undertaking further evaluations.

First, the study may not have been as successful without the flexibility afforded by the host school. The teachers' experience with previous interventions prepared them for unforeseen circumstances. BrainQuest was initially allotted 60 minutes of total session time, either during a PE session or an alternative exercise during class time. However, following initial game setup issues, the teachers permitted an additional 10 minutes before each session to enable researchers to communicate information with the children and answer questions. They allowed sessions to be extended by 10 minutes in case of any unforeseen delays. Fortunately, there were no session cancellations due to weather constraints but the teachers planned contingency sessions on other days. Flexibility also applied to the time-intensive pre- and post-testing which took approximately an hour per child – time taken out of class work. Meanwhile, the school even provided permanent space for the researchers to conduct the assessments.

There were also variables affecting generalizability to other educational environments, e.g. BrainQuest's space, hardware, software, and human requirements. Limited school AstroTurf space meant only 5 games (15 square metres), each comprising 3 children could take place at once. As one observer was dedicated to the case study group, the other observer(s) had to simultaneously police and troubleshoot the remaining 4 games. This became easier towards the end of the study but the observers were initially bombarded with game setup and bug queries, leading early sessions to run over time. To make the game more space efficient, wider play spaces hosting greater numbers of participants is a possible solution but this may further increase the data collection demands, e.g. increasing the complexity of observations and data logging challenges. Hence, increasing the chance of missing important events.

Another issue predicating BrainQuest's real-world success could be the level of teacher support. In current form, the complex rules and procedures make BrainQuest complicated and time-consuming for teachers to integrate into an average school day. Yet if the game's usability could be simplified and in-game support (e.g. animated tutorials) incorporated, it may improve the viability of using BrainQuest in schools without needing auxiliary support.

The choice between randomized and pre-defined study groups is also difficult. Although it is desirable to create bias-free and internally valid study settings by using randomization, sometimes this is impossible in school settings with the presence of interpersonal and ability factors. In the BrainQuest study, researchers initially pre-defined groups of mixed EF ability to understand if the game interface could mitigate differences in ability. However, this was sometimes obstructed due to absences and, on teacher advice, in response to misbehaviour. Thus, groups were matched by balancing ability and the likely suitability of social interactions. Though this was not always successful, it mostly appeared to be an appropriate compromise.

7.7.3 Potential Interaction of Pre-Session Activities

One issue which would be considered before designing another evaluation concerns pre-session activities. For example, in one session each week of the evaluation children interchanged between BrainQuest and their PE lesson. Though there were not any observed reports of this directly affecting BrainQuest performance, in retrospect, it seems reasonable that undertaking PE lessons before playing an exergame may have been impactful. If the PE session was particularly exerting, this may have affected the physical activity undertaken during BrainQuest because of fatigue and this may also have negative consequences for cognitive performance. Equally, given the positive acute effects of PA on cognition (Chapter 2, Section 2.4, p.57), users playing BrainQuest following PE could conceivably have an advantage. Furthermore, if the PE was especially engaging, it could impact their motivation for BrainQuest play. Hence, future studies should consider participant activities prior to sessions.

7.7.4 Instruments for Exergame Evaluation

Source triangulation was critical to providing rich accounts of user experiences. The interviews were very important for corroborating conclusions drawn by other data sources.

As the data couldn't be analysed before the end of the study, it meant interview questions were deductive rather than inductive and solely concerned the Diamond model and design decisions. Identical questions were posed to each participant, making the interviews easier to analyse. However, being able to study data (i.e. observations and game logs) prior to the interviews may have allowed additional tailored questions to corroborate initial conclusions. E.g., confirming motivations, relationships, and strategies etc. Consequently, there were some aspects of the interviews which contradicted data from other sources.

Video observations could have provided an even richer triangulation of behaviour and performance and would have allowed retrospective analysis from other, experienced researchers. It was attempted during the study but stopped due to the risk of equipment damage from strong winds throughout many sessions. Future evaluations should invest in weather-appropriate equipment. 'Go-pro' footage may also have been a useful addition; correct head mounting could have tracked user interface interactions in real time.

Accelerometers would have garnered greater understanding of PA challenge as well as its contributions to MVPA. Sadly, the additional logistical challenge made this infeasible during the main evaluation of BrainQuest. Reliable accelerometers, such as Actigraph, require pre-planned programming of specific dates and times. While this would have been achievable had all the children been played the games as scheduled, absences, players playing multiple games, delays in session start times, the requirement of recording exact game start/stop times for each child, and the additional time taken to fit/remove the devices on the children made it impossible. Further studies making use of accelerometry data are required to establish a clearer account of PA.

There were some lessons learned from the PA benchmarking assessments. These assessments were implemented by the PE teacher beyond the scope of the study but there were some problems accepting this data at face value. E.g., mile times were perceived to be more accurate than the bleep test as the data had been gathered 4 weeks prior to the study, which was most recent. However, within the 4-week lead-in to the study, changes could have occurred to child fitness levels with the potential to influence their cognitive performance. The bleep test suffered from the problem of having maximum ability capped by the PE teacher out of concern for safety. Hence, a greater differentiation between children who achieved the ceiling was impossible. Future studies should consider implementing their own PA measures.

7.8 Technical Lessons and Future Changes

7.8.1 Lessons for Using Technology in Research

In general, the translation of the design guidelines into the chosen technological implementation was very successful. Though there were bugs present in the system during initial sessions (Chapter Six, Section 6.3.3.3, p. 255), overall playability was mostly unaffected. Notwithstanding, the system bugs provide an obvious lesson for researchers and game designers alike: evaluation of software over several single and isolated sessions on a subset of devices and a subset of participants may bear little resemblance a larger-scale evaluation.

A few isolated queries in a single session evaluation with 6 children, can be amplified beyond envisaged human resource requirements – costing time and resulting in frustration of users, as well as distractions which can affect other children who are not experiencing technical problems. For complex software, it is advisable for a short pilot study to be undertaken, not just to provide early results or to refine the design but also to mimic data collection and ensure accuracy.

One additional lesson, ensuring software integrity, is relevant to those using a UCD methodology. Following the final single session evaluation, additional changes were made to the game before the main evaluation. Some of the changes were a product of the UCD process and contributed to game bugs because they did not undergo any additional testing. Thus, game designers should define a cut-off point where all changes must be finalized and tested, otherwise, additional tests must be scheduled.

With respect to main evaluations, there are lessons which can be learned to ensure the success of sessions. A large part of the success is in the preparation. Firstly, if more than one researcher is involved in the evaluation session, they should all be proficient with the technology to troubleshoot any issues which may arise. Similarly, tutorial sessions can be useful for participants. However, when attempting to explain complex aspects of the technology to the children, it may be advisable to do so once before letting them use the technology so as they can listen without distraction. Paper handout instructions can also be useful in reducing strain on researchers when working with children and unfamiliar technology.

Depending on the technology used, the evaluation environment should be pre-tested by researchers. E.g., if a network connection is required, we need to know whether a Wi-Fi

connection is in range or if the speed of mobile data connection can cope with the software demands.

7.8.2 Solving the Technology Difficulties

7.8.2.1 Hardware

Several technology challenges remain. Though already refined by the UCD process, the NFC technology could be further improved. There were still occasions in the evaluation where children had scanning difficulties because they did not touch the NFC sticker to the correct point of the phone for long enough. Hence, allowing for greater NFC proximities would be beneficial.

One simple solution would be to equip phones with NFC range extension kits which would increase scanning range between the phone and the tag. Alternatively, low-energy Bluetooth could be used to calculate the proximity to another Bluetooth enabled device within a 100-metre radius. Low-energy Bluetooth beacons inserted into game objects could be programmed to activate when a user picks up an animal, approaches a pen, or comes within a set distance of a rustler. Thus, removing the need to scan any items and potentially being able to provide objectivity to hero-rustler interactions, thereby settling the ‘caught or not’ arguments. Furthermore, being able to determine proximities may inform planning and strategizing performance measurement e.g. when the heroes attempt to catch rustlers, are they doing so at appropriate moments?

The existence of game rule misunderstandings regarding the procedures of each task suggests that the written and audio instructions were not always understandable. Instead, more illustrative methods should be developed, for example, in-game animated tutorials. Tutorials may also be applicable to game space setup.

The use of smartphones, in general, are another potential issue. Though in the BrainQuest evaluation there were no incidences of accidents resulting in broken devices, there remains a danger in running while holding a device, particularly if it is obstructing your field of vision. This may be an increasing danger if future versions include bigger games with more children and, therefore, a more crowded game space. The future potential of augmented and virtual reality technology may be able to provide ways of overlaying digital information over the real world or providing multiplayer fully virtual game worlds using digital visual devices.

However, while we wait for technology to catch up, using smart-watch technology may be a more feasible solution.

Many smart-watches are equipped with NFC as well as Bluetooth and some are also able to record a variety of physiological data. Hence, they may be a natural way of recording all aspects of performance data and may provide real-time PA feedback to users. One shortcoming is that the user interface is much smaller and there may not be the opportunity to use the interface as a form of variable challenge. However, as discussed earlier in this chapter, there are alternative methods of varying BrainQuest's challenge. All data provided by children in the game could be collated by a centralized tablet device as a method of visualizing performance feedback and presenting achievements.

7.8.2.2 Software

Suggestions for software improvements are summarised below:

1. Further maintenance of novel cognitive challenge as well as supporting a wider range of user ability levels by extending variable difficulty system to affect the complexity of game rules and create additional spontaneous and unforeseen problems to solve.
2. Modification of PA challenge so that it is not fully determined by opponent ability. Introducing wider games with more participants of different ability levels is one option, as well as creating personal PA challenges for users to achieve which are determined by the variable difficulty system.
3. Wider games with more participants can also be introduced to support great variation (autonomy) and frequency of social interactions.
4. Cooperation should be further encouraged with respect to gameplay and more obvious opportunities presented to the user, such as additional shared objectives to be undertaken.
5. Historical data should also document relationships with other players and shared achievements.
6. Homogenization of game roles may create greater feelings of autonomy for users – freedom of task choice and self-expression.
7. Self-expression should be reported by recognizing individual game styles.

8. Facilities for goal-setting should be extended and be supported enabling the user to create a record of formal goals as well as presenting feedback of progress towards goals, and a range of visible achievements.
9. Feedback should be extended to be more constructive, informative, and support goal progress.

7.9 Summary

This chapter presented a discussion of the impact of the findings from the 5-week BrainQuest evaluation upon the field of CTGs, exergames, and the parent genre of serious games.

In general, BrainQuest implemented its envisaged design to great effect and there is evidence to support the use of EF skills from users during gameplay. Firstly, there was a moderate correlation between hypothesized BrainQuest EF performance measures and the 6E test. Furthermore, the interactions between the hero and rustler roles appeared to require hot EF as designed as were deployed in a context familiar to everyday playground situations – ecologically valid and more likely to transfer.

In contrast with many previous CTGs, BrainQuest appeared to be able to preserve (to some extent) novel challenge, characterized by the generation of multiple, unique, and complexity varying strategies which are affected by a range of different factors – i.e. social or goal-orientation. Corroborating the persistence of challenge are the reports characterizing WM difficulties during later difficulty levels for some children, the interplay between challenge and user points, and the fact that many children were unable to complete all the difficulty levels before the end of the study. Hence, BrainQuest appeared to sustain the need for conscious and controlled EF skills rather than simply efficient refinement of familiar strategies and pre-learned task solutions. Nevertheless, the challenge did not appear to be equal across all difficulty levels and there appeared to be a separate challenge of learning the initial rules and mastering an unfamiliar technology. Finally, with respect to the transfer of EF skills, though there exists some limited evidence of improvement to the 6E test, further research is required to define BrainQuest's effectiveness and potential real-world contribution.

With regards to PA, there was evidence BrainQuest gameplay was consistent with MVPA through the interview and observation data but it was unclear how much the gameplay

sessions contributed to daily PA guidelines let alone behaviour change towards more physically active lifestyles. This may need to be explored through further accelerometry-based study. Nonetheless, unlike previous exergame studies, there did not appear to be the drop off in PA towards the end of the study for most case study children – further emphasising the absence of a novelty effect.

In addition to highlighting the successful and unsuccessful aspects of the game, some additional design, methodological, and technical lessons have been established to inform future designers, educators, and PA practitioners.

8. Conclusions

This chapter summarises the primary contributions and findings of the work presented in this thesis before relating these conclusions to the research questions outlined in Chapter One (Section 1.4, p. 6). Finally, a closing statement brings the thesis to an end.

8.1 Contributions

The primary contributions of this thesis can be summarised as follows:

- A conceptual review of EF, highlighting different paradigms, subcomponents, real-world implications of EF ability, and EF training methods, as well as a detailed critique of CTGs.
- A review and comparison of several notable motivational theories used in the engaging game design, considering their application to cognitive training and exergames.
- Identification of design requirements (and associated methods) which address all pathways of Diamond's holistic model – defined by the literature review and by a group of end-users.
- Identification of methodological concerns pertinent to the design and evaluation of CTGs and exergames.
- Iterative, user-centred implementation of design guidelines to create the first-ever cognitive training exergame, focusing upon planning/strategizing, WM, and IC EFs as well as the integration of hot and cool cognition.
- A 5-week evaluation to establish the efficacy of the game as a tool for training EF and understanding user experience.
- Results from the described evaluation highlighted the applicability of longitudinal study and mixed methods triangulation to assess EFs, as well as the complex process of understanding training efficacy and generalizability to the real world.

- Results on the suitability of motivational game design theories emphasised the importance of promoting feelings of competence, relatedness, and autonomy within serious games to ensure the longevity and appeal of the game.

8.2 Findings

The following findings add to the existing body of knowledge on CTGs and more generally, serious game design.

8.2.1 User Experience Findings

- There was enthusiasm towards BrainQuest from the school children who participated in the evaluations, who derived enjoyment and pride from the experience.
- The enthusiasm was shared by the teachers, who felt the game had provided it had been an engaging experience with a positive impact on the confidence, self-efficacy, and social relationships of children.
- Children's enthusiasm towards the game did not appear to suffer from the novelty engagement effects seen in previous exergame interventions and the study highlighted the value of goal-setting and social interaction. However, 8 study sessions may not have been long enough for novelty to emerge.
- The evaluation of BrainQuest was consistent with motivation theories incorporated into its design – the most enjoyable aspects of the game were deemed to be those promoting feelings of competence or relatedness.
- BrainQuest was accessible to players of different EF and physical ability levels, who played together without negatively impacting game enjoyment.
- The user experience and even long-term EF challenge of games are likely better served by rejecting lone gamification of cognitive tests without closer integration

with game design theory. However, cognitive assessments are useful in understanding the types of activities relevant to cognition and EF.

- Gamification elements, like extrinsic rewards or point systems, may be a useful tool for amplifying user interest provided they are integrated with intrinsically motivating environments which facilitate competence, autonomy, and relatedness.
- Adopting a UCD process was an appropriate development methodology to generate game content, rules, and interaction design.

8.2.2 Executive Function Findings

- The case study analysis produced the most important evidence to suggest the challenge experienced by users involved EFs:
 - BrainQuest challenged strategizing skills by eliciting the generation of new and unique strategies to cope with changes in the way the tasks were presented on the user interface.
 - Strategies varied in complexity and were influenced by changes in difficulty level, goal, previous success, and social factors.
 - BrainQuest required regulation of emotion and inhibition of desired responses, congruent with hot EF and these were common causes of rule breaks.
 - Most case study users reported finding it hard to remember spans of previously completed tasks on later difficulty levels.
- Correlation between game performance and BADS-C performance validated aspects of BrainQuest's EF challenge:
 - 6E performance was moderately correlated with 4 measures of performance – both hero and rustler.

- The pre-test Key Search was also moderately correlated with rustler performance measures.
- Significant statistical evidence concerning transfer of EF improvements was not captured by the study:
 - Mean scores improved on all BADS-C subtests but only the Water Test produced statistically significant improvements from pre- to post-testing and was assumed to be consequent of practice effects.
- There remained some cause for future optimism regarding transfer, however:
 - Transfer was still achieved in some individual cases – one case study participant deployed a BrainQuest generate strategy at 6E post-test.
 - Other case study children showed increased strategizing ability at post-test following BrainQuest.
- Suitability of the BADS-C was uncertain and may have influenced the observed results:
 - Poor test-retest reliability.
 - Underpowered normative reliability data.
 - Inability to assess hot EF.
- Evidence of cognitive challenge taken together with PA findings indicate BrainQuest characterized ‘cognitively engaging PA’.
- There is some limited evidence of positive relationship change beyond the scope of the study, as reported by some case study children and the teachers.

- BrainQuest sustained a novel challenge to some extent by incrementally changing interface demands but aspects of the initial challenge were not recaptured e.g. technology and rule challenges.
- BrainQuest has highlighted the difficulties in keeping challenge balanced and at the cusp of user ability – important for both EF and user motivation. Some difficulty levels were harder than others and difficulty was also mitigated by strategy complexity and usage of task ordering tools. For example, some children developed strategies of a complexity beyond that required of the current difficulty level, while others did not use the task history support tools intrinsically linked to the difficulty level.
- The effectiveness of BrainQuest’s challenge varied depending on user ability level and this emphasises the importance of designing for ability levels at opposite ends of the spectrum, even in a population of similarly aged users.
- Capturing the ‘process’ through data triangulation of log files and observations allows for greater detail by capturing data across time and allow disambiguation of the results of outcome measures, such as pre-to post-test differences.

8.3 Research Questions Revisited

This section summarises each of the research questions addressed by the work in this thesis. The motivations behind each the question, as well as the design decisions taken to address the question are first summarised before the findings and their implications are concluded.

RQ1. *To what extent does the game support the indirect pathways to EF improvement identified by the Diamond pathways: joy, social belonging, physical fitness and pride/confidence/self-efficacy?*

BrainQuest promoted each of the Diamond pathways during gameplay and there was some limited additional evidence to suggest a positive impact on all pathways beyond the scope of the game.

The aim of this work was to develop a holistic method for promoting EF skills, able to tie together many different research strands. Social and physical activities have been associated

with many of the positive real-world executive ability outcomes which have so far eluded CTGs. Therefore, it was hoped that an approach utilizing a range of established techniques may be more impactful than just one training method.

The review of literature established a rigorous definition of what Diamond (2012) refers to as “*joy*” – a product of engaging experiences supporting basic human needs. According to motivational theories, most notably Self-Determination Theory (SDT) (Ryan & Deci, 2000), engaging experiences are also built by fostering social interactions and self-esteem. Given the obvious relationship between SDT and the pathways of Diamond’s model, as well its application to game design literature, it was an obvious choice to shape *joy*, *social belonging*, and *pride/confidence/self-efficacy* pathways involved in the game. The PA pathway of the game was heavily influenced by the findings of Macvean and Robertson (2013; 2012), who advocated the modelling of playground game PA patterns.

The literature also influenced the inclusion of: variable challenge (*pride/confidence/self-efficacy*), immediate and historical feedback (*pride/confidence/self-efficacy*), reward systems (*pride/confidence/self-efficacy*), sounds and graphics to reinforce fantasy (*joy*), ‘cognitively engaging PA’ (*PA*), social interactions promoting endogenous cooperation and competition (*social*).

The UCD process was also key to the design, where children of the game’s target age refined the game according to their needs, placing emphasis on: modelling game activities around playground games (*joy*), the importance of social interaction during gameplay (*social*); a need to reduce rule complexity to make rules easier to understand (*pride/confidence/self-efficacy*); increasing PA by reducing the technology interaction time (*PA*), increasing the range of fantasy sounds and graphics (*joy*); extending the point system to all game roles (*PA*); and adding a leaderboard system (*social*).

The main evaluation produced several conclusions for each pathway. The joy pathway was explored as a description of user engagement and it was clear that it was derived in part from *social*, *pride/confidence/self-efficacy*, and *PA pathways*. However, in general, the game remained engaging for the users throughout the study and did not present any decrease in engagement consistent with previous serious games – though it may not have been long enough to see the emergence of novelty effects. The most engaging aspects of the game were the social interactions but the goal-setting sponsored by the reward system was also useful.

Social pathways were best promoted by the hero-rustler interactions where the nature of interactions was mostly endogenously competitive. Cooperation applied to children teaching

each other the rules, setup up of the play space, and exchanging strategic advice. There were only a few accounts of cooperation during gameplay, suggesting future game evolutions need to refine this aspect. The reward system was also the catalyst for social activity with comparisons of leaderboard score, trophies, and statistics. Accounts of teachers and some children also suggested benefits in social relationships beyond the scope of the study – meriting future exploration.

Pride/confidence/self-efficacy was supported by the support tools and used by many children to follow the task ordering rules, yet many of the children most in need of support did not use them. Hence, future tools need to be more obvious to use. The variable difficulty level became a source of pride and happiness – several children acknowledged feelings of self-efficacy after progressing through game levels. However, the variable difficulty system did not go far enough in keeping challenge balanced. This meant that for high ability children, BrainQuest did not present enough of a challenge, while for low ability users challenge was sometimes insurmountable. Trophy and the leaderboard performance were sources of pride and were used as a method of goal setting – this should be extended in future versions. The teachers described some children who had appeared to gain confidence beyond the scope of the study and justified the need for future contemplation of real-world transfer.

Pride/confidence/self-efficacy was also noted towards PA and some case study children, even those with poor physical ability, appeared to take positives from the physical aspect of the game. PA was most intense during hero-rustler interactions and during periods of extended rustler shuttle running. Future versions may be able to increase PA by increasing the number of social interactions through homogenizing roles, increasing the number of players in each game to represent a diverse range of abilities, or by creating variable physical challenge within the game. Future studies are needed to define the amount of MVPA undertaken during gameplay, as well as whether it can encourage PA increases beyond the scope of the game – to understand BrainQuest’s contribution to physical wellbeing.

In conclusion, BrainQuest has proven its efficacy in addressing each of Diamond’s indirect pathways but it is unclear the extent to which pathways are addressed. Future studies must establish this as well as the real-world effects on mental and physical wellbeing. Finally, some modifications can be made to the game design to make it more accessible to a wider range of ability levels and to build upon initial user engagement.

RQ2. What evidence is there to suggest that the children experience EF challenge and improvement through playing BrainQuest?

BrainQuest challenged the EF skills (planning/strategizing, WM, and hot IC) during gameplay which was consistent with its design and game performance measures shared moderate correlations with 6E and Key Search performance. However, notable improvements on 5 BADS-C subtests at post-test did not reach significance and further study is required to assess the extent EF training transfer.

Another primary aim of this work was to create a game which challenged cognition directly and focused on the development of EF skills which are particularly important for children. To do this BrainQuest integrated the structure and task ordering rules of an assessment of EF called the 6E test – a test characterized by its novel challenge. As EF skills are required most fervently in unfamiliar circumstances requiring the generation of fresh strategies to direct a series of planned actions, the preservation of task novelty is fundamental in maintaining EF challenge and keeping skills at the cusp of ability. Consequently, unlike other CTGs which attempt to maintain their cognitive challenge by increasing the number of items to attend to or by increasing the speed in which one must process information, BrainQuest maintains challenge by altering strategic task demands. BrainQuest’s variable difficulty not only increases the number of items for the user to store and manipulate in WM but alters the way in which a user must approach the activity. Despite the 6E ability to create a novel test of EF, it remains a cool cognitive test which is emotionally neutral. Kerr & Zelazo (2004) highlighted the need for including hot EF challenge, involving the regulation of emotion, to gain an understanding of EF which is representative of the real-world. Hence, BrainQuest incorporates both hot and cool EF challenges by adding a social game aspect in which players can interact cooperatively and competitively.

The UCD process helped to refine the suitable level of challenge for the target age group and as well as the hot EF component of the game. The evaluation sessions concluded the initial rule complexity of BrainQuest, which had increased from the 6E test, was beyond the initial ability level of most users so it was reverted to mirror the 6E exactly. Furthermore, the comparison between digital and non-digital prototypes defined the hot EF challenge as most effective when it involved human rather than AI opponents.

The main evaluation concentrated primarily on the efficacy of BrainQuest’s design and garnered data to understand the extent EF skills were challenged during gameplay and whether this challenge was sustainable. As a secondary goal, the study sought to ascertain any observable EF improvements beyond the scope of gameplay. The evaluation adopted a

unique mixed methods approach including case studies which triangulated multiple data sources and the results of repeated BADS-C EF assessment. Hence, there was an emphasis on explaining findings and providing recommendations for future research rather than passive observation of change through quantitative assessments alone.

The variable difficulty level suggested challenges to planning/strategizing, WM, and IC EFs. Most notable was the late spike in the number of game failures on Legendary difficulty where some case study children suggested a test of their WM while comparing potential task choices with previously completed tasks. Attempting new difficulty levels also appeared to render previous strategies ineffectual, forcing the generation of new approaches. Thus, planning and strategizing appeared to be the EF skill most commonly challenged in BrainQuest and the case study self-reports as well as game logs showed the generation of a range of strategies of different complexities. In addition to the difficulty level there appeared to be other factors on strategy: motivation to achieve a particular goal, previous success, and social challenges. Strategizing on post-test 6E showed limited improvements for the case studies. Therefore, future work is needed to understand whether positive changes in planning/strategizing ability observed in BrainQuest transfers to disparate contexts. Hot EF inhibitory challenges were both observed and reported by children as factors affecting task choices and adherence to task ordering rules and game procedures. The class teachers stated the improvement in self-regulatory skills with respect to some of the children following the study, yet further evaluations are required to provide clarity on any real-world improvements.

The quantitative data also produced some interesting findings. Pre-test 6E performance shared significant and moderate correlations with 4 measures of BrainQuest performance and post-test did the same for 2 measures, including both hero and rustler roles. Furthermore, the pre-test Key Search shared significant and moderate correlations with 2 rustler role performance measures. Nevertheless, there were no statistically significant improvements in BADS-C post-test performance apart from in the Water Test which was likely to be attributed to practice effects. However, the dubiety over test-retest reliability and the lack of study power of both the BrainQuest evaluation and the provided BADS-C norms, casts doubt over whether the testing battery was a suitable means of assessing performance changes. Future evaluations may need to identify more appropriate means of assessment.

In conclusion, from the triangulation of quantitative and qualitative sources, BrainQuest appears to represent a viable challenge to EF, most notably planning/strategizing, WM, and IC (hot EF aspects). Though there is also some limited evidence of transfer of performance

from BrainQuest to the 6E test as well as some self and teacher reported real-world improvements in hot EF regulation of emotion, it remains unclear whether BrainQuest training can produce generalizable EF improvements. There remains a need to consider the game's effectiveness and skill transferability in greater depth, through well-designed experimental and real-world evaluations.

8.4 Wider Implications

The work presented in this thesis may be one of the first steps towards redesigning CTGs so that they provide a viable means of training cognitive skills which generalize to real-world abilities. The criticisms and lack of far transfer evidence reported in previous studies requires introspection from those involved in marketing current CTGs. BrainQuest may not yet present a major breakthrough in achieving tangible cognitive improvements following training but more evaluation is required. However, it confirms the ability of challenging cognition through serious games and represents the much-needed revolution away from gamification design of cognitive assessments and towards building on engaging gameplay with assimilated cognitive challenges.

For CTG designers, there is a clear message – by modelling activities on the interests and requirements of end-users and contemplating motivational theory, we can create engaging serious games with longevity. After this platform is created, cognitive challenges can be synthesized and modelled on real-world contexts and content which should reduce the size of transfer gaps between training and reality. Furthermore, for cognitive training researchers evaluating new or existing interventions, the work in this thesis showcases the value of undertaking rigorous, mixed methods feasibility study to preclude premature assumptions of efficacy and subsequent lack of effectiveness. Finally, HCI practitioners will also be interested in how the serious and complex goals were balanced with user engagement goals by the researchers while still empowering the children who participated in the UCD process.

8.5 Closing Statement

This thesis investigated the feasibility of an active smartphone game for promoting EF in children approaching their teenage years. Tying together many strands of EF training: using computer games; PA; and social play; as well as motivational design literature, the BrainQuest system was developed to take an interdisciplinary and unique approach to

challenging cognition. The main evaluation of the system established the efficacy and promise of BrainQuest in supporting the EF building pathways identified by the work of Diamond, yet additional design refinement and empirical work are required to establish the impact upon real-world functioning. The evaluation presented in this thesis provides lessons for cognitive training practitioners seeking to understand how to create more engaging experiences using motivational theory without compromising serious training goals. Though the need to improve cognitive and physical outcomes are often seen as distinct problems with different solutions (e.g. CTGs vs exergames), this thesis emphasises the relationship between both domains and the similar difficulties in their training. Thus, the most viable contributions towards overall well-being may need simultaneous ways of supporting and improving both domains. BrainQuest may well be the starting point.

Appendix A – Supplementary Design Process

Material

This appendix provides additional details regarding the design decisions taken throughout the BrainQuest development process and their relationship with relevant literature, including requirements (R) and design methods (MD). Furthermore, additional details are provided for the Gamestorming UCD session.

A1 Additional Gamestorming Content

A1.1 Gamestorming Activities

Gamestorming sessions follow the pattern of an opening segment, exploring segment, closing segment *“to manage the flow of the activity and receive the best possible outcomes from any group”* (Gray et al., 2010). Opening segments of each activity were designed to generate ideas and creating discussion between different perspectives, while the exploration segments were dedicated to thinking about old ideas in new ways and to build something new. Finally, the closing segment was where ideas converged and conclusions generated. The incorporation of the post boxes added an element of fun to the activity with children competing to see who could generate the most ideas.

A1.2 Opening: Blank Spaces Activity

During the first part of the session, the children undertook the ‘blank keyword tasks’, where multiple cards either red or green in colour were distributed at each table. The green cards were designed to gauge positive previous exergame experiences, while the red cards were designed to capture negative experiences. The children had to write in the blank space in order to complete the following sentence which was written on each card:

Green Card - “One thing I liked about other exergames was

_____”

Red Card - "One thing I did not like about other exergames was

"

The children could complete as many cards as they wished and once each card was completed they inserted it into one of three classroom post boxes – one for good experience, one for bad, and one for new ideas. This activity, part of the opening segment of the session, was designed to facilitate the discussion of previous exergame experiences in preparation for later creative activities. The feedback collected at this stage of the session served to inform general design decisions for the first exergame prototype.

A1.3 Exploring: Design Your Perfect Game

The 'design your perfect exergame' was used as the exploratory segment of the session. Having already thought about their previous experiences, the children engaged in designing their own exergame. During this activity the children had six cards to read, each detailing a different exergame design aspect (previously played exergames) before they explained how their exergame design would differ. Example sentences are listed below:

- *"In iFitQuest, you had to run away from a wolf for a short amount of time. What would players of your game do for a short amount of time (30 seconds or less)?*
In my game players
would" _____
- *"In iFitQuest, not all mini games were tiring. How would you make players of your game tired?*
In my game players would be tired
because" _____
- *"What would players of your game be able to do between playing mini games?*
In my game players
would" _____
- *"In iFitQuest, there was an animal theme e.g. wolf, sheep, chicken etc. What would be the theme in your game?*

In my game there would

be” _____

- *“In iFitQuest, there was only one player playing against the computer. How many players would be in your game?*

In my game, I would”

- *“If your game allowed you to play with friends, would you want to be on the same team or would you like to play against them?*

In my game, I would”

While this part of exercise constrained the scope of creativity, it was necessary to channel the session towards gathering useful feedback usable to guide important design decisions and to establish user requirements. The second part of the exercise was a creative activity which presented the children with a picture of a smartphone screen on the back of each card. On the screen, they were asked to make sketches of their ideal exergame and provide a written description of the idea, including game name; characters involved; the plot; and activities to undertake. Following completion of game sketches, the children then posted their submission into a post-box.



Figure 54: Gamestorming Design Example

A1.4 Closing: Whole Group Discussion

The closing segment of the session aimed to draw different ideas together and establish an understanding of how the ideas of individuals would appeal to a wider audience. The main researcher led a whole class discussion and invited children who wished to do so to share their ideas and receive feedback from their peers.

A2 Additional Prototype 1 Content

A2.1 Prototype 1: Goals

The design of BrainQuest was formed by the requirements generated from the Gamestorming and expert discussion sessions, as well as literature reviewed in Chapters 2 and 3. The main researcher consolidated the different requirements and recommendations by defining a series of short-term goals for the first prototype and also longer term goals for future design generations. The development goals at the stage of prototype 1 are shown in Table 32.

Prototype 1 goals and the long term project goals were balanced with respect to the UCD and rapid prototyping methodologies – development goals had to be balanced between priority and implementation time. Consequently, two user requirements, the social and reward components of the game were shelved for future development due to the need for a system backend to support data gathering and exchange.

BrainQuest Prototype 1 Short-term Goals	BrainQuest Long-term Goals
1. Translate paper mock-up into smartphone app using Google Maps interface and appraise the chosen technology.	1. Develop a social component to the game – including opportunities for competition and co-operation.
2. Implement initial aspects of fantasy, including characters, objects, and themes from paper mock-up.	2. Create in-game structures for encouraging confidence, self-efficacy, and pride.
3. Define rustler movement patterns and speeds, and physical distances between objects in order to pose a physical challenge to the user.	3. Create additional performance-based measures of EF.

4. Develop a scoring system for the game that rewards EF successes.	4. Create reward system and public achievements.
5. Create a technology-free version of the game which meets all user requirements.	5. Incorporate further aspects of EF and game design literature in future game iterations.

Table 32: Prototype 1 Development Goals

A2.2 Prototype 1: Game Rules and Scoring

Using the rules and structure from the 6 Elements Test (6E), in BrainQuest the user must repetitively interleave a set of 3 EF tasks (Tasks 1, 2, and 3). The rules of the 6E and prototype 1 are described below:

A2.2.1 6E Test

1. Each task contains two parts (A and B), where only one may be undertaken at a time. Furthermore, once one task type is completed, the same task may not be re-chosen until the user has completed a further task of a different type, e.g. If Task 1A is chosen and then completed, then the user may not choose any part of Task 1 until a part of Task 2 or Task 3 are completed.
2. Within the 5-minute time limit, the user must make sure that they have attempted all 6 subtasks while following Rule 1.

The task and subtasks involved in the 6E test are named, structured and described below:

4. How many? – in these tasks the user must perform some sums written on a series of cards before writing the answer down on paper
 - a. How many? Part 1
 - b. How many? Part 2
5. What is it? – in these tasks the user must write down on paper which object that they see on each card
 - a. What is it? Part 1
 - b. What is it? Part 2
6. Sort it – in these tasks the user must sort items into their box lids, according to a picture drawn on the inside of each box lid:

- a. Sort it Part 1
- b. Sort it Part 2

Note: though the undertaking of both parts (A and B) of each task are identical, the content is different e.g. in ‘Sort it Part 1’, the user sorts bolts, while in ‘Sort it Part 2’, the user sorts beads.

In the scoring system for the 6E test, the user earns 2 points per unique task attempted (e.g. 4 different tasks = 8 points) with a maximum of 12 points available. The user loses a mark for every unique task type in which they break the rules (e.g. ‘What is it? Part 1’, followed by ‘What is it? Part 2’ = -1 points) with a maximum of 3 penalty points. Finally, the user can earn extra points for using a discernible strategy, such as task ordering or time management strategies, while they may also lose an extra point for persistent rule breaking.

A2.2.2 BrainQuest Prototype 1

Prototype 1 applied the task structure of the 6E test to an ‘animal rustling’ theme. The list below denotes the translation of task structure from the 6E test to BrainQuest:

1. Herd animal – the user must herd animals from the play space into the appropriate pen
 - a. Herd a cow back to player cow pen
 - b. Herd a sheep back to player sheep pen
2. Save sheep from Rustler animal pens – the user must save sheep that has been stolen from them by rustlers and set them free to the play space
 - a. a. Save a cow from Rustler cow pen
 - b. b. Save a sheep from Rustler sheep pen
3. Stop Rustlers from stealing from player animal pens – the user must chase and stop rustlers who have stolen their animals
 - a. Stop Rustler stealing from player cow pen
 - b. Stop Rustler stealing from player sheep pen

In prototype 1, the task ordering rules remain but are made slightly more difficult to maintain the EF challenge of the game:

1. Like the 6E test, the user must change task type for each task choice but must also complete a task of each type before returning to the undertake a previously chosen task.

2. Within the 5-minute time limit, the user must make sure that they have attempted all 6 subtasks while following Rule 1.

The scoring system for prototype 1 awarded the hero player 10 points multiplied by a combo bonus per successfully completed task. For every completed task, following task ordering rule 1, the combo bonus is incremented by 1 until the user breaks the rule. At this point, the combo bonus is reset to its initial value of 1. Furthermore, 100 overall bonus points are awarded for accurately following task ordering Rules 1 and 2. The formula is explained below:

- **Completed Task Points = 10 x Combo Bonus**
- **Total Task Points = Completed Task Points + Task Ordering Rules Bonus**

The combo bonus is a method of scoring distinct aspects of EF (WM/task switching ability) separately and more accurately than just relying on the overall score because it is the equivalent of ‘rule error scoring’ in the 6E test. For example, the combo bonus indicates the maximum span of correct task choices made.

A2.3 Prototype 1: Implementing Design Methods

Creating a fun and rewarding experience can be more accurately defined through motivational theories such as those described in Self-Determination Theory, Le Blanc’s Taxonomy, and Lepper and Malone’s framework. This section describes the design decisions taken in the first prototype compared to the design methods outlined by the literature.

A2.3.1 General User Engagement

Design methods included: MD11, MD13

Prototype 1 made use of intrinsic fantasy by utilizing a location-based design. This allowed the user’s direct input (e.g. running or rotating etc.) and use of skill (e.g. task switching, planning etc.) to affect the fantasy itself, rather than the fantasy being external to the activity (e.g. for each correct task type chosen, something happens) (MD11). Similarly, events which occurred within the game’s fantasy reciprocated by affecting the actions taken by the user input (e.g. a rustler picking up a hero cow encourages the user to task switch and change their direction of focus). Thus, it was hypothesized that the use of intrinsic fantasy would be more likely to transfer to other cognitively engaging physical activities.

Prototype 1 attempted to create a fantasy requiring the regulation of emotion through the battle between the hero and the rustlers (MD13). The rustlers were portrayed an evil force within the game, whom the hero had to counteract to stop them from destroying their collection of rescued animals. It was hoped that the player would have to exercise self-control and suppress a powerful desire to constantly catch rustlers in order to achieve their long-term goal of splitting time between different tasks. The battle between the user and the rustlers was inspired by the results of the Gamestorming session (MD13).

A2.3.2 Competence

Design methods included: MD1, MD4, MD7, MD8

In prototype 1, before the user could begin the game, they had to read an information screen outlining the game rules in full (MD1).

In prototype 1 the difficulty method of the game was determined by the difficulty of an opponent (MD7, C) by the moving speed of the rustlers. However, the user could alter the difficulty level at the end of each game (MD7, B). Furthermore, the time delay allocated to the rustlers to open animal pens also decreased as the difficulty increased, further reducing the time taken for the rustlers to steal animals. The difficulty was also determined by the density of the animals available for the hero to collect from the play space – making the player travel further distances to collect the desired animal.

As the user was unfamiliar with the initial game complexity, Level 1 was played with rustlers moving at a walking pace and also they had to wait 5 seconds before stealing from animal pens. The difficulty levels incremented by one until Level 10, where the rustlers moved at a sprinting pace and their animal pen wait time was only one second. As the levels increased the animals available in the play space became sparse.

The idea was to challenge the user physically by increasing the distances and speed which they had to run to collect animals and stop rustlers. With respect to EF, as the speed of the game increased, the user had to plan more efficiently to undertake as many of the 6 task types as possible within the time limit (MD4, MD8).

With respect to self-esteem, the scoring system implemented in prototype 1 rewarded positive performance by giving bonus points and did not impose penalty points for mistakes (MD8).

A2.3.3 Autonomy

Design methods included: MD15

In Prototype 1 there was a provision of choice between the 6 different tasks. However, the provision of choice exists in the game as much out of necessity as it does for maintaining intrinsically motivating design. Choice existed as an EF challenge to use IC to resist the desire to constantly catch rustlers as well challenge WM in comparing previously implemented tasks against a range of options in following a set of rules.

Consequently, in following the task ordering rules proficiently, the user's choice became increasingly constrained until a set of all 3 task types have been completed, where more variety of choice then becomes available. However, at no point was the user coerced to following the task ordering rules nor does a rule breaking task choice become physically forbidden – the user has the power to follow the task order rules or not and are ultimately autonomous (MD15).

A2.3.4 Cognitively Engaging Physical Activity

Design methods included: MD12, MD25, MD26, MD28, MD29, MD30

With the coupling of a cognitive task (following the task ordering rules) and PA (MD25), it would be reasonable to assume prototype 1 involved cognitively engaging PA but there were additional contributions. It was hypothesized the co-ordination between real-world movement and on-screen positioning of objects as well as opponent movements may be a means of cognitively engaging PA (MD26). For example, motor coordination and selective attention between screen contents and the real world.

The PA pattern of the game was intended to mimic that of playground games (MD12, MD29) – requiring sprinting (depending on the level of difficulty) to chase moving rustlers but interspersed with collecting static objects as a lower intensity task. Thus, attempting to follow an interval training style pattern of activity, consistent with MVPA (MD28). It was intended that aerobic PA would occur during 'save' and 'return' tasks but anaerobic activity would occur during 'catch rustler' tasks.

The variable difficulty was also designed to make the game accessible to those of different fitness levels and there was no disparity between the points on each level in an attempt to create a level playing field (MD30).

A2.4 Prototype 1: Reviewing EF Challenge

The integration of 6E rules and structure sought to enable Prototype 1 to directly challenge EFs. However, BrainQuest was designed to broaden the spectrum of EF skills challenged as well as require the exercise of hot EF, not involved in the 6E test and beyond the scope of the CTGs. The EF design requirements and the methods to implement them within Prototype 1 are noted below. In this section, the hypothesized correspondence between the challenge of individual EFs in the 6E test and BrainQuest is considered.

The challenge of individual EF subcomponents are described in this section but the execution of the skills overlap in practice. In keeping with the requirements (R1, R17), BrainQuest sought to take a wider scope than many CTGs, by facilitating activities to challenge not by exclusively isolating WM but by training WM as well as higher level cognitive skills and EFs directly and collectively (R8).

A2.4.1 Motor-Cognitive Coordination

Design methods included: MD26

Prototype 1 requires general coupling of motor and cognitive demands between coordination of real-world and on-screen movements (MD26). The user must orient their body to move in the correct direction and at an appropriate speed to catch rustlers, collect objects, and visit pens.

A2.4.2 Working Memory

Design methods included: MD5, MD6

Like the 6E, WM in Prototype 1 was challenged by remembering previously completed tasks and checking the potential new tasks against the task ordering rules. Due to the extra layer of task ordering rule complexity, the user had to remember an additional task spans – perhaps an even greater challenge. To this degree, the WM challenge is similar to that of a ‘complex span’ tasks often deployed in CTGs. Furthermore, users also had to retain information regarding the task procedures from long term memory (MD6).

However, challenge of selecting the best next task was also a dynamic one rustlers stealing cattle and items at different proximities to the user’s current position, the user had to strategize and use WM to make sense of an evolving environment. The user had to map these

onscreen events to real-world locations to be able to interact with rustlers. Hence, it may also have involved the manipulation of spatial information in WM (MD5).

A2.4.3 Inhibitory Control

Design methods included: MD2, MD6

Prototype 1, involves cool IC challenges of sustained and selective attention – dividing attention between concentrating on the task at hand and the end goal, as well as paying attention to the movements of multiple rustlers (MD6).

For example, Prototype 1 was a dynamic task which presented ‘rustlers’ as multiple moving perceptual stimuli on the phone screen (MD2). The user had to switch between sustained and selective attention, as well as inhibition of action. Prototype 1 aimed to require hot EF by inhibition of action while faced with the short-term temptation of catching rustlers in favour of achieving pursuing a long-term goal.

A2.4.4 Planning/Strategizing

Design methods included: MD2, MD25

In Prototype 1 planning/strategizing was necessary for optimally sequencing tasks in the same way as the 6E (MD25). Some strategies were more efficient than others and enabled the user to complete all 6 tasks faster – important when faced with a time limit. Furthermore, as stated the appropriateness of catching rustlers is another aspect of strategizing involved in the game. For example, by catching the rustler before they arrive at the hero’s pen, the rustler has to first return to their own pen as a penalty. This buys the hero extra time before the rustler can return to attempt to steal an animal again. Distance between the user and next task is another factor and the user will earn more points by choosing tasks physically nearest their current position while following the task ordering rules.

A2.4.5 Cognitive Flexibility/Set Shifting

Design methods included: MD2

Cognitive flexibility/set shifting was designed to be the same in Prototype 1 as the 6E test - the user had to split time between all 6 tasks rather than commit game time to one single

task. Furthermore, in Prototype 1 cognitive flexibility was required to respond to changes to the game environment (e.g. noticing that the rustler is in proximity and interrupting the planned sequence to take advantage).

A2.4.6 Task Scheduling & Performance Monitoring

Design methods included: MD6

Task scheduling between Prototype 1 and the 6E was the same – the user had to time manage to make implement all task types within the time limit.

Performance monitoring also occurred in the same way between prototype 1 and the 6E test – the user had to remember past choices to follow the task ordering rules. However, in prototype 1 the user also had points scores and a combo bonus to use as a reference of performance.

A3 Additional Prototype 2 Content

A3.1 Prototype 2: Goals

Following the problems uncovered in understanding the game even on the easiest difficulty level during the evaluation of Prototype 1, all experts agreed that the new prototype should concentrate upon improving the most basic aspects of the user experience while maintaining aspects of the previous design which received positive feedback. Hence, goals for further development iterations were divided into short and long-term targets, with the former taking precedence for Prototype 2 – shown in the table below.

Prototype 2: Short Term Goals	Long Term Goals
1. Redevelop user-object interaction method.	1. Redevelop variable difficulty system for the new platform.
2. Add support to aid understanding of game rules.	2. Develop user EF support structures.
3. Maintain a scoring system for the new prototype.	3. Develop self-esteem cultivating feedback.

4. Create opportunities for social interaction or multiplayer capabilities.	4. Expansion of scoring system.
5. Re-develop the fantasy themes for the new prototype.	5. Expansion of EF performance measurement.

Table 33: Prototype 2 Short and Long Term Goals

A3.2 Prototype 2: Game Rules and Scoring

A3.2.1 Retained Rules

Some rules were retained for BrainQuest Prototype 2 from the previous iteration:

- Task ordering rules
- The 5-minute time limit
- The attribution of Hero Points

A3.2.2 Task Procedures

With the changes to the interaction design and the inclusion of additional players, supplementary rules had to be introduced.

Return Tasks: the hero must first collect an animal from the play space by scanning it before taking it to the appropriate hero animal pen. On arrival at the pen, the hero scans the pen to open it and then scans the animal and drops it into the pen.

Save Tasks: the hero must go to a rustler animal pen and scan the pen to open it, then pick up an animal from the pen and scan it before throwing it back into the play space to set it free.

Stop Rustler Tasks: the hero must chase and catch a rustler by physically tagging them. If the rustler is holding an animal, they must relinquish it to the hero who scans it, then returns to the appropriate hero animal pen, scans the pen to unlock it and then scans the animal before dropping it into the pen. Meanwhile, the rustler must return to their animal pen. If the rustler does not have any animals in their possession when caught, they must return to their animal pen, while the hero presses the ‘no animal’ button to complete the task.

Note, the many scanning operations required to complete tasks in this prototype were necessary for ownership of objects to be continually updated.

A3.2.3 General Rules

There were general rules governing the game:

- Rustlers must stick to one type of animal e.g. sheep rustlers carry sheep and cow rustlers carry cows.
- The hero must adhere to the task type which has been chosen e.g. if the hero opts to do a return task, they are forbidden from interrupting that task in favour of another until their chosen task has been completed (Note: the player is allowed to press the back button before the first scanning operation of the process).
The hero must also adhere to the type of animal chosen e.g. if the hero selects to save a cow, he cannot save a sheep.
- Heroes and rustlers are permitted only to carry one animal at one time.
- Each player plays in their initial role (hero, cow rustler, sheep rustler) for 5 minutes before swapping roles, until every player has played in every game role.

A3.2.4 Scoring Formula

The scoring formula is shown below:

- Total Task Points = Completed Task Points + Task Ordering Rules Bonus (100 points)
- Completed Task Points = 10 x Combo Bonus
- Combo Bonus = IF (Correct Choice = Combo Bonus +1), ELSE (Combo Bonus = 0)

A3.3 Prototype 2: Implementing Design Methods

The section compares the motivational design methods from the literature review with new design decisions taken for BrainQuest Prototype 2.

A3.3.1 General User Engagement

Design methods included: MD11, MD13, MD14

Intrinsic fantasy is like prototype 1 and the user's direct input (e.g. running, rotating, scanning, catching others) and use of skill (e.g. task switching, planning etc.) affected the fantasy itself, while the current game context affected user decisions and activities (MD11).

The introduction of real people; physical objects; noises and images reflected the animal rustling theme and were designed to enhance the fantasy from the previous iteration. The introduction of real people in the role of rustlers was motivated by the initial user requirements, end-user evaluation of prototype 1, and to increase the emotional fantasy involved in the game through competition (MD13).

The in-app graphics corresponded to the physical bean bag toy animals as well as the signs beside cattle pens (MD14). Sound and images were used to enhance the fantasy and have been created with humorous intent as comedy is important for the user to derive pleasure. The sounds and images occurred in conjunction with a user's game action – e.g. a picture and 'bah' sound occurred after scanning a sheep.

A3.3.2 Competence

Design methods included: MD1, MD7, MD10

An information screen outlining the game rules in full remained from Prototype 1. On the selected task screen, each task was broken down into a series of steps and shown to the user by written instructions which update following the completion of each step. There was also the option to listen to instructions as audio commentary (MD1). The design of the task choice screen was used as a representation system. 6 thumbnails each depicted the different game tasks – the pictures on the thumbnails corresponded to the pictures and colours associated with individual tasks (MD1).

In prototype 2, difficulty level was determined only by opponent's skill (MD7, C) as the variable difficulty was temporarily scaled back during this iteration. Regarding EF, it was determined that varying difficulty should fundamentally change task demands to refresh the novelty of the challenge – something to be implemented in future evolutions.

Furthermore, prototype 1's variable difficulty seemed unable to impact PA as planned, whereas the physical version of the game appeared to be more consistent with the type of PA desired. Hence, the physical or cognitive challenge of prototype 2 was only determined by opponents – in this prototype real people rather than computer controlled characters.

Performance feedback (MD10) within Prototype 2 was limited to providing the user with, (1) frequent and (2) clear feedback, with further contributions to user support deemed a long-term development goal.

Immediate feedback was provided in different ways. Successful scanning of a tag resulted in the appearance of an image representation of the scanned object and an associated sound appearing on the phone. After a tag had been scanned, the instruction message updated to confirm the completed procedure and instructed the user's next step of the task to complete. In the case of an error, such as the user failing to correctly scan a tag, a prompt would appear on the screen to notify them. Historic feedback was offered as a means of gauging performance on a screen following each completed game (MD10).

A3.3.3 Autonomy

Design methods included: MD15, MD16, MD17

Although the extent of user choice was limited to 6 tasks, like prototype 1, there was an increased choice of roles – hero and rustler roles (MD15). The social implementation of the game provided opportunities for different play styles, tailored tactics depending upon opponent, and socially influenced goal setting (MD17).

For example, additional goals could emerge beyond following the task ordering rules as a product of competition or collaboration with other players – the hero might decide to weight their task choices more heavily towards stopping rustlers in order to settle a personal score (MD16).

Rustlers could not control whether the hero successfully completed or failed a game as the hero was in control of their task choices. The hero also had the option to press a button to complete the rustling task empty handed if they failed to catch the rustler. However, more time spent chasing rustlers of the hero's volition would likely result less time to complete other tasks and negatively impact points (MD15).

A3.3.4 Social Interaction

Design methods included: MD27, MD31, MD32, MD33, MD34

The competition involved in prototype 2 was endogenous and occurred face to face in real time between heroes and the rustlers (MD32). However, the fact that there were two rustlers

also provided opportunities to work together to make the hero's job as hard as possible e.g. timing runs to steal from hero pens simultaneously (MD27).

Though the fantasy implied a competitive dynamic between hero and rustler roles, this was not a requirement. Heroes and rustlers could cooperate with each other, by heroes topping up pens regularly and rustlers making themselves easy to catch (MD33, MD34). At the very least it was hoped that the hero-rustler dynamic would allow players chances to receive attention from others and to feel as if their actions impacted on their peers – key to feelings of relatedness (MD31).

A3.3.5 Cognitively Engaging Physical Activity

Design methods included: MD12, MD26, MD28, MD29

The activities in the game were supported by on-screen events and structured according to 6E rules but occurred in the real world and were similar to many playground games, hence, less contextually specific than other CTGs (MD12, MD29). Thus, it was hoped any executive improvements would be more likely to transfer to real-world behaviour.

The PA pattern of the game was intended to mimic that of playground games and be consistent with the patterns of PA observed in the physical version of BrainQuest. For the hero, it was hoped this would resemble moderate intensity jogging and running during return and save tasks, interspersed by high intensity sprinting during stop rustler tasks. For the rustler, it was hoped this would resemble continuous moderate intensity shuttle runs. Both consistent with MVPA (MD28, MD29).

Hence, there was less coordination required between the user's technology and real-world movements e.g. no consistency between virtual and real-world location required. However, the user still had to utilize the phone interface in order to interact with task choice selection menus, on-screen instructions, and on-screen graphics (MD26). Moreover, the new social component of the game meant that users had to couple regulation of emotion with PA – bringing a different style of cognitively challenging PA to prototype 2.

A3.4 Prototype 2: Reviewing EF Challenge

In this section, the hypothesized correspondence between the challenge of individual EFs in the 6E test and Prototype 2 is considered. As in the previous prototype, Prototype 2 may

challenge individual EF skills but did not attempted to train them collectively rather than in isolation (R8).

Prototype 2 increased the dynamic nature of the activity and allowing a social factor to affect the challenge presented ensured that no two game sessions were predictable nor the same. Hence, going beyond refinement of specific and repeatable processes (R9) common to previous CTGs.

A3.4.1 Motor-Cognitive Coordination

Design methods included: MD25, MD26, MD27

Prototype 2 requires coupling of motor and cognitive demands between coordination of real-world PA and on-screen activities (MD26) – e.g. instructions, task choices, animations, points. However, the user also used motor-cognitive coordination during hero-rustler interactions in anticipating the movements and speeds of opponents, as well as strategizing to follow the rules (MD25). Similarly, the rustlers could choose to coordinate their activities and real-world movements to maximise their chances of successfully capturing animals (MD27).

A3.4.2 Working Memory

Design methods included: MD2, MD3, MD5, MD6

The challenge to WM remained from Prototype 1: remember the previously completed tasks and whether the planned action is compliant with task ordering rules. However, the Prototype 2 WM challenge went beyond incremental refinement of following the task ordering rules alone.

Furthermore, the inclusion of real rustlers (besides meeting user social requirements) increasingly involved WM to track visual, spatial, and auditory information of opponent's movements, positions, and actions – less consistent than the virtual rustlers. For example, a hero may have needed to hold in mind tactics characteristically deployed by individual rustlers and anticipate their behaviour throughout the game session to maximise chances of catching them. This was designed to require (MD6) the manipulation of both short (following task ordering rules, task procedures, opponent movements) and long term memory (opponent characteristics, counter strategies), and using attentional skills to switch between the use of each and manipulate the information to inform actions (MD2, MD6).

Thus, WM challenge was unique in every game went further than refinement of specific processes, such as complex span tasks, n-back tasks, number of items, commonly used in other CTGs (MD3).

A3.4.3 Inhibitory Control

Design methods included: MD2, MD6

There appeared a greater inhibitory aspect to Prototype 2. With respect to attention, there were again multiple perceptual stimuli but the movement patterns of rustlers were less predictable (MD2). Thus, the hero may have to switch more regularly between sustained attention, selective attention and inhibition of action (MD6).

Prototype 2 attempted to challenge hot EF through the game's social component. Interaction with real rustlers seemed potentially more enticing than the presence of virtual opponents, adding to the challenge of IC. Interactions themselves also were designed to challenge inhibitory skills. For example, if a rustler does not want to give up possession of their animal to the hero, they are forced to suppress their desire to conform to the rules. This may be even more challenging depending on the personal relationship between the two players. Hence, the nature of the interaction and the amount of self-control required may be influenced by many social factors.

Furthermore, the challenges of social interaction, unlike many of the other skills tested in BrainQuest, are not decontextualized from real-world executive functioning. Instead they are applicable to interactions with friends, strangers, rivals – depending on whom is involved in the current game. Hence, training inhibitory skills in a real-world context may increase the likelihood of their transfer.

A3.4.4 Planning / Strategizing

Design methods included: MD2, MD6, MD25

In many ways planning/strategizing is the product of the WM and IC subcomponents (R7). In BrainQuest Prototype 2, planning/strategizing was necessary for optimally sequencing tasks and following the task ordering rules but was more pronounced than the previous iteration with respect to changes in the game environment (MD25).

Unlike in Prototype 1 where rustler movements were consistent, real people in rustler roles required the expansion of planning and strategizing within the game. The rustler had to employ strategies in changing speed, direction, and cooperation with the other rustler. For example, both rustlers coordinating their runs to make it impossible for the hero to catch them both. Alternatively, rustlers who did not want to cooperate (or impact the points of another) could adjust their strategy to encourage the hero to catch an opponent.

The hero needed to develop a dynamic strategy to deal with different opponents as efficiently as possible while accounting for previously acquired information regarding opponents – retrieving characteristics from long-term memory (MD6). Like the previous prototype, it was advantageous from a points perspective to do as many tasks as possible. Thus, undertaking possible tasks in close proximity remained a factor. Meanwhile it was beneficial to catch rustlers as they arrived at the hero's pen to maximise the distance they had to run (and therefore time) before they returned to the hero pen. If rustlers could escape with animals, the hero had to spend additional time returning captured animals to their pens.

A3.4.5 Cognitive Flexibility/Set Shifting

Design methods included: MD2

The challenge to cognitive flexibility/set shifting remained from Prototype 1: the user must not dedicate too much game time to a single type of task but instead split time between all 6 tasks. However, the increased dynamicity of the task involving the rustlers was designed to require greater cognitive flexibility in response to changes to the game environment or arising opportunities to catch rustlers as quickly as possible.

A3.4.6 Task Scheduling & Performance Monitoring

Design methods included: MD6

Task scheduling in Prototype 2 was required by the user allocating time to each subtask in order to complete all 6 tasks. However, task scheduling may have been inhibited by the increased task dynamicity. For example, competitive chases between the hero and rustlers may take longer than return or save tasks. In this case, the user must know when to accept defeat and give up the chase without rescuing the cattle and instead press the 'No Animal' button to have enough time to complete all 6 tasks.

Performance monitoring partly remained from Prototype 1: the user had points scores and a combo bonus to use as a reference of performance. However, the graphics and sounds were also used for reinforcement of action.

A4 Additional Prototype 3 Content

A4.1 Prototype 3: Goals

From the prototype 2 evaluation it was clear the NFC-based interface was a promising approach and many of the short-term goals had been at least partially achieved but more had to be done to further integrate BrainQuest with the design guidelines as well as streamlining of existing design aspects. The goals of the BrainQuest prototype 3 focused on addressing unmet short-term goals from the previous iteration as well as approaching some of the outstanding long-term development targets before further implementing additional end-user requirements:

BrainQuest Prototype 3 Short-Term Goals	BrainQuest Long-Term Goals
1. Decrease PA fragmentation during user-object interactions.	1. Develop in-game EF performance measurement.
2. Add further support for the user understanding of game rules.	2. Expand opportunities for social interaction or multiplayer capabilities.
3. Increase the usability of the task choice selection screen.	3. Create initial ways of measuring EF performance.
4. Develop a variable difficulty system for hero task choices.	
5. Implement rustler scoring.	
6. Expand fantasy – sounds and graphics – for all game roles.	

Table 34: Prototype 3 Short and Long Term Goals

A4.2 Prototype 3: Updated Rules and Scoring

The hero score system remained the same as prototype 2 but added rustler point scoring. However, since the hero role was the primary measure of performance and the role most consistent with all pathways of the Diamond model (2012), the weighting of points was distributed more closely towards hero role. Instead, rustler points were designed as a means of ‘topping up’ one’s total score. Using the updated score system, users were presented a rolling score as they played through each of the 3 roles. The final points total was shown at the end of the 3 games in the feedback screen, including a breakdown of points earned for each of the roles.

Rustler points were attributed initially using Rustler Score System V1, which was assessed in user evaluation 1 (Appendix A4.2, p). However, following feedback at that session, minor updates were made to the system, creating Rustler Score System V2.

A4.2.1 Rustler Score System V1

Rustler points were predicated upon the delivery of hero animals, with 10 points per animal attributed but nothing rewarded for shuttle runs alone. This rule sought to add a limited element of strategy to rustling duties, providing an opportunity for coordination and cooperation between rustlers. For example, coordination of rustler runs could be used to help maximise points as a hero was only able to chase one at a time.

A4.2.2 Rustler Score System V2

Following feedback, the scoring system was changed to attribute 10 points per shuttle run between the hero and rustler pen and an extra 10 points were gifted for delivering an animal. This change sought to preserve the strategic aspect of rustling while generating rewards for PA.

A4.3 Prototype 3: Implementing Design Methods

The section compares the motivational design methods from the literature review with design decisions taken in prototype 3, as well as the methods retained from Prototype 2.

A4.3.1 General User Engagement

Design methods included: MD11, MD13, MD14

Intrinsic fantasy was similar to the previous prototype but further sounds and graphics in both hero and rustler roles were introduced. New prop signs (corresponding to aspects of the user interface) were added in an attempt to create stronger intrinsic links between the PA and the fantasy involved.

A4.3.2 Competence

Design methods included: MD1, MD3, MD4, MD7, MD8, MD10

The clear written and audio instructions, as well as the pre- and in-game rule explanations remained in prototype 3 (MD1).

In prototype 3, difficulty level was determined by opponent's skill (MD7, C) with respect to the rustlers. However, the difficulty was also manipulated with respect to following the task ordering rules through the variable difficulty level system (MD8). This required fundamentally changing task demands to refresh the novelty of the challenge (MD3, MD4). Hence, the variable level of challenge went beyond increasing the speed at which the user must act or the number of tasks to remember while utilizing the same strategy – it required strategic reformation. Plausible strategies on one difficulty level became redundant following a step up in level. Despite this, there was no evidence of children being able to follow the Prototype 2 task ordering rules at the default difficulty level (equivalent to World Class), so the experts proposed lowering the initial level of difficulty encountered by the user – this justified the inclusion of Rookie and Professional difficulties.

A variable time limit was also introduced to increase the difficulty and extend the length of time users had to concentrate. The variable difficulty allowed users to select the level which they were confident to play (MD7, B). However, during the evaluation sessions and the main intervention detailed in Chapter, user difficulty levels were based on performance (MD7, A).

Prototype 3 used support tools at different difficulty levels to bestow the user with confidence in their abilities (MD8) e.g. the task shading tool was designed to help the user understand the task ordering rules and instil confidence ahead of future difficulty levels. The task history tool allowed the user to keep track of previous tasks and inform their decision making.

While the performance feedback within the previous prototype was able only to provide the user with **(A)** frequent and **(B)** clear feedback, prototype 3 added **(C)** constructive feedback to the design (MD10). The user could now review task performance using the task history tool during and after each, which used colour (green and red) to represent correct and incorrect task choices - identifying success and unsuccessful decisions to the user.

A4.3.3 Autonomy

Design methods included: MD15, MD16, MD17

Autonomy was facilitated identically to the previous prototype: choice provided by different game roles and the opportunities provided by the social component of the game for different play styles and goal setting.

A4.3.4 Social Interaction

Design methods included: MD27, MD30, MD31, MD32, MD33, MD34

The dynamic between heroes and rustlers remained largely the same for prototype 3.

However, the introduction of rustler scoring was designed to enhance the influence of competition and in turn, promote higher intensity PA during chase activities. For example, for the hero, there was added incentive to catch the rustler, as they would be impacting the points haul of the rustler by catching them.

The variable difficulty level was also designed to level the playing field of different ability levels (MD30). From a physical perspective, it was designed to slow down and make the game difficult for successful players, impacting point scores. Hence, giving less advanced players, who playing at an easier difficulty but at a faster pace, an opportunity to catch up on their point scores at the very least.

A4.3.5 Cognitively Engaging Physical Activity

Design methods included: MD12, MD26, MD28, MD29

The cognitive engagement challenges remained from the previous prototype: demands of following task ordering rules, emotional regulation during social interactions, and coordination between onscreen and real-world activities.

However, prototype 3 sought to increase the physical activity intensity by modifying the number of procedures involved in each task and duration of NFC scanning operations.

A4.4 Prototype 3: Reviewing EF Challenge

In this section, the hypothesized correspondence between the challenge of individual EFs in the 6E test and prototype 3 is considered.

A4.4.1 Motor-Cognitive Coordination

Design methods included: MD25, MD26, MD27

The challenge of task scheduling remained from prototype 2: coordinate on-screen and real-world activities as well as opponent movements. Thus, motor-cognitive coordination involved planning and strategizing.

A4.4.2 Working Memory

Design methods included: MD2, MD3, MD4, MD5, MD6

The challenge to WM remained from prototype 2 with respect to the mechanisms of following the rules and handling rustlers. However, the introduction of variable difficulty and support tools, Task History and Task Shading, was designed to support and decrease the initial WM challenge, while incremental tool removal and the introduction of the Task Randomizer sought to maintain challenge at ability cusp (addressing R22-R24).

On difficulty level 1 the Task Shading tool supported the user by reminding them to change task type each time, thereby, following one of the task ordering rules. On difficulty levels 1 and 2, the Task History tool helped the user track previously completed tasks. The tool could be used by the user when remembering the span of previous tasks eluded them.

In later difficulty levels, the goal was to support ability improvement through layering additional challenge. On difficulty level 3 (comparable to prototype 2 difficulty), all supports were removed but at difficulty level 4 the Task Randomizer tool was introduced to disrupt the user's mental representation of the expected interface by scrambling the order of task choice thumbnails. Thus, this was designed to corrupt existing visual information regarding

the game held in WM and force a mental manipulation of visual images to remember previously completed tasks – sustaining user WM challenge at the cusp of ability (MD4).

A4.4.3 Inhibitory Control

Design methods included: MD2, MD6

The challenge to IC mostly remained from prototype 2: users had to switch between sustained attention and selective attention to understanding their environment and complete tasks. There was also the need to inhibit pre-potent responses and exercise self-control with regard to hero-rustler interactions. However, there was potentially an added temptation for the hero to catch rustlers – the chance to impact upon the rustler’s total point score by stopping them achieving bonus points for successful rustling. This exploited the competitive element of the game to increase the level of self-control required during interactions (MD34).

A4.4.4 Planning / Strategizing

Design methods included: MD2, MD3, MD6, MD25

The challenge to planning/strategizing partly remained from prototype 2: optimally sequence tasks and develop strategies to counter the rustlers. However, for the hero, planning/strategizing skills were to be challenged uniquely at each difficulty level, thereby, potentially requiring changes in strategy (MD3). The different difficulty levels and associated support tools attempted to force the user to reformulate previously successful strategies to successfully follow the task ordering rules. e.g. using the task history tool to support a task choice strategy (such as selecting successively different task types) on difficulty 2, would no longer be a suitable strategy on difficulty level 3 because the tool is removed. Hence, a more sophisticated strategy may be required. This was designed to inhibit training to specific strategies and content and instead encouraging the user to develop novel strategies and exercise strategic flexibility in light of changing circumstances – the underlying context-general skills more likely to transfer to real-world functioning.

A4.4.5 Cognitive Flexibility/Set Shifting

Design methods included: MD2

The challenge to cognitive flexibility/sets shifting remained partly the same as prototype 2: the user had to manage time and react to changes in their environment or arising opportunities. However, cognitive flexibility was also challenged when reformulating plans or strategies when attempting a new difficulty level for the first time.

A4.4.6 Task Scheduling & Performance Monitoring

Design methods included: MD6

The challenge to task scheduling remained from Prototype 2: the user had to allocate time to each subtask in order to complete all 6 tasks.

Performance monitoring partly remained from Prototype 2: the user had points scores and a combo bonus to use as a reference of performance as well as graphics and sounds which were also used for reinforcement of action. Moreover, the task history tool was another means of performance feedback regarding choices.

A5 Additional Final Prototype Content

A5.1 Final Prototype: Goals

Before assessment of the BrainQuest in a longitudinal evaluation, some final additions were made to the game to accomplish the outstanding development goals:

1. Reduce task ordering rule complexity
2. Develop EF performance measures
3. Expand opportunities for social interaction or multiplayer capabilities

The final changes made to BrainQuest were based upon analysis of the prototype 3 evaluation session as well as utilizing the design guidelines taken from the literature.

A5.2 Final Prototype: Rule Changes

The rules of prototypes 1-3 had sought to promote the challenge of WM at the cusp of ability by asking the user to mentally hold and manipulate complex task ordering rules, yet ensuring the rules were comprehensible for the target age group. However, evaluations 3 and 4 highlighted the game rules were too complex for most end-users to explain properly, even

with the addition of the variable difficulty level and support tools. Hence, after some consideration, BrainQuest's task rules were reduced in difficulty to exactly replicate the 6E test – noted below:

1. Like the 6E test, the user must change task type for each task choice.
2. Within the 5-minute time limit, the user must make sure that they have attempted all 6 subtasks while following Rule 1.

A5.3 Final Prototype: Implementing Design Methods

The section compares the motivational design methods from the literature review with new design decisions taken for the final prototype, as well as the methods retained from prototypes 2 and 3.

A5.3.1 General User Engagement

Design methods included: MD11, MD13, MD14, MD24

Intrinsic fantasy was similar to the previous prototype but further sounds and graphics were related to the trophies were introduced – a trophy splash screen appeared after a user successfully completed a difficulty level and was accompanied by 'victory music'. Thus, the user had to earn the trophies and they were presented intermittently rather than being a token gesture (MD24).

A5.3.2 Competence

Design methods included: MD1, MD3, MD4, MD7, MD8, MD9, MD10, MD22, MD23

All provisions for competence remained from prototype 3 but there were some additional supports. The introduction of trophies (MD23), the leaderboard, and historical statistics were designed to provide an additional means of performance feedback for the user. Earning a trophy or improving leaderboard rank corresponded to one's actions and represented a positive performance progression. Hence, it symbolized competence aimed to encourage users. Nevertheless, the leaderboard was an opt-out system for those who might respond to peer comparison negatively (MD22). These additional means of positive feedback attempted to layer challenge by establishing more than just one way of scoring performance (MD9).

A5.3.3 Autonomy

Design methods included: MD15, MD16, MD17, MD20, MD21

The trophies were an additional goal for users beyond simply following the task ordering rules and increased choice over potential goals (MD20, MD21). Leaderboards were also a goal, as were using the historical performance data to break one's own records. For example, user goals could be short term (e.g. earning points or stopping rustlers) or long-term goal (e.g. collecting all or specific trophies, targeting a specific position on the leaderboard or specific peers to beat, improving on one's maximum hero points score from the historical data).

A5.3.4 Social Interaction

Design methods included: MD18, MD19, MD27, MD31, MD32, MD33, MD34

Being able to review accomplished trophies, a collection of aesthetic belongings, aimed to be the catalyst for a social system of reputation and competition (MD18). Similarly, the leaderboard was designed to facilitate competition for those who were of a competitive nature – with specific players or with the entire class (MD19).

A5.3.5 Cognitively Engaging Physical Activity

Design methods included: MD12, MD26, MD28, MD29

These challenges remained the same from previous prototypes.

A5.4 Final Prototype: Reviewing EF Challenge

EF challenges remained the same as prototype 3.

A5.5 BrainQuest Completed Development Goals

The completed short-term development goals for prototypes 1-4 are shown the Table 35 below:

Completed BrainQuest Prototype 1 Goals	Completed BrainQuest Prototype 2 Goals	Completed BrainQuest Prototype 3 Goals	Completed BrainQuest Prototype 4 Goals
1. Translate paper mock-up into smartphone app using Google Maps interface and appraise the chosen technology.	1. Redevelop user-object interaction method.	1. Decrease PA fragmentation during user-object interactions.	1. Reduce task ordering rule complexity
2. Implement initial aspects of fantasy, including characters, objects, and themes from paper mock-up.	2. Add support to aid understanding of game rules.	2. Add further support for the user understanding of game rules.	2. Develop EF Performance Measures
3. Define rustler movement patterns and speeds, and physical distances between objects in order to pose a physical challenge to the user.	3. Maintain a scoring system for the new prototype.	3. Increase the usability of the task choice selection screen.	3. Expand opportunities for social interaction or multiplayer capabilities
4. Develop a score system for the game that rewards EF successes.	4. Create opportunities for social interaction or multiplayer capabilities.	4. Develop a variable difficulty system for hero task choices.	
5. Create a technology-free	5. Redevelop the fantasy themes	5. Implement rustler scoring.	

version of the game which meets all user requirements.	for the new prototype.		
		6. Expand fantasy – sounds and graphics – for all game roles.	

Table 35: BrainQuest Completed Development Goals

Appendix B – Additional Case Studies

This section presents 5 additional case studies created following the 5-week BrainQuest evaluation.

B1.1 Case Study 1: Rachel

B1.1.1 Overview

Rachel performed poorly on the EF pre-test measures and ranked similarly on the EF-focused, Trophy/Game measure of BrainQuest. Her mile rank suggested her to be one of the fittest children, yet her physical ability in BrainQuest was average as measured by Shuttle Runs/Game and Rustler Points/Game. She particularly enjoyed the leaderboard aspect of the game and invested in the game’s social dynamic.

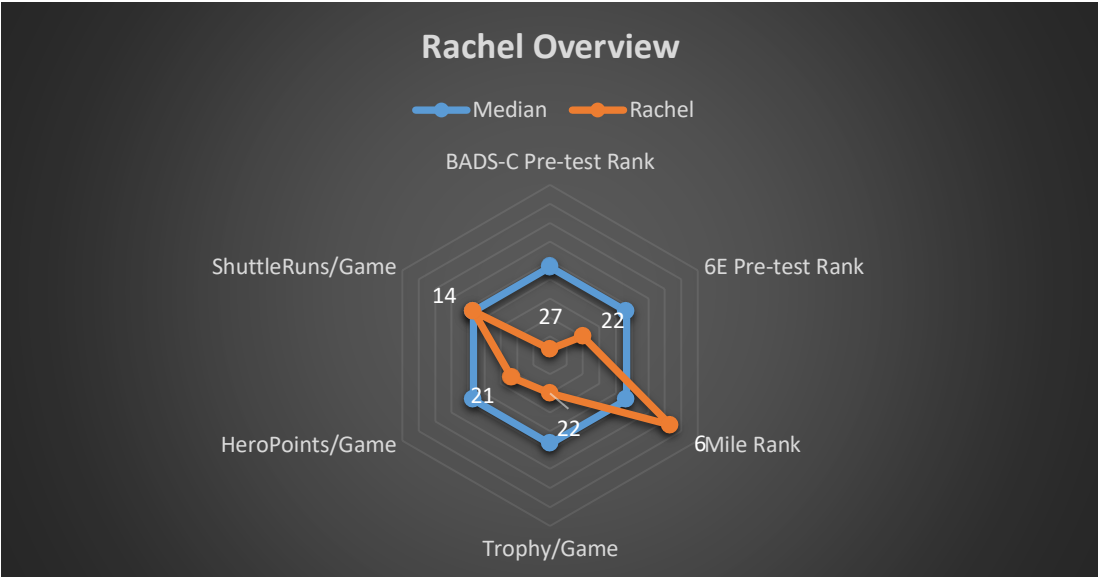


Figure 55: Rachel Overview

B1.1.2 BADS-C Performance

Low pre-test BADS-C performance, low 6E performance– Rachel was selected as a participant with low EF ability per the BADS-C pre-test, recording rank 27th BADS-C score and rank 22nd 6E score. In the 6E test, she followed one of the task ordering rules but not the other – she did not do the same task types in succession but she only completed 3 of the 6 task types. Hence, she achieved a profile score of 6 and a total score of 6.

6E improvement – At post-test on the 6E test Rachel could follow one task ordering rules – attempting each of the different task types but she made one mistake by doing two red task types in succession, scoring a profile score of 11. She also revisited the same task 3 or more times, subtracting 1 point and leaving a total score of 10.

B1.1.3 BrainQuest Performance

B1.1.3.1 Cognitive Training Performance

Low BrainQuest EF performance – Rachel ranked a little bit higher on measures of BrainQuest hero performance than the BADS-C but comparably with her 6E performance - Trophy/Game ranked 22nd and Hero Points/Game ranked 21st.

Slow start – In Rachel’s BrainQuest Test Game, she did not attempt to follow the task ordering rules and scored poorly on Trophy Score and Hero Points (Figure 56), suggesting she misunderstood the objective of the game. However, the following Game 1 she appeared to follow at least one of the task ordering rules and developed an initial strategy – substantially improving on these performance measures.

Repeated difficulties – On Rachel’s second attempt at Rookie-level she progressed and posted a study-high Hero Points score but she then met adversity and required 3 attempts before successfully passing Professional difficulty level. Furthermore, she then encountered problems while attempting to overcome World Class-level, a battle she did not prevail.

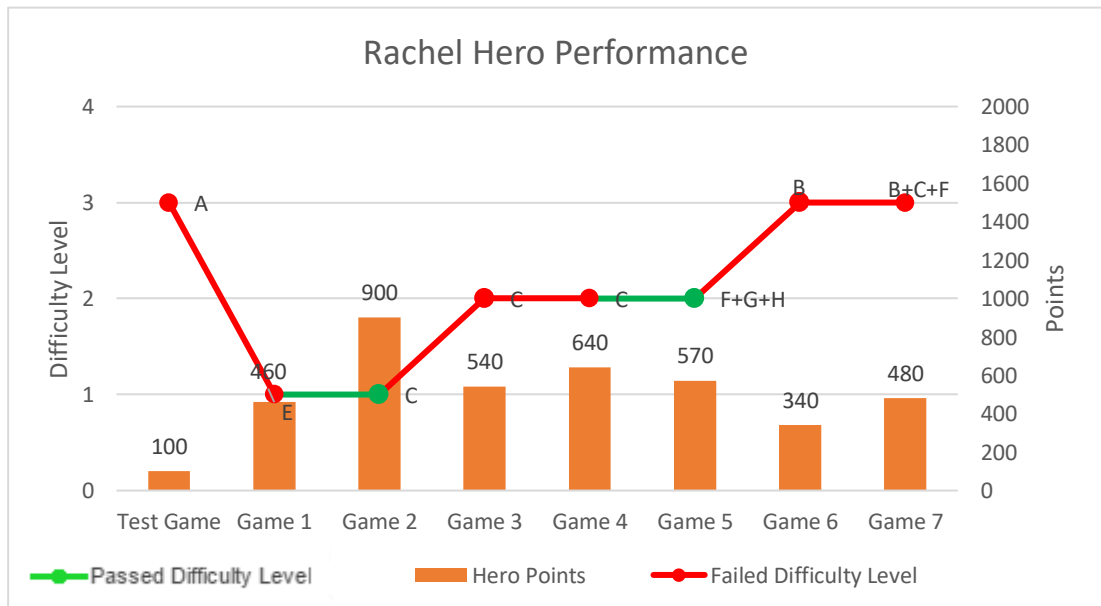


Figure 56: Rachel Hero Performance - Strategy Line

During Games 6 and 7 her Trophy Score and Hero Points (Figure 56) fell to their lowest since Game 1, reflecting the magnitude of the challenge. In general, Rachel's Hero Points scores ebbed and flowed but following Game 2, they appeared to be on a downward trajectory.

B1.1.3.2 Strategy Evolution

Early adoption of simple strategies – Rachel appeared to form her first strategy in Game 1 (Figure 57), where she undertook a task of the same type at every other task choice but tasks of a different type in-between. Though she did not make any mistakes, she failed to perform every subtask before the end of the time. Following this, on Rachel's third attempt to clear Rookie difficulty level, she successfully reverted to a simple task change strategy but her success was short-lived as she was unable to progress while using the strategy on the following 2 Professional level games. Perhaps one issue was that Rachel only made limited use of the task history tool and only used it once in Game 3 and twice in Game 4.

Socially influenced strategies – There may have been a social factor which impacted Rachel's strategizing. Rachel stated in her interview that there were times when she changed her strategy to catch Patrick:

“unless Patrick is trying to steal one of my cows. That's how I got wrong because I don't want him to...and then I just went to his pen and stole it back” – Rachel, Interview

The data logs supported this to some degree and during the session dated 12/03/15, Rachel (playing as the hero) displayed a bias towards stopping Patrick (playing as the sheep rustler) and stealing back his sheep – 7/13 tasks involved either catching Patrick or stealing his sheep and were the only tasks upon which she repeated in succession, thus, breaking the rules.

Game 5 was briefly successful and Rachel progressed past Professional difficulty by selecting tasks in cycles of 3 different task types (F), grouping by an animal (G) to ensure each of the 6 types were completed, and keeping a repeatable order (H). This is compounded by her post-intervention interview, where she stated *“I did top to bottom”* and then pointed from top to bottom and left to right on an example interface. However, the observations also hinted that Rachel's strategy may have been a product of cooperation with another case study individual, Alexa, with whom Rachel was close friends. Alexa had developed a very similar strategy the previous session before Rachel used it. Furthermore, Alexa's absence in the games which followed may have removed Rachel's source of advice.

Rachel attempted World Class difficulty twice in the final session, where she was placed in a group with two of her friends, Angelina and Celeste, because her regular partners, Patrick and Alexa, were absent. Although the strategy she adopted during Professional difficulty was suitable at World Class difficulty, Rachel did not deploy it in the same way. Instead, on both occasions Rachel appeared to double up on task choices, grouping tasks of the same task type together and changing task type every second time. Rachel’s interview may account for the reason behind the change as she stated that she deviated from her strategy:

“when someone wanted a cow, and someone wanted a sheep, I couldn’t just say no”
 – Rachel, Interview

Further evidence supported this assertion in the observations which reported a game in which Rachel’s regular case study group mates were absent and instead involved Rachel’s friends, Joanna, and Angelina. The game was described in the observations as:

“a group effort between the girls and they seem less competitive with each other, especially Rachel” – Main Researcher, General Observations

Rachel and Joanna were observed agreeing to keep each other’s pens topped up. Thus, we can again conclude a social factor upon strategizing but also an example of direct cooperation.

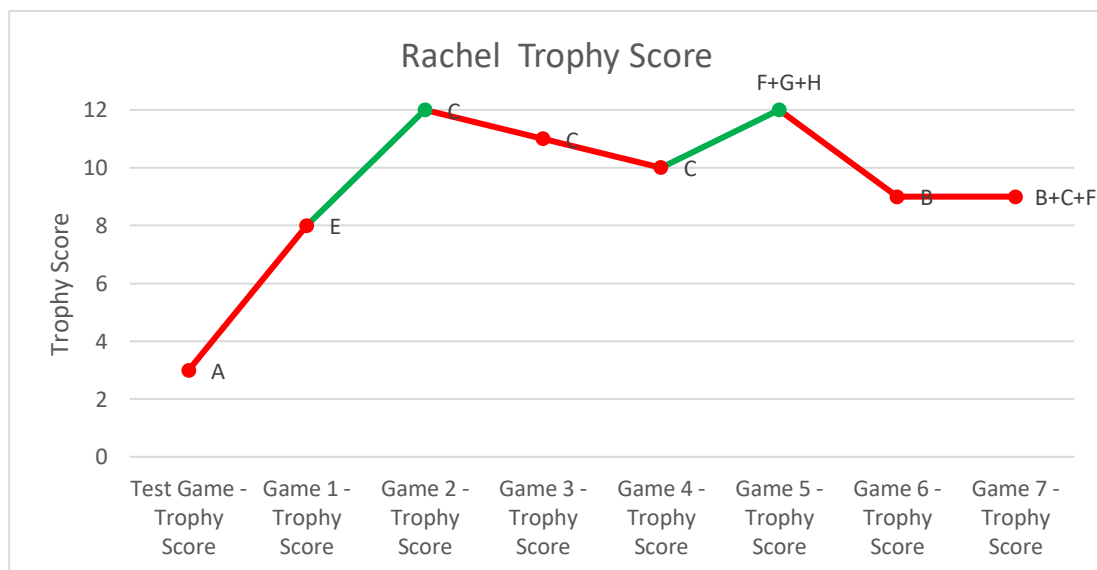


Figure 57: Rachel Trophy Score

B1.1.4 Physical Activity

High physical ability, low BrainQuest performance – Rachel’s PA ability was strong and ranked 6th in the class for mile time and 7th for the beep test. She was described by her

teachers as being “*very fit*”. However, this ability did not translate into her rustler performance where she ranked 16th in terms of her Rustler Points/Games and 14th for Shuttle Runs/Games.

Modest incline in PA – Unlike her Hero Points which were more varied, measures of Rachel’s rustler performance showed a steady but modest incline, particularly her Shuttle Runs which began at their lowest point in Game 1 (Figure 59) and peaked in the penultimate game. However, her mean number of Shuttle Runs (Mean = 6.4; SD = 1.3) only matched the class mean of 6.4. Despite this, Rachel’s Rustler Points (Figure 58) surpassed the class mean at 73.8 (Mean = 73.8; SD = 24.7) and log files suggested this was because of great efficiency in successfully capturing animals – timing runs to evade capture.

Average perceived exertion – In Rachel’s post-intervention interview she reported BrainQuest as being a 5 on the fatigue scale (where 1 is not tiring and 10 is exhausting) but agreed that the level of fatigue depended on with whom one was playing:

“it was harder when I played with Melvin and Martin, not Patrick” – Rachel, Interview

The observations noted variable intensities during gameplay (“*skipping*”, “*walking*”, “*jogging*”, “*sprinting*”), Rachel appeared to slow down to a walking pace or even standing still at times when reading the smartphone interface but ran fast when interacting with other players.

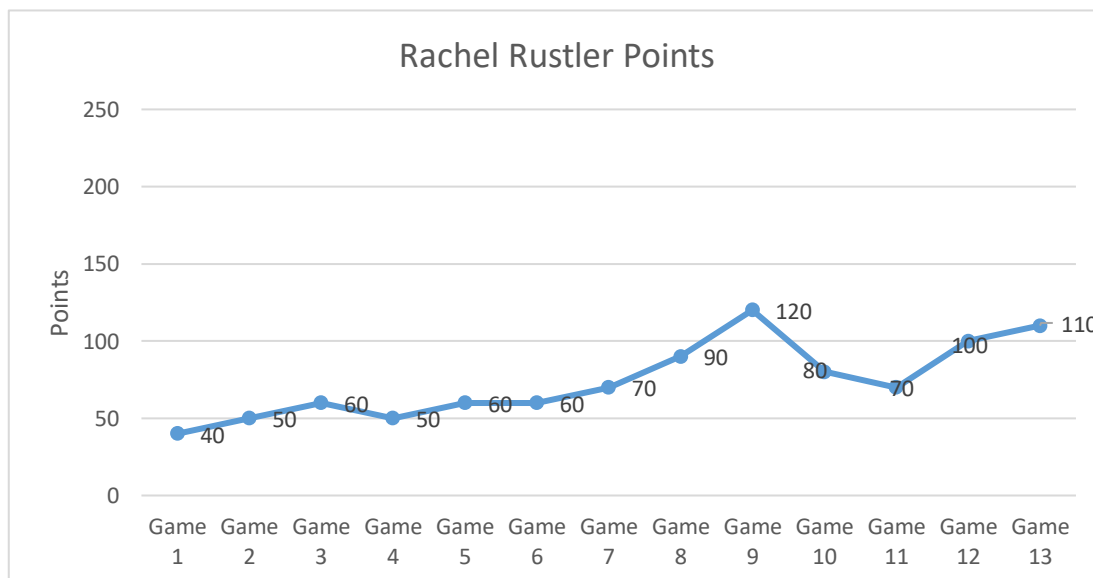


Figure 58: Rachel Rustler Points

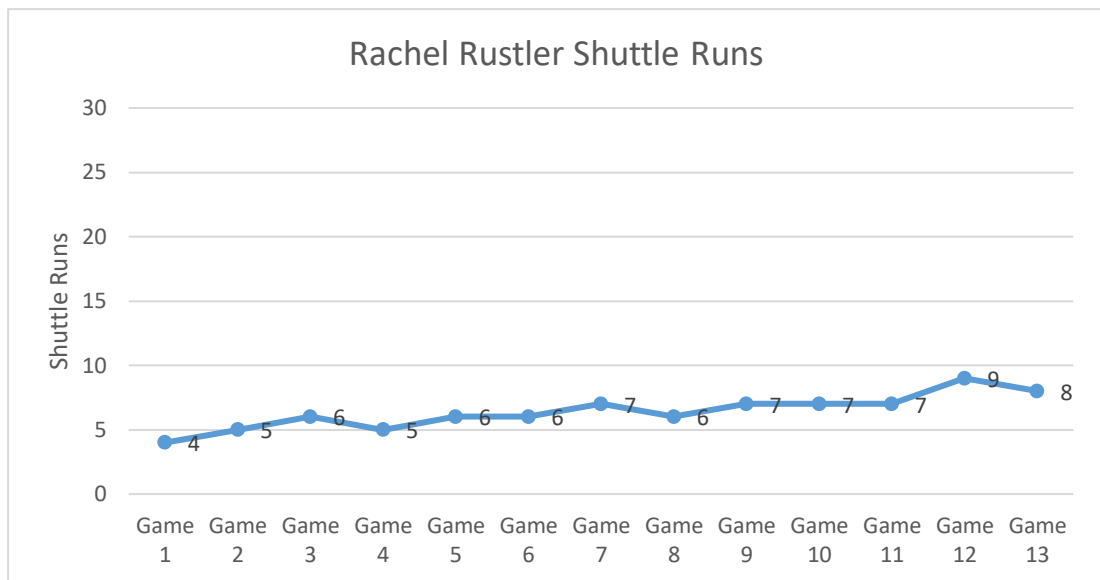


Figure 59: Rachel Rustler Shuttle Runs

B1.1.5 Joy + Pride/Confidence/Self-efficacy

Investment in leaderboard – Rachel appeared to have social motivations for play and emphasised leaderboard performance. Her total hero points led to being ranked 13th on the leaderboard (much higher than her Hero Points/Game) but she played 23 games (both hero and rustler) in total - the 3rd highest number in the study and offered to play in additional games during absences. Throughout the observations, there are instances of Rachel looking at the leaderboard and stating her desire to improve her position:

“she saw she was the bottom of the leaderboard and she wasn’t very happy and she wants to be higher than Mustafa” – Observer, General Observations

Rachel exhibited an emotional reaction towards her position:

“Rachel was giving herself a hard time about being 13th on the leaderboard” – Observer, Case Study Observations.

Rachel stated the importance of the leaderboard herself, and declared that if she could change one thing about the game, it was to be *“top of the leaderboard”*. Thus, despite the limited ability suggested by her performance rankings, Rachel maintained her leaderboard position through hard work and undertaking a lot of gameplay.

Though not quite as important, Rachel still valued the trophies involved in the game and was observed logging into the game specifically to view her trophy cabinet as well as stating her disappointment at only winning 2 trophies – *“I wanted 3”*.

Increasing rule self-efficacy – With respect to her self-efficacy towards the game, Rachel felt like she had improved throughout the intervention. While she initially misunderstood some of the game rules and was “*confused*”, it made her feel “*happy*” to have gotten better. It seemed as if Rachel’s confidence grew as the study progressed and she was observed sharing her achievements with other players and the researchers. Rachel described the game in one word as being “*fun*”.

B1.1.6 Social Experience

Love/Hate relationship - Rachel endured a complex relationship with Patrick, a case study in her group, who she appeared not to get on with prior to the study. Throughout the study, Rachel was less than complimentary of Patrick when questioned about their relationship, yet she spent a great deal of time interacting with him during and beyond gameplay and the observers frequently noticed warm interactions during the intervention – “*laughing and smiling*”, “*engaging in banter*”. Meanwhile, Patrick was willing to help Rachel throughout the study – explaining the rules, giving advice, and even providing encouragement. Hence, the game facilitated positive social interactions between the two and questioned whether the publicly negative rhetoric was genuine dislike. Nevertheless, neither Rachel nor Patrick felt their relationship had changed following the study.

Teasing & cooperation with friends – On the other hand, Rachel and Alexa, who were close friends prior to the study, similarly also endured competitiveness and cooperation. Rachel and Alexa teased each other during hero-rustler interactions but also exchanged advice regarding the game rules. Rachel stated that she would not have felt as motivated to play the game without Alexa and despite their competitiveness, was observed applauding her friend on her achievements.

Furthermore, as stated, Rachel was one of the only to exhibit cooperative gameplay which she undertook even to the detriment of her own performance and this suggested BrainQuest could provide her with a means for creating social belonging.

B1.1.7 Rachel Summary

Contributions towards RQ1 – Indirect Pathways Summary	Contributions towards RQ2 – Direct Pathways Summary
<p>Joy + Pride/Confidence/Self-efficacy</p> <ul style="list-style-type: none"> • Set a goal of topping the leaderboard • Was also motivated by playing with her friend, Alexa • Found the game hard to understand initially • Felt more confident regarding the rules by the end • Broadcasted her achievements to other players • Described BrainQuest as “<i>fun</i>” 	<p>Pre-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 27^h • Achieved 6E score of 6 • Able to follow task ordering rule 1 but not rule 2 • No strategy <p>Post-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 11th • Overall age scaled score improved • Achieved 6E score of 11 • Able to follow task ordering rule 2 but not rule 1 • No strategy <p>BrainQuest Performance Evolution</p> <ul style="list-style-type: none"> • Strategy complexity increased in Game 5 but then became infeasible • Light use of task history tool • Appeared to be a social influence upon strategy in the final 2 games • Deployed strategies of low, high and very high complexity • No maintenance strategies used • Deployed 5 different feasible strategies • Deployed 5 different feasible strategy combinations • Highest Difficulty Level Completed: 2 • Trophies/Games: 2/7 • Highest Hero Points Score: 900 • Difficulty Level (Win/Lose) <ul style="list-style-type: none"> ○ Rookie: 1/2 ○ Professional: 2/1
<p>PA</p> <ul style="list-style-type: none"> • Mile Rank: 6th • Mean Rustler Shuttle Runs Rank: 14th • Mean Rustler Shuttle Runs: 6.4 • Shuttle runs peaked Game 12/13 • Number of Shuttle Runs increased with number of games • Fatigue scale: 5/10 • Physical difficulty depended on whom opponent was • Said she was “<i>enjoying the running</i>” 	
<p>Social Experience</p> <ul style="list-style-type: none"> • Cooperation <ul style="list-style-type: none"> ○ Cooperated with Alexa in learning the game rules ○ Rachel felt engaging with Alexa helped motivate her to play ○ Cooperated directly with Angelina and Joanna to help maximize group gains of all roles • Competition 	

<ul style="list-style-type: none"> ○ Rachel’s goal to top the leaderboard alluded to her competitiveness ○ Previously had a difficult relationship with Patrick prior to the study and at points during the study but they also interacted with each other positively as well 	<ul style="list-style-type: none"> ○ World Class: 0/2
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Table 36: Rachel Summary

B1.2 Case Study 2: Leonard

B1.2.1 Overview

Leonard performed poorly on the BADS-C EF battery, though he scored better on the 6E subtest. His physical ability was also among the worst in the class and his BrainQuest performance on EF and physical ability measures corresponded with his pre-testing. However, Leonard enjoyed competing with his case study peers and set a goal of being the best in his group. He also appeared to form a good relationship with Natalia over the course of the BrainQuest sessions.



Figure 60: Leonard Overview

B1.2.2 BADS-C Performance

Low pre-test BADS-C performance, Moderate 6E performance– Leonard was selected as a participant with low EF ability per the BADS-C pre-test – ranked 26th overall BADS-C score but his pre-test 6E score ranked 16th in the class. On the pre-test 6E, he followed one but not both task ordering rules correctly – he successfully changed task type each time but was unable to attempt each of the 6 parts as he only left himself 2 seconds to complete green part 2, not enough time to attempt the task. Leonard’s strategy was to undertake one part of each task type in a cycle of 3 before choosing the previously unattempted part of each type upon the following cycle but there was no clear order to his choices. He also earned two additional strategy points for undertaking a set number of items for each task. Thus, he scored a total of 12 points.

6E decrease– On the post-test 6E, Leonard recorded a decreased score of 11/16 and though able to undertake all task types, he broke the other task ordering rule twice – repeating 2 red tasks and 2 blue tasks back to back. He maintained the same strategy as before but returned to each task type more than 3 times, hence, scoring an additional strategy score of 1.

B1.2.3 BrainQuest Performance

B1.2.3.1 Cognitive Training Performance

Low BrainQuest EF performance: On EF-focused measures of BrainQuest performance Leonard was ranked 20th for Trophy/Game and 24th for Hero Points/Game. These were similar to his overall pre-test BADS-C ranked 26th but slightly worse than his pre-test 6E, ranked 16th.

Challenged by Professional difficulty – In Leonard’s BrainQuest Test Game he was unable to follow either task ordering rule and recorded a low Trophy Score and Hero Points (Figure 61). In Game 1 Leonard made an improvement and appeared to develop a strategy but he remained unsuccessful with respect to winning a trophy. Following this Leonard successfully completed Rookie-level for the first time and recorded one of his highest Hero Point scores but this success was short-lived and Leonard then took 4 attempts to complete Professional difficulty. Meanwhile, Leonard’s Hero Points remained relatively stable but notably dipped in Game 5. On his final attempt, he successfully completed the game on Professional difficulty level but his Hero Points did not rebound.

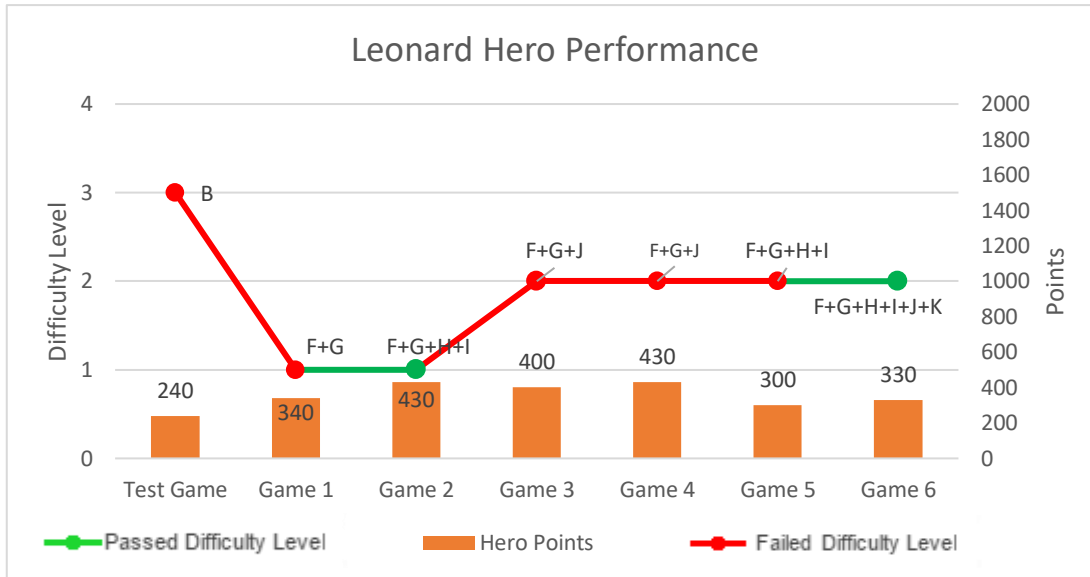


Figure 61: Leonard Hero Performance - Strategy Line

B1.2.3.2 Strategy Evolution

Complex but unsuccessful early strategies – Leonard initially attempted (Figure 62) to group tasks of the same type together during the test game and did not form a feasible strategy until Game 1 where he started to select tasks of each type in cycles of 3 until all task types had been completed (F) and also grouping by an animal (G). However, on his last of his 6 completed task types, he made a mistake and again chose a previously implemented task, thus, losing two points towards his total Trophy Score. On his next attempt (Game 2), however, Leonard was able to successfully pass Rookie difficulty level and maintained his strategy but added additional complexity – not only did he do (F) and (G) but he chose tasks in a repeatable order (H) and chose them in the order of top to bottom (I).

Socially influenced strategies – In Game 3 Leonard attempted the same strategy as before but this time, he made a mistake midway through and selected 2 consecutive ‘Return Cow’ tasks, though this was the only time he deviated from the strategy. Leonard did the same in Games 4 and 5 but selected 2 consecutive ‘Return Sheep’ and ‘Stop Cow Rustler’ tasks respectively. The observations suggested a social factor affecting Leonard’s task choices in Games 3, 5, and 6 as he interrupted tasks to repeatedly stop Natalia:

Game 3: “Leonard was carrying a cow towards the hero cow pen, saw Natalia, stopped what he was doing to chase her and catch her and is now randomly carrying a cow” – Observer, Case Study Observations

Game 5: “Leonard starts with a return task but upon seeing Natalia escape with a cow, he tags her” – Observer, Case Study Observations

Game 6: “Leonard stops his task to follow Natalia around” – Observer, Case Study Observations

Reliance on task history tool – Alternatively, the variety of the different tasks where errors occurred during different games and the fact that not all rule breaks were made to catch rustlers, implied additional cognitive reasons for mistakes. Furthermore, the data logs showed Leonard making use of the task history tool – twice in Game 3, once in Game 4, and 4 times in Game 5 – which suggested he was trying to follow the task ordering rules. The post-intervention interview supported this assertion as Leonard cited the task history tool as a means of supporting his task choices.

Strategic breakthrough – Finally, on Leonard’s last game he successfully carried out a complex strategy like those which he’d persistently attempted to implement in previous games. Though Leonard did not attempt difficulty levels beyond Professional, the observations indicated he devised strategies in advance of attempting more difficult levels. He stated with regards to Legendary difficulty:

“You know how the rustler tasks are red, the save cow and save sheep tasks are blue, and the stop ones are yellow, so you could remember them if you’ve just done a red and cow task and then remember that you need to do now either a blue and save task or a like a blue cow task or a yellow cow task” – Leonard, Interview

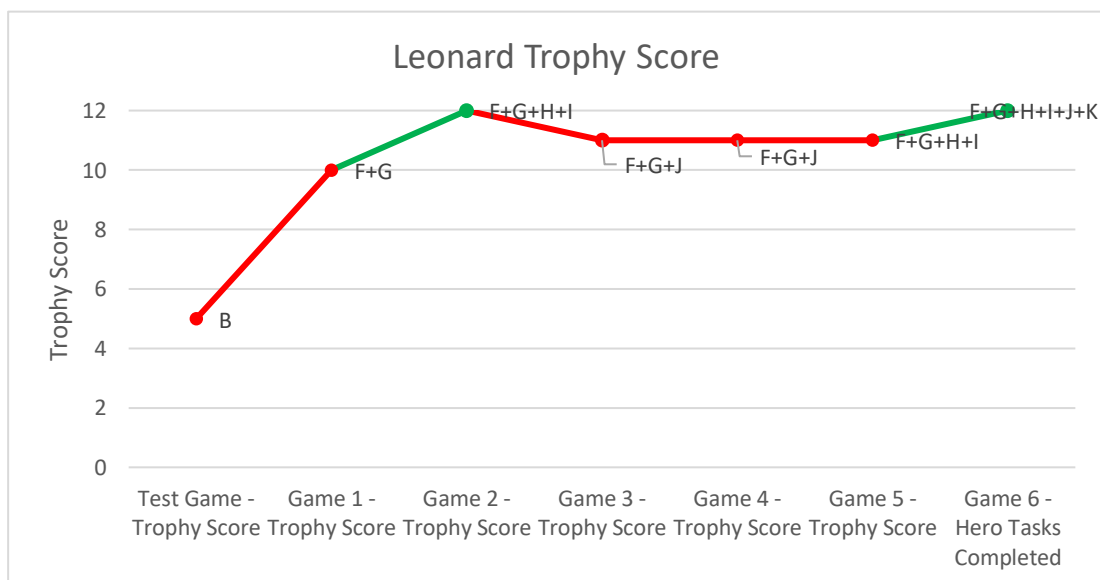


Figure 62: Leonard Trophy Score

B1.2.4 Physical Activity

Low physical ability and low BrainQuest performance – Leonard’s physical ability was among one of the worst in the class, something emphasised by his teachers, and he ranked 25th for mile time (there was no bleep test data available). His BrainQuest PA measures reflected this and he ranked 27th for Shuttle Runs/Game and 26th for Rustler Points/Game. This suggested the motivational game design in BrainQuest was unable to push Leonard beyond his usual physical limits.

Volatile before declining runs – Leonard’s Shuttle Run graph indicated low amounts of PA compared to other participants (Figure 64). His Shuttle Run mean was 3.2 (SD=1.8) – far lower than the class mean of 6.4. Leonard’s achieved number of runs varied – they were volatile in the middle part of the study between games 4 and 9 recording steep peaks and troughs. Leonard’s PA declined drastically towards the end of the study and he barely made any Shuttle Runs at all in later games, thus, emphasising BrainQuest’s inability to sustain his uptake in PA. Leonard’s Rustler Points (Figure 63) followed almost the identical trajectory and his mean of 31.7 was also well below that of his peers (53.4).

Running required motivation – On the other hand, there was evidence Leonard’s low levels of PA could be accounted for by his desire to always return with either a cow or sheep. During Game 6, an observer noticed Leonard timing his runs, though his score suggested this strategy was not always effective:

“Leonard seems to be timing his runs so that he always returns with something rather than running for the extra 10 points” – Observer, Case Study Observations

Leonard’s interview supported this assertion as he described a technique where he’d wait until the hero was at the opposite end of the play space before attempting to steal an animal. This also highlighted how strategizing was not limited to the hero role.

Another contributing factor towards the low PA was the extrinsic focus of his gameplay goals. For example, it seemed like he desired to obstruct other players to reduce their points rather than scoring points for himself:

“Leonard has a strategy of trying to hide cows under the pen” – Observer, Case Study Observations

Despite this, the observations suggested that Leonard had mixed fortunes:

“every single one of you tried to ruin my strategy” – Leonard, General Observations

In addition, Leonard stated that he *“didn’t like running for nothing”*, in reference to doing shuttle runs where there were no animals available to steal from the hero pen.

Socially influenced PA – There also seemed to be a social factor, particularly his warm relationship with Natalia which caused him to adjust his timing to increase the frequency of interactions with her:

“it is as if Leonard want to be caught as he is spending time between two the pens, waiting for Natalia” – Observer, Case Study Observations

In his post-test interview Leonard stated that he enjoyed the *“thinking”* aspects of the game better than the *“physical stuff”*, yet on the contrary, he described BrainQuest as being a 4 on the fatigue scale and found the running *“fine”*. However, there were many observed instances of Leonard *“running”* and he was described as *“out of breath”* following a chase with Natalia. Finally, the teachers noticed an improvement Leonard’s PA following the study:

“Leonard has really surprised me because the boy has trouble walking and he ran a mile this morning” – PE Teacher, Interview

“I could not believe it” – Class Teacher, Interview

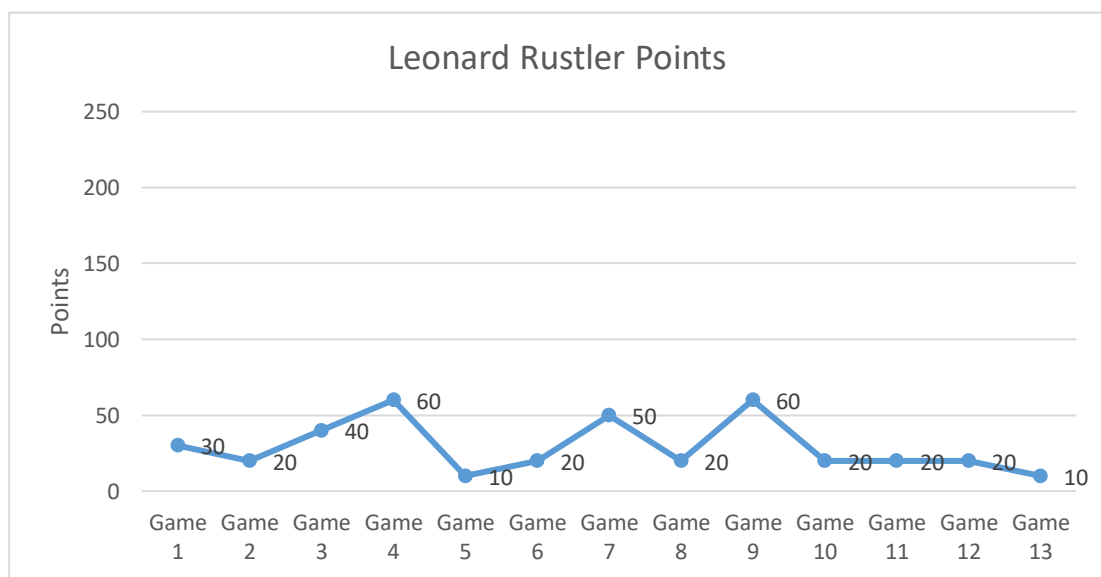


Figure 63: Leonard Rustler Points

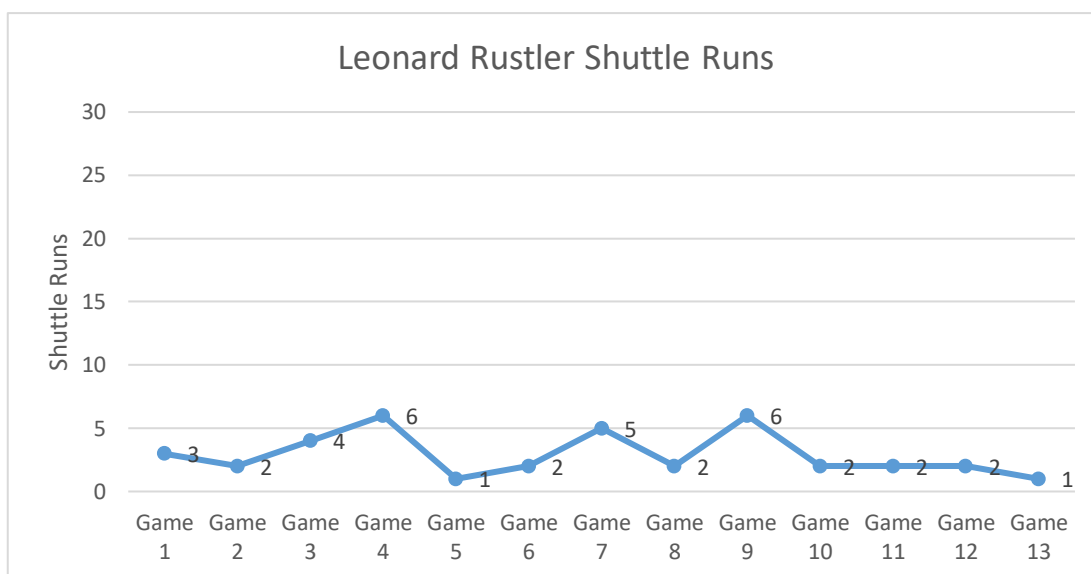


Figure 64: Leonard Rustler Shuttle Runs

B1.2.5 Joy + Pride/Confidence/Self-efficacy

Investment in trophies – Leonard seemed motivated by both the leaderboard and the trophies. Leonard was observed setting trophy goals, describing his disappointment not to have won a trophy after certain games, and celebrating enthusiastically following trophy wins. Leonard described a feeling of “*pride*” in his trophy achievements during his interview.

Motivation to beat specific people – Leonard found the leaderboard to be even more motivational than the trophies. Unlike many of the other case study children, his leaderboard goals were to beat specific individuals rather than all his peers:

“I was aiming for a higher score than my teammates every match. I wasn’t aiming for like any sort of milestone on the leaderboard, just a higher score than my teammates on a match. Not ever, just if they got a higher score than me on one match, then I tried to get a higher score than them on the other match” – Leonard, Interview

The individuals he wanted to beat were his case study opponents, Natalia and Angelina.

Hero-rustler interactions above all – It appeared that Leonard’s favourite aspect of the game were the hero-rustler interactions and he was frequently observed enjoying chases with

Natalia. Thus, even activities involving PA component were enjoyable, even for a child of limited physical ability.

Increasing game self-efficacy – Leonard appeared to be aware of his cognitive limitations as he described himself as having a poor memory – “*I have a really short term memory...like a fish*”. However, his self-efficacy towards the activity improved throughout the study and he felt increasingly competent:

“I feel like I’ve gotten better at the game. The first match I wasn’t too good because I didn’t really know how to play but 4 weeks, I got better” – Leonard, Interview

Leonard was proud of this achievement:

“I feel really good about myself, like proud I guess” – Leonard, Interview

Leonard even asked to play on World Class difficulty level before he had completed Professional, which illustrated his increasing confidence. In one word Leonard described his BrainQuest experience as being “*awesome*”.

B1.2.6 Social Experience

Social interaction bias – As stated, Leonard and Natalia interacted a great deal during gameplay and they appeared to develop a fierce competition, often becoming embroiled in arguments, accusations of cheating, and chases beyond the game boundaries – on one occasion Natalia fell over during a chase. Despite this, Leonard and Natalia appeared to develop a good relationship and, though competitive, Leonard particularly seemed to enjoy their interactions – he was regularly described as “*laughing*” and “*smiling*” while chasing her. Furthermore, it may have been this enjoyment which affected his task choices and levels of PA as Leonard appeared to maximise opportunities to socialize with Natalia. Leonard was also observed with sharing his strategies bilaterally with Natalia, something which he promised not to do with any other players.

Notwithstanding, Leonard appeared to interact in a different way with Angelina, the other case study individual in his group – he didn’t opt to catch her often and the observation notes highlight this bias. Leonard reported “*no change*” in his relationship with the other players in his group, which contradicted the observations regarding Natalia. Furthermore, at Leonard’s hero Game 4, he played with friends due to an absence in another game – a game he was observed particularly enjoying.

B1.2.7 Leonard Summary

Contributions towards RQ1 – Indirect Pathways Summary	Contributions towards RQ2 – Direct Pathways Summary
<p>Joy + Pride/Confidence/Self-efficacy</p> <ul style="list-style-type: none"> • Used trophies as a form of goal setting • Expressed pride in his trophy achievements • Wanted to beat particular individuals on the leaderboard • Broadcasted his achievements to other players • Appeared to enjoy interactions with other children more than any other activity • Expressed himself by trying to be cunning and hide stolen animals under pen signs • Found the game hard to understand initially • Self-reported having poor memory ability • Felt more confident regarding the rules by the end • Enjoyed the game more at the end than the start • Described BrainQuest as “<i>awesome</i>” 	<p>Pre-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 26th • Achieved 6E score of 12 • Able to follow task ordering rules 1 but not 2 • Deployed strategy – set number of parts <p>Post-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 17th • Overall age scaled score improved • Achieved 6E score of 11 • Able to follow task ordering rule 2 but not rule 1 • Deployed strategy – set number of parts <p>BrainQuest Performance Evolution</p> <ul style="list-style-type: none"> • Complex strategies were developed and attempted from Game 1 but was commonly unable to successfully implement them • Moderate use of task history tool • May have been a social influence upon strategy • Deployed strategies high and very high complexity • Maintenance strategies used • Deployed 6 different feasible strategies • Deployed 4 different strategy combinations • Highest Difficulty Level Completed: 2
<p>PA</p> <ul style="list-style-type: none"> • Mile Rank: 25th • Rustler Shuttle Run Rank: 27th • Mean Rustler Shuttle Runs: 3.2 • Shuttle runs peaked in Games 4 and 6/13 • Number of runs reduced towards end of study • Fatigue scale: 4/10 • Appeared to compensate for his lack of physical ability by being economical and using strategy in his PA 	

<ul style="list-style-type: none"> • Only wanted to run when there was the possibility of returning with an animal • Following BrainQuest, PE noticed improvement in his physical ability beyond the context of the study 	<ul style="list-style-type: none"> • Trophies/Games: 2/7 • Highest Hero Points Score: 430 <ul style="list-style-type: none"> ○ Rookie: 1/1 ○ Professional: 1/3
<p>Social Experience</p> <ul style="list-style-type: none"> • Cooperation <ul style="list-style-type: none"> ○ Leonard shared his strategies only with Natalia • Competition <ul style="list-style-type: none"> ○ Leonard and Natalia chased each other beyond the game boundaries and argued • Relationship Change <ul style="list-style-type: none"> ○ Leonard and Natalia appeared to develop a good relationship but he felt there to be no change in his relationships with other group members post-study 	

Table 37: Leonard Summary

B1.3 Case Study 3: Natalia

B1.3.1 Overview

Natalia was the highest ranked performer on the BADS-C EF testing battery and scored well on the 6E subtest. This seemed to reflect on the EF-focused BrainQuest measure, Trophy/Game. However, she performed less well on measures incorporating some form of PA – Hero Points/Game, Rustler Points/Game, Shuttle Runs/Game – and this is consistent with her pre-test physical ability measures. She was very fair with her opponents and gave a lot of help and advice to the other children in her group but she enjoyed competing with them as well, particularly Leonard.

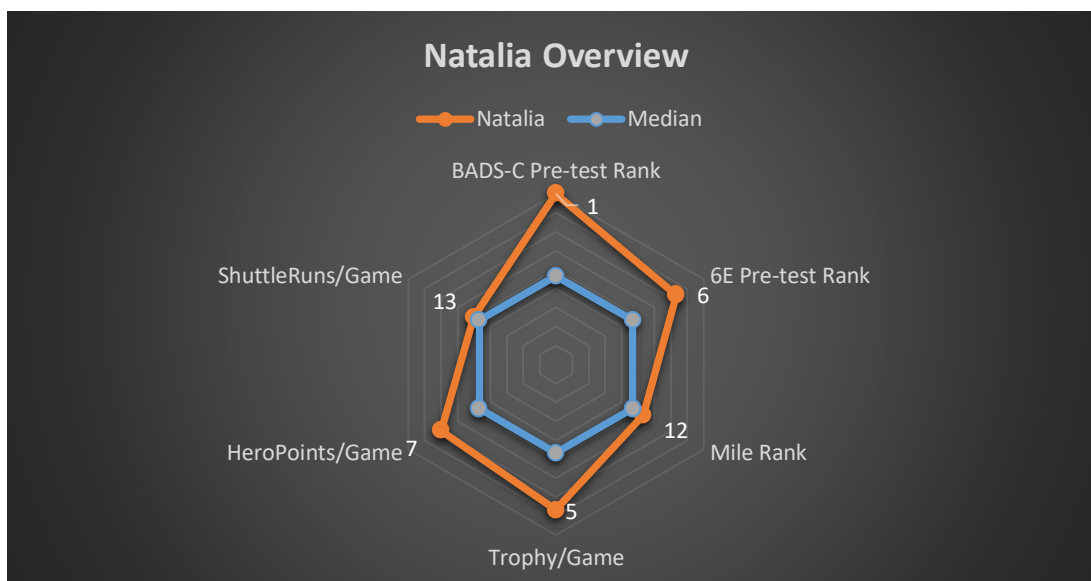


Figure 65: Natalia Overview

B1.3.2 BADS-C Performance

High pre-test BADS-C performance, High 6E performance – Natalia was selected as a participant with high EF ability per the BADS-C pre-test, recording the rank 1st overall BADS-C score but her pre-test 6E score ranked 6th in the class. On the pre-test 6E, she could follow one but not both task ordering rules correctly, deploying a strategy in which she did part 1 of each task type followed by part 2, scoring 2 additional strategy points. Note Natalia only did each of the 6 tasks one time. Thus, she scored a total of 14 points.

6E Improvement – On the post-test 6E, Natalia recorded an improved 16/16, scoring a full profile score in following the task ordering rules in full and maintained the same strategy as before, undertaking (for the most part) part 1 of each task type followed by part 2 but she also set several items for each written part – doing 3 at a time. Natalia did each part only once apart from green part 2 which she did twice – the second time coming at the end. Hence, she scored an additional strategy score of 4.

B1.3.3 BrainQuest Performance

B1.3.3.1 Cognitive Training Performance

High BrainQuest EF performance – On measures of hero role performance Natalia performed well, ranked 5th for Trophy/Game and 7th for Hero Points/Game. These were slightly less than her overall pre-test BADS-C, ranked 1st but similar to her pre-test 6E, ranked 6th.

Increasing difficulty, decreasing Hero Points– In Natalia’s BrainQuest Test Game she was unable to follow either task ordering rule (Figure 66). Natalia developed an appropriate strategy in Game 1 and more than doubled her Hero Points in comparison to the Test Game, yet she was still unable to follow the task ordering rules in their entirety. However, the following game marked the start of a 3-game streak of completing difficulty levels – first Rookie, then Professional, and finally World Class. Meanwhile, following a Hero Points peak in Game 2, the points drastically declined with each new difficulty level attempted until Game 6. This suggested Natalia found each increase in difficulty incrementally harder, an assertion supported by her reliance upon the task history tool during Game 3 – according to game logs and observations. Further, during Game 4 Natalia was observed as looking “*confused*” by the researchers, who noted she twice went to the wrong cattle pen before realizing her mistake, forgot to collect a sheep before returning to her pen and was talking to herself throughout. Finally, in her post-intervention interview, Natalia stated each difficulty level to be “*harder*” than the last but the biggest difficulty jump was between World Class and Legendary.

Task Randomizer impacted performance – There may have been multiple reasons for Natalia’s particularly poor performance in Game 5. Firstly, Natalia appeared confused by the change in the interface task demands as she said to the observer, “*It’s all jumbled up*” and looked “*confused*” during the game. A second issue was an NFC scanning bug which would have cost her as a small amount of time to fix and likely interrupted her concentration. Though Natalia only completed 5 tasks, perhaps because she had to reset her NFC system, the bug itself would not have taken long to fix and she also neglected to complete more than one of the 6 tasks. Thus, Natalia would have likely failed the difficulty level regardless. Despite this Natalia could complete Legendary difficulty at the second attempt and her points rebounded to 670.

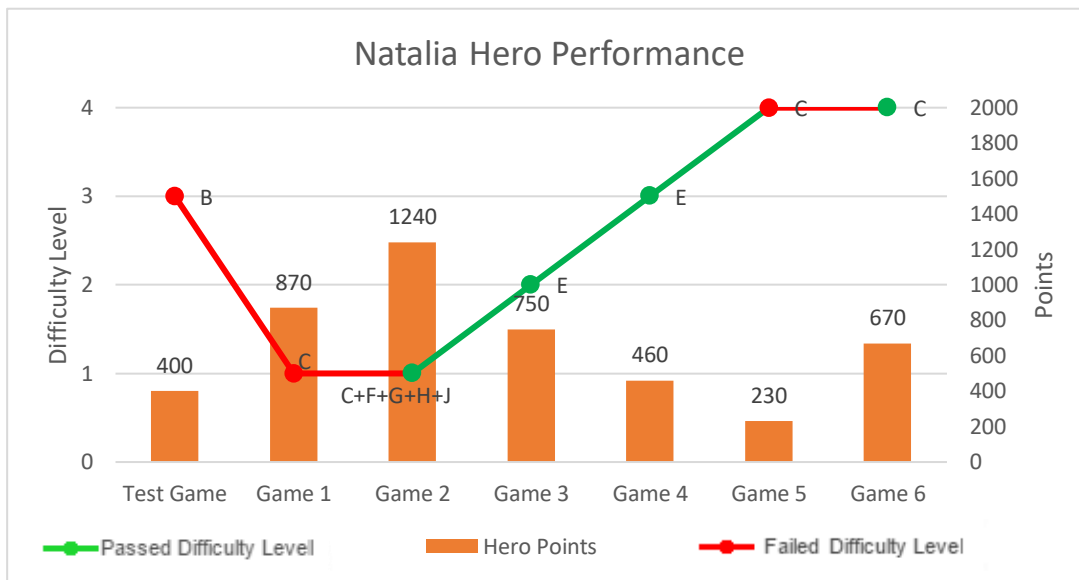


Figure 66: Natalia Hero Performance - Strategy Line

B1.3.3.2 Strategy Evolution

Early deployment of a very complex strategy – Natalia initially attempted to group tasks of the same type together during the Test Game (Figure 67) and did not form a feasible strategy until Game 1 where she unsuccessfully implemented a simple task type change – she failed to ‘Stop Sheep Rustler’ despite completing 11 tasks. On her next attempt (Game 2), however, Natalia was able to successfully pass Rookie difficulty level, adding complexity to her strategy but adding some additional complexity – she selected tasks of each type in cycles of 3 until all task types had been completed (F), grouping by animal (G), maintaining a repeatable order (H) and choosing them in the order of top to bottom (I) before changing tact after completing all 6 tasks (J) and undertaking a simple task change each time (C). It was this specific strategy which Natalia alluded to in her post-intervention interview:

“When playing as the hero did you have a strategy when trying to follow the task ordering rule?” – Main Researcher, Interview

“Yeh once you’ve done, like if you were saving a sheep you could just go to stop the sheep rustler then you can go to the... what’s the other one?” – Natalia, Interview

“Return a sheep” – Main Researcher, Interview

“Yeh return the sheep” – Natalia, Interview

Adopting a more flexible strategy to increase social interaction – Natalia also stated that following the development of this strategy, she maintained it throughout the study but the data logs show otherwise. In Game 3 Natalia drastically changed her strategy (Figure 67) to

undertake a task of the same type for every other task choice and tasks of a different type in-between but not consistently implementing a previously unchosen subtype (E). The data log suggested the involvement of a social factor as each of the consistent task choices was a ‘Stop Rustler’ task but she split her time evenly between the different rustlers so this was not a product of particular relationships.

Making use of support tools – Natalia still successfully progressed passed Professional difficulty at her first attempt with the help of the task history tool which she used 10 times, something she acknowledged during the post-study interview. In Game 4 Natalia successfully deployed the same strategy to progress through World Class difficulty but this time the repeated task was a ‘Save’.

Task Randomizer affected strategy – On Natalia’s first attempt at Legendary difficulty she changed strategy again but this time was unsuccessful as she attempted a simple task change (C). When asked by the researcher in the interview if there were any points where it was difficult to remember which task to do next, Natalia replied that it was “*a little hard on Legendary*”. Despite this, Natalia passed Legendary difficulty with the same strategy on her second attempt.

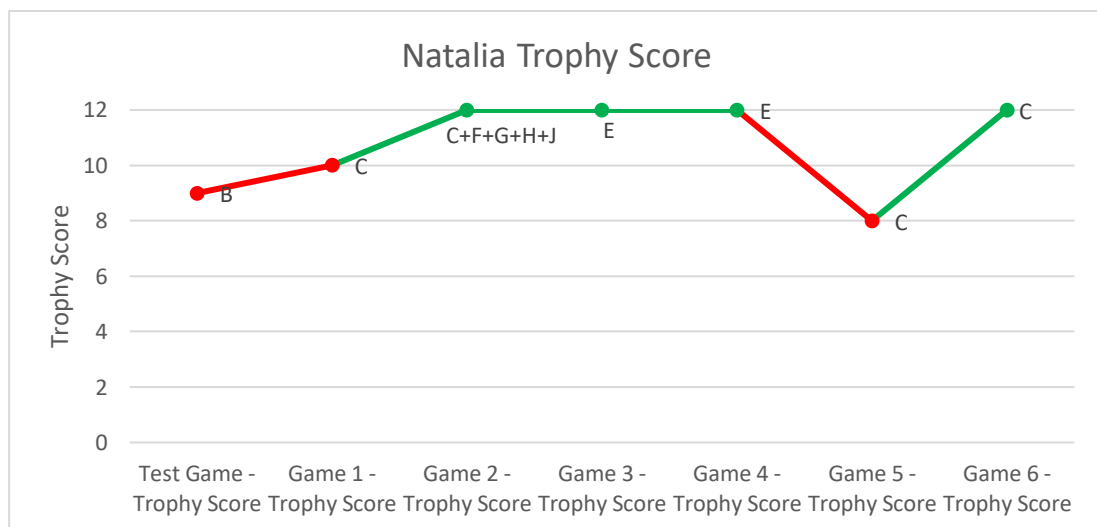


Figure 67: Natalia Trophy Score

B1.3.4 Physical Activity

Moderate physical ability and moderate BrainQuest performance – Natalia’s PA ability was ranked 12th for mile time and 16th for the beep test and her teachers described her

physical ability as being within the “top 60-70% of the class”. Her BrainQuest PA performance and she ranked 12th for Shuttle Runs/Game and 11th for Rustler Points/Game.

Maintaining PA – Natalia’s Shuttle Run mean of 6.9 was above that of the class mean (6.4, SD=1.6). Her Shuttle Runs were relatively stable throughout (Figure 69) but included some intermittent peaks. There was no drop-off in Shuttle Runs by the end of the study and BrainQuest appeared to sustain Natalia’s PA throughout the study. This pattern was similar to her Rustler Points (Figure 68) where there were steeper peaks, particularly in Games 3 and 13 and would suggest that in certain games she was able to successfully return more animals.

Disparity between observed and reported exertion – However, the intensity of the PA was unclear. Natalia claimed not to find BrainQuest tiring and described the game as being a 3 on the fatigue scale but the observations noted her complaining about feeling “tired” and during Game 11 complained:

“I’ve got sore legs, I can’t even run” – Natalia, Case Study Observations

In general, the observations presented instances of Natalia undertaking a broad spectrum of PA intensities throughout the study – walking, jogging, running, sprinting, skipping and dancing.

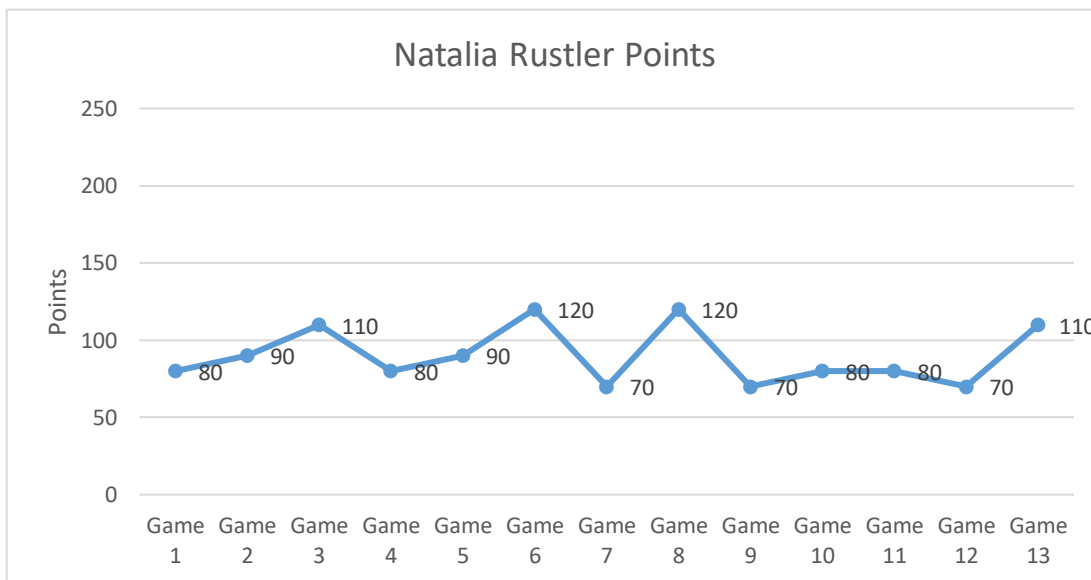


Figure 68: Natalia Rustler Points

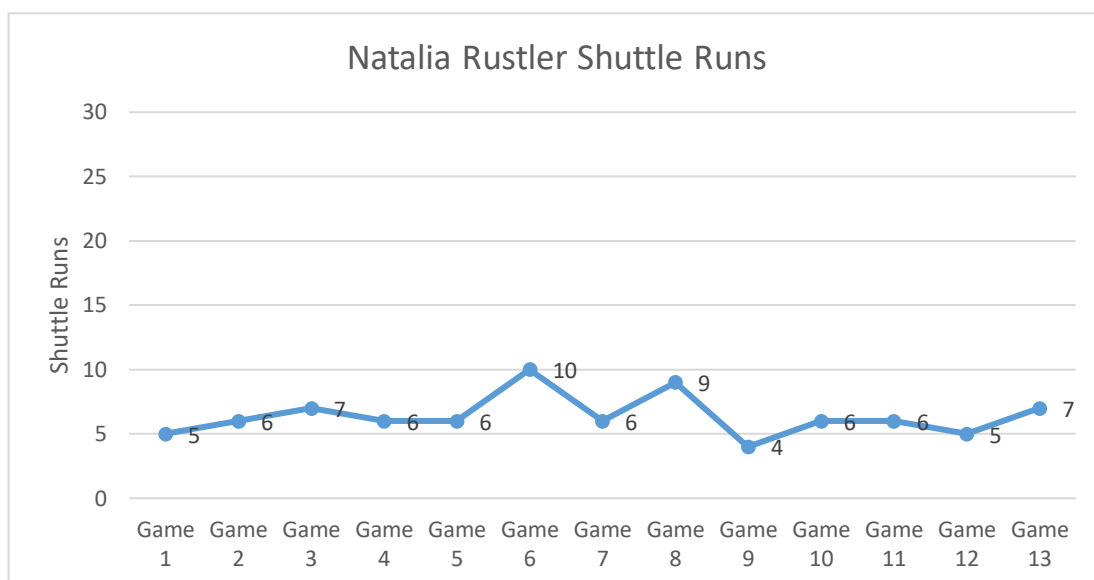


Figure 69: Natalia Rustler Shuttle Runs

B1.3.5 Joy + Pride/Confidence/Self-efficacy

Trophy pride – Natalia appeared to enjoy the game and was one of the children who requested the opportunity to fill in for absent peer during the sessions. During the study, Natalia appeared to take great pride in her trophy and leaderboard achievements and she sometimes danced in celebration following trophy wins, broadcasted her achievements to other players, and showed an interest peer performance. She described winning trophies as making her feel “*proud*”. Furthermore, Natalia intimated both an increasing enjoyment of the game and working harder towards the end of the study because of the trophies:

“*Did your opinion change on Brainquest change over the sessions?*” – Main Researcher, Interview

“*It was really really good over the weeks and it was really fun.*” – Natalia, Interview

“*Did you enjoy it more at the beginning or more at the end?*” – Main Researcher, Interview

“*More at the end.*” – Natalia, Interview

“*Why was that?*” – Main Researcher, Interview

“*Because at the end, I got more trophies and I worked harder.*” – Natalia, Interview

Improvement in self-efficacy – With respect to self-efficacy, Natalia said during her interview that she had got better at the game as the sessions progressed. She found the jump between World Class and Legendary the most difficult and she “*couldn’t believe*” she’d

overcome it. However, her PE teacher had also noticed a positive change in her confidence during PE sessions:

“She just seems to hold herself a bit more and stand out a bit more. I think she seems a bit more confident in herself and there is a lot of stuff going on with these P7 girls and hormones and growing up but she just looks like she’s just happy in herself at the moment, she seems a bit taller, but I think it’s her stature rather than her height.” – PE Teacher, Interview

B1.3.6 Social Experience

Unbiased and warm competition – Natalia stated the most motivating aspect of BrainQuest was being able to *“run around with friends”* and she stated particularly enjoying the interactions with Leonard and Angelina in her post-test interview. Though she appeared competitive with Leonard, it did not affect her task ordering rule performance to the same extent as Leonard’s. For example, on some occasions, Natalia opted to catch rustlers more frequently than other tasks but there was no bias in her task choices towards a particular opponent. Moreover, she even complained when she felt Leonard was persistently choosing to catch her rather than Angelina. Notwithstanding, she was observed increasingly *“laughing”* and *“smiling”* during interactions with Leonard throughout the study, which may have suggested a warming relationship.

Advising peers – Natalia was one of the case study children most open to cooperation and regularly gave advice to her opponents during the study *“because it felt like the right thing to do”* and there are examples from every game advising Leonard and Angelina on game rules, procedures, and setup.

B1.3.7 Natalia Summary

Contributions towards RQ1 – Indirect Pathways Summary	Contributions towards RQ2 – Direct Pathways Summary
<p>Joy + Pride/Confidence/Self-efficacy</p> <ul style="list-style-type: none"> • Interacting with her classmates was her biggest motivation for play • Enjoyed trophies and leaderboard • Expressed pride in her trophy achievements 	<p>Pre-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 1st • Achieved 6E score of 14 • Able to follow task ordering rules 2 but not 1

<ul style="list-style-type: none"> • Stated working harder and enjoying the game more after winning trophies • Broadcasted her achievements to other players • Found the game hard to understand initially • Felt more confident regarding the rules by the end • PE teacher noticed a positive change in her confidence during and following the study 	<ul style="list-style-type: none"> • Deployed strategy – equivalent to BrainQuest strategies F and G <p>Post-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 3rd • Overall age scaled score improved but not as much as some of her peers • Achieved 6E score of 16 • Able to follow task ordering rules 1 and 2 • Deployed strategy – equivalent to BrainQuest strategies F and G • She managed her time much more efficiently
<p>PA</p> <ul style="list-style-type: none"> • Mile Rank: 12th • Beep Test Rank: 16th • Rustler Shuttle Run Rank: 12th • Fatigue scale: 3/10 • Mean Rustler Shuttle Runs: 6.9 • Shuttle runs peaked in Games 6/13 • Number of runs peaked in the middle of the study but maintained around her mean towards the end of the study 	<p>BrainQuest Performance Evolution</p> <ul style="list-style-type: none"> • Strategies varied in terms of complexity, and after increasing quickly in complexity, they became more basic again towards the end of the study • Heavy use of task history tool • May have been a social influence upon strategy • Deployed strategies of low, moderate, high, and very high complexity • Maintenance strategies used • Deployed 6 different feasible strategies • Deployed 3 different strategy combinations • Highest Difficulty Level Completed: 4 • Trophies/Games: 4/7 • Highest Hero Points Score: 1240 • Difficulty Level (Win/Lose) <ul style="list-style-type: none"> ○ Rookie: 1/1 ○ Professional: 1/0 ○ World Class: 1/0 ○ Legendary: 1/1
<p>Social Experience</p> <ul style="list-style-type: none"> • Cooperative <ul style="list-style-type: none"> ○ Natalia reported and was observed helping people understand the game rules and giving them advice ○ Natalia stated enjoying playing with other children • Competitive <ul style="list-style-type: none"> ○ Natalia argued with Leonard and chased him beyond the boundaries of the game • Relationship Change <ul style="list-style-type: none"> ○ Natalia seemed to increasingly enjoy playing with Leonard throughout the study 	

Table 38: Natalia Summary

B1.4 Case Study 4: Angelina

B1.4.1 Overview

Angelina's BADS-C EF testing battery performance was the class median but she scored best on the 6E subtest. Angelina was also the fittest girl in the class and one of the fittest overall. She was a great all round BrainQuest player and ranked highly on all performance measures. However, she was less social than the other members of the group and was focused on earning as many points as possible.

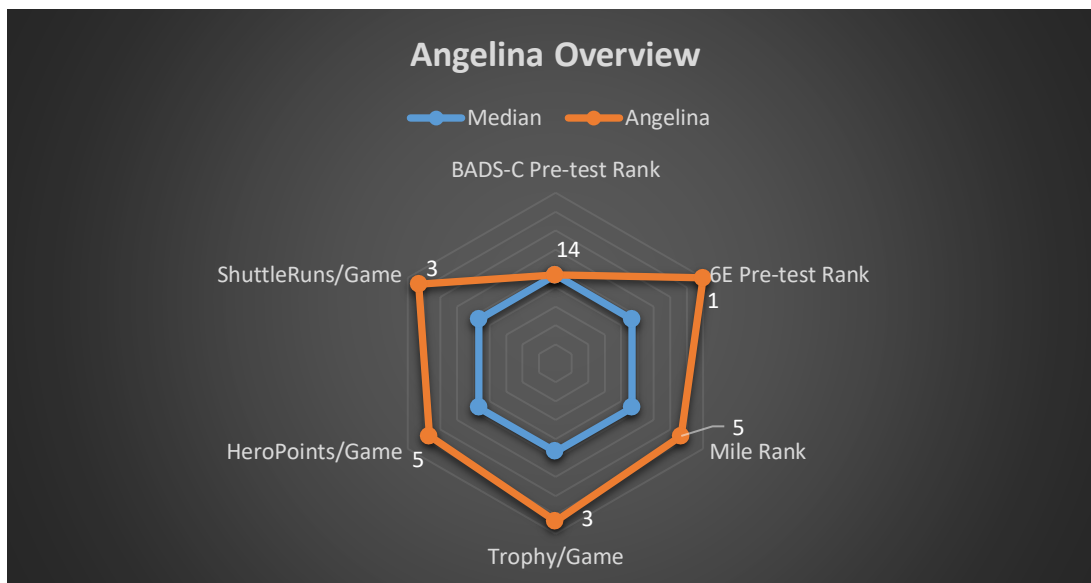


Figure 70: Angelina Overview

B1.4.2 BADS-C Performance

Moderate BADS-C performance, high 6E performance – Angelina was selected as a participant with middling EF ability per the BADS-C pre-test, ranked 14th overall BADS-C score but her pre-test 6E score ranked 1st in the class. In the pre-test 6E, she was able to follow both tasks ordering rules correctly – maximum 12 points for profile score. Angelina's strategy was to do part 1 of each task type followed by part 2, scoring 2 additional strategy points. She earned a further 2 strategy points for undertaking a set number of items for each task. Thus, scoring a maximum of 16 points.

Maintenance at 6E ceiling – On the post-test 6E, Angelina recorded the same score as at pre-test and maintained the same strategy, though she undertook each task more than once. Angelina’s post-test BADS-C rank was 1st in the class.

B1.4.3 BrainQuest Performance

B1.4.3.1 Cognitive Training Performance

High BrainQuest EF performance – On measures of hero role performance, Angelina was ranked 3rd for Trophy/Game and 6th for Hero Points/Game. These were slightly less than her overall pre-test 6E where she ranked 1st but much higher than her overall BADS-C which was ranked 14th.

Early inconsistency – In Angelina’s BrainQuest Test Game, she successfully followed the task ordering rules (Figure 71) earning a respectable number of Hero Points and even appeared to be following a strategy. In Game 1 she further developed the complexity of her strategy but narrowly missed out on a trophy. However, in her second attempt at Rookie-level Angelina passed successfully and posted her highest number of Hero Points score of all.

Making use of the support tools – Angelina said that she had made use of the task shading tool during Games 1 and 2 and the task history tool during Games 3 and 4, as well as the post-game feedback tool if she failed to win a trophy. In Game 3 Angelina consulted the task history tool 7 times and in Game 4 used it 11 times.

In Game 3 Angelina failed to progress past Professional difficulty and her points slumped. Note, due to a delay in starting the session Angelina did not play as the hero against her regular case study opponents during Game 3 and instead played against Melvin and Martin. Furthermore, Angelina initially misunderstood the task history tool during this game, and thought the most recent task was displayed at the bottom rather than the top – perhaps confusing her.

Increasing difficulty, stagnating points – Following this, Angelina went on a run of 3 successful games and progressed through Professional, World Class, and Legendary difficulty. Furthermore, Angelina’s points somewhat rebounded but she was unable to get anywhere near her Game 2 score. Angelina stated that she sometimes found it hard to remember the next appropriate task in trying to follow the rules, particularly on Legendary.

Changing approach after trophy cabinet completion – Following Angelina’s accomplishment of all trophies, her approach appeared to change. In her final game, she was unable to win a trophy but it seemed her approach to the game may have changed on account of her perception that completing more tasks resulted in a greater haul of points (though it would not yield a trophy) – she asked the researchers if she had to follow the rules. Alternatively, as described later, a social factor may account for the failure to win a trophy.

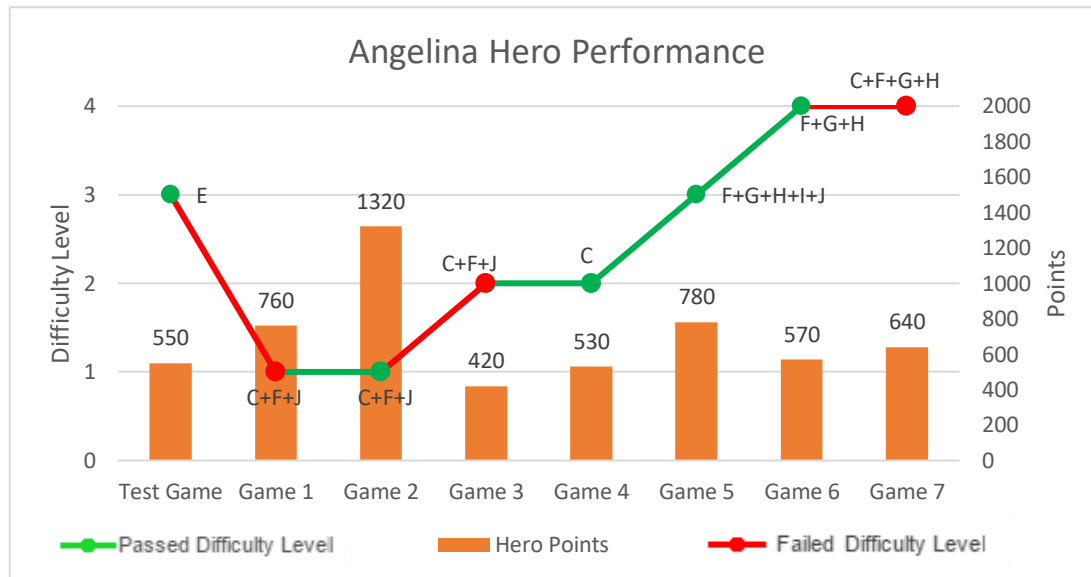


Figure 71: Angelina Hero Performance - Strategy Line

B1.4.3.2 Strategy Evolution

Early complex strategies, difficulty implementing them – Angelina deployed a strategy as early as the Test Game (Figure 72) and successfully did a task of the same type at every other task choice and tasks of a different type in-between (E). In Game 1, Angelina made her strategizing more efficient and selected tasks of each type in cycles of 3 until all task types had been completed (F) before changing tact (J) to undertake a simple task change each time (C). Despite this Angelina’s attempted strategy failed as she selected to ‘Stop Sheep Rustler’ for a second time (according to her pattern) rather than to ‘Stop Cow Rustler’. During her post-intervention interview Angelina described organising her strategy by animal:

“I did all the sheep tasks first and then did all the cow tasks after” – Angelina, Interview

In Game 2 she deployed the same strategy and successfully completed Rookie difficulty. However, at Professional level her strategy failed and she was forced to re-attempt

Professional difficulty but this time she successfully utilized a simple task switch (C). The observations suggested Angelina was taking more time over her task choices during Game 3:

“Angelina’s looking at her screen for a few seconds deciding on the task to do before opting for a return task” – Observer, Case Study Observations

Furthermore, unlike her initial attempt Angelina made use of the task history tool and used it 3 times during her second attempt.

Adopting more flexible strategies – World Class difficulty Angelina successfully selected tasks of each type in cycles of 3 until all task types had been completed (F) while grouping by an animal (G) and for a period of 6 task choices she maintained a repeatable order (H), going from top to bottom through the interface (I). Angelina used a similar strategy during her first and successful attempt at Legendary difficulty but she maintained the same order throughout the entire game (H) and did not follow in the order of top to bottom. The observations further suggest that Angelina may have dropped the top to bottom strategy in order to increase her flexibility to catch rustlers at opportune moments:

“Angelina was going to do a particular task but then saw an opportunity to easily stop a rustler so changed her chosen task” – Observer, Case Study Observations

In her interview, Angelina stated that she changed her strategy to *“remember the colors”* of tasks rather than the order in which they appeared on the game’s interface. Moreover, she continued to take time and care over her task choices:

“Looking at her screen for about 30 seconds while choosing a task” – Observer, Case Study Observations

Uncharacteristic final game – Angelina’s last game was unsuccessful. For parts of the game she appeared to deploy strategies (F), (G), and (H) but at other times her choices appeared to be of random different types (C). However, Angelina made 2 mistakes, consecutively repeating task types twice during the game. In spite of this, it appeared unclear as to whether or not it was a mistake made as a result of cognition, misunderstanding of the scoring system, or a social factor. On one hand, she stated that the jump from World Class to Legendary difficulty was the hardest part of the game during her interview. On the other, she was observed cooperating with other girls, Rachel and Joanna during Game 7 and the girls were described as *“helping each other earn points”* through teamwork.

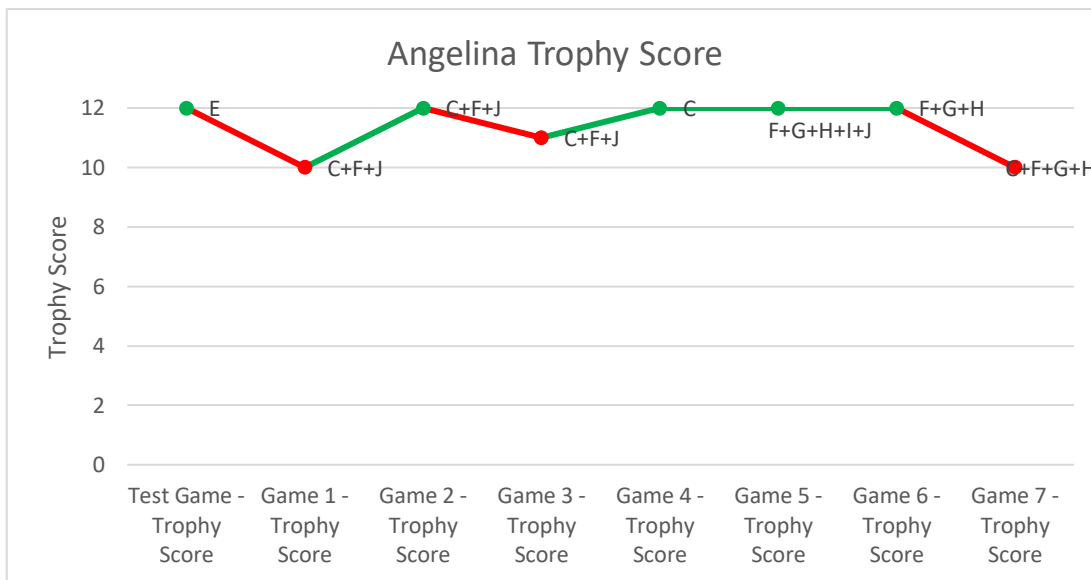


Figure 72: Angelina Trophy Score

B1.4.4 Physical Activity

High physical ability, high BrainQuest performance – Angelina presented one of the highest levels of PA ability in the class and was ranked 5th for mile time and joint 1st for the beep test. Angelina was described as “*very fit*” by her teachers and she told the researchers that she “*runs a lot*” in her spare time. Her BrainQuest PA measures were reflective and she was ranked 3rd for Shuttle Runs/Game and 5th for Rustler Points/Game.

Accumulating substantial rustler bonus points – Angelina’s Shuttle Run mean was 10.1 and Rustler Points mean was 53.4 which are both far above the class means – 6.4 and 53.4, respectively. The number of Shuttle Runs were stable throughout (Figure 74) and did not drop off at the end of the study, without any steep peaks or troughs. Her Rustler Points (Figure 73) were more variable and followed a mostly repeated pattern of intermittent short peaks and troughs throughout – the peaks indicating substantial bonus points for successful animal capture. Thus, her rustling strategy appeared to be very successful in many games.

Moderately perceived exertion – The observations described Angelina’s PA as being constant and a high level throughout the study, mostly described as “*running*” or “*sprinting*” during hero-rustler interactions and was less interspersed with low-intensity PA than the other case studies. Angelina rated BrainQuest a 5 on the fatigue scale but felt it tiring during the rustler role towards the end of the time limit:

“Like in the middle when you are a rustler and you’ve been running a long time.” –
 Angelina, Interview

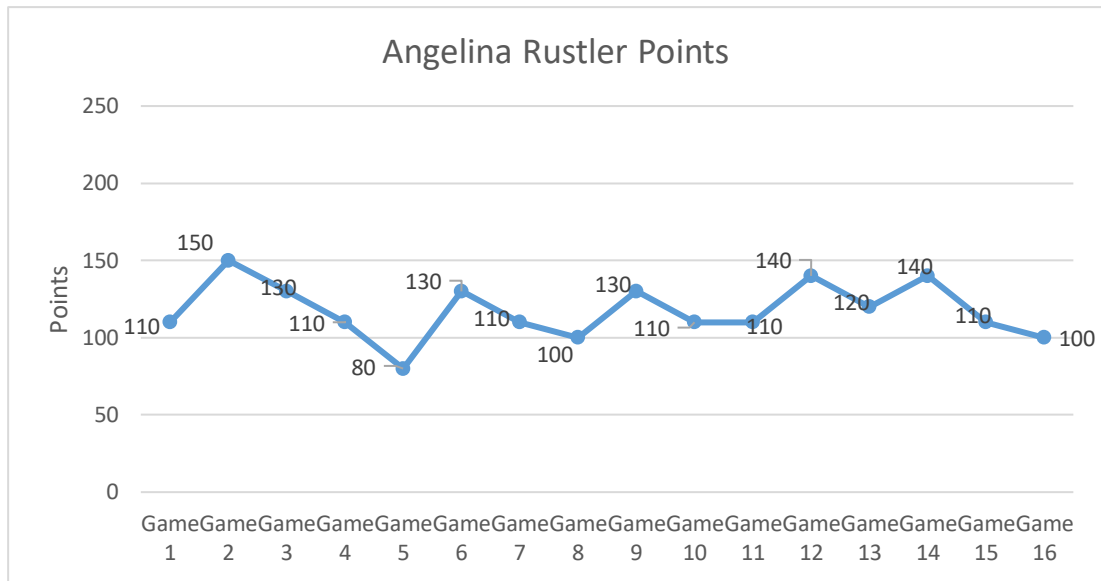


Figure 73: Angelina Rustler Points

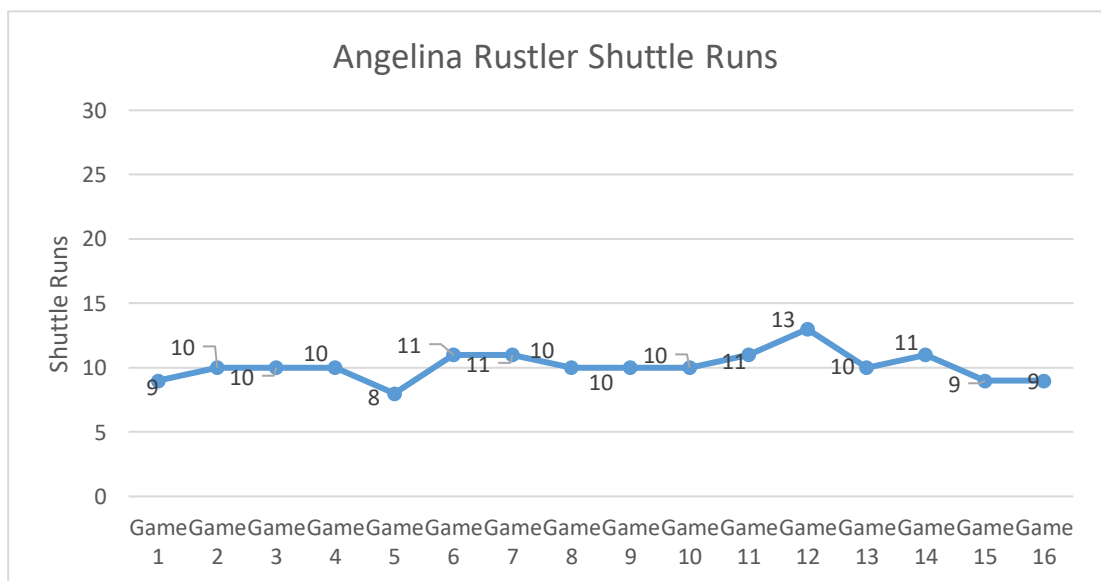


Figure 74: Angelina Rustler Shuttle Runs

B1.4.5 Joy + Pride/Confidence/Self-efficacy

Increasing self-efficacy – There was limited evidence of Angelina broadcasting her achievements to other children, though she clarified her feelings during the interview.

Angelina felt that she had improved at the game throughout the study because she “understood” the game more, something which made her feel “good”.

Pride in leaderboard performance – Angelina’s achievements were the greatest source of pride. Angelina said her primary motivation was to do well on the leaderboard during her interview and this was apparent from the observations which described her disappointment when beaten by other individuals, elation with points scores, and goal setting using the leaderboard. Angelina wanted to beat all of her peers and finish top of the leaderboard but though she did not achieve her goal, she was both proud of her ranking and her trophy achievements:

“Now, was there anything that made you feel proud about playing BQ?” – Main Researcher, Interview

“Yeh being fourth on the leader board” – Angelina, Interview

“Yes that was a good achievement, we were super impressed!” – Main Researcher, Interview

“And getting my Legendary trophy” – Angelina, Interview

Enjoyment of running – The running in the game was also a source of enjoyment for Angelina, as stated in her interview.

“What was your favourite thing about the Brainquest app?” – Main Researcher, Interview

“Having to run about and trying to beat the top person” – Angelina, Interview

“Great so you enjoyed the running aspect?” – Main Researcher, Interview

“Yeh!” – Angelina, Interview

Increasing BrainQuest enjoyment – Angelina also seemed to enjoy the game just as much at the end as she did at the start as she said in the interview that she initially thought that the game “would be a bit boring”, yet by the end she “enjoyed it”. In one word, Angelina described the BrainQuest experience as being “fun”.

B1.4.6 Social Experience

Underwhelmed by interaction with case study group – Angelina appeared to be the least social member of the group but perhaps this is understandable given Leonard’s bias towards interactions with Natalia. Consequently, Angelina appeared underwhelmed by the social

aspect of BrainQuest and appeared hesitant when asked whether she had enjoyed playing the game with the other children in her case study group, saying “*it was okay*”.

Engaged and enjoying the interaction with friends – Despite this, Angelina frequently cooperated with Natalia by discussing plausible strategies. However, Angelina became very social when given the opportunity to play with her friends, Joanna and Rachel. In the game, she provided advice but also appeared to engage in some in-play strategic cooperation (cognitively engaging PA) – she encouraged Rachel to fill up her rustler pen and appeared to be part of a group effort to maximize points. Hence, Angelina may have benefitted more from a diverse range of social interactions.

B1.4.7 Angelina Summary

Contributions towards RQ1 – Indirect Pathways Summary	Contributions towards RQ2 – Direct Pathways Summary
<p>Joy + Pride/Confidence/Self-efficacy</p> <ul style="list-style-type: none"> • Set a goal of topping leaderboard • Expressed pride in his trophy achievements • Did not broadcast results to her peers • Felt more confident regarding the rules by the end • Enjoyed the game more at the end • Enjoyed the running involved in the game • Described BrainQuest experience as “fun” 	<p>Pre-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 14th • Achieved 6E score of 16 • Able to follow both task ordering rules 1 and 2 • Deployed strategy – set number of items <p>Post-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 1st • Overall age scaled score improved • Achieved 6E score of 16 • Able to follow both task ordering rules 1 and 2 • Deployed strategy – set number of items
<p>PA</p> <ul style="list-style-type: none"> • Mile Rank: 5th • Bleep Test: 1st • Rustler Shuttle Run Rank: 3rd • Mean Rustler Shuttle Runs: 10.1 • Shuttle runs peaked in Game 12/16 • Number of remained relatively stable throughout the study and there appeared to be no significant drop off towards the end of the study, nor major increase from early games 	<p>BrainQuest Performance Evolution</p> <ul style="list-style-type: none"> • Strategies varied in terms of complexity but became increasing complex with the number of games • Heavy use of task history tool

<ul style="list-style-type: none"> • Fatigue scale: 5/10 • Found BrainQuest tiring during the rustler role after continuously doing shuttle runs 	<ul style="list-style-type: none"> • Deployed strategies of low, moderate, high and very high complexity • Maintenance strategies used • Deployed 8 different feasible strategies • Deployed 6 different strategy combinations • Highest Difficulty Level Completed: 4
<p>Social Experience</p> <ul style="list-style-type: none"> • Cooperative <ul style="list-style-type: none"> ○ Angelina was observed discussing strategies ○ Angelina played cooperatively with Rachel by keeping pens topped up as the hero to help Rachel maximize her Rustler Points • Competitive <ul style="list-style-type: none"> ○ Angelina wanted to finish top of the leaderboard ○ Angelina appeared more competitive over scores rather than hero-rustler interactions 	<ul style="list-style-type: none"> • Trophies/Games: 5/8 • Highest Hero Points Score: 1320 • Difficulty Level (Win/Lose) <ul style="list-style-type: none"> ○ Rookie: 1/1 ○ Professional: 1/1 ○ World Class: 1/0 ○ Legendary: 1/1

Table 39: Angelina Summary

B1.5 Case Study 5: Stevie

B1.5.1 Overview

Stevie was performed slightly below average on the BADS-C EF testing battery and scored poorly on the 6E subtest. He ranked highly on the most EF-focused BrainQuest game measure, Trophy/Game but less well on Hero Points/Game. Reflecting his strong mile ranking, his Rustler Points/Game and Shuttle Runs/Game measures were also high. It appeared Stevie limited the number of tasks undertaken during hero roles to limit the cognitive demands of the activity and ensure he won a trophy. He invested in winning trophies more than anything else. He contributed to his points totals putting in a great deal of physical effort during rustler roles instead.



Figure 75: Stevie Overview

B1.5.2 BADS-C Performance

Moderate BADS-C performance, Low 6E performance – Stevie was selected as a participant with middling EF ability per the BADS-C pre-test, recording the 17th highest BADS-C score but his pre-test 6E score ranked only 21st in the class. In the pre-test 6E, he was able to follow one but not both task ordering rules correctly – he was able to attempt each of the 6 parts but failed to change task type each time. Stevie appeared to find it hard to understand the rules as he asked many questions before beginning the task and during the task switched very rapidly between different parts, repeating many parts more three times – something which the scoring system subtracts a mark for doing. He also routinely undertook

tasks of the same type back to back. Thus, he scored a profile score of 9, scored -1 for the strategies where he had a point deducted – scoring a total of 8 points.

6E performance improvement – On the post-test 6E, Stevie recorded 12/16 with a full profile score for following the task ordering rules correctly. Though he scored no strategy points corresponding to the pre-defined strategies outlined in the BADS-C scoring system, Stevie did each of the 6 tasks only once during the time limit – the same strategy as he deployed during BrainQuest. Stevie’s post-test ranking was 4th in the class, making a massive overall improvement.

B1.5.3 BrainQuest Performance

B1.5.3.1 Cognitive Training Performance

High (Trophy/Game) and Low (HeroPoints/Game) BrainQuest EF performance –

Although there was a close correlation between BrainQuest performance measures, Stevie was an outlier. On one measure of hero performance, Trophy/Game, Stevie was ranked 5th in the class but he was only ranked 20th for Hero Points/Game. However, this was explained both by Stevie’s data log regarding strategies, observations, and interview all which emphasise Stevie’s high regard for collecting trophies above all else.

Early difficulties in understanding – Similar to the pre-test 6E, Stevie selected a number of the same task types back to back on his first time playing BrainQuest (Test Game) but unlike the 6E Stevie was unable to attempt each of the 6 task types – only selecting 4 different types throughout. Stevie seemed to find the rules of BrainQuest hard to understand initially, something which was reported in the observations where Stevie approached the researchers on several occasions to ask for explanation and also from his interview where he said:

“The first time I played I thought it was really complicated but when you know all how to do it, it’s easy” - Stevie, Interview

Disparity between reported and recorded challenge – Contradicting his claims regarding game challenge, the data logs showed Stevie’s failure to win a trophy in 2 subsequent games (Figure 76) – once on Professional and once on Legendary difficulty. Hence, Stevie was successfully able to follow the task ordering rules on 4 of 7 hero games played but he eventually completed every difficulty level.

Restricting span of tasks to guarantee trophies – While his Trophy/Game ratio was the 5th best in the class, his point scores were low in comparison, ranked only 20th. Furthermore, Stevie also said in the interview that on Legendary difficulty:

“it was hard to remember what other ones there was...because you can’t see what you’ve done” – Stevie, Interview

Over the course of the study, Stevie’s points fluctuated (Figure 76) – they peaked in Game 1 and bottomed in Game 5. He recorded low points scores on games where he won a trophy – Games 4 and 6. However, the cause of fluctuation from Game 4 onwards related to Stevie’s strategies – he either ceased or undertook a small number of additional tasks following the satisfaction of one task ordering rule which would guarantee him a trophy – completing all 6 tasks at least once.

This safe option drew a few of alternative conclusions. (1) Stevie did not care about the points and leaderboard, (2) Stevie lacked confidence or (3) his cognitive ability was not good enough to follow the task ordering rules for a sustained period of time while increasing a complex span of task choices.

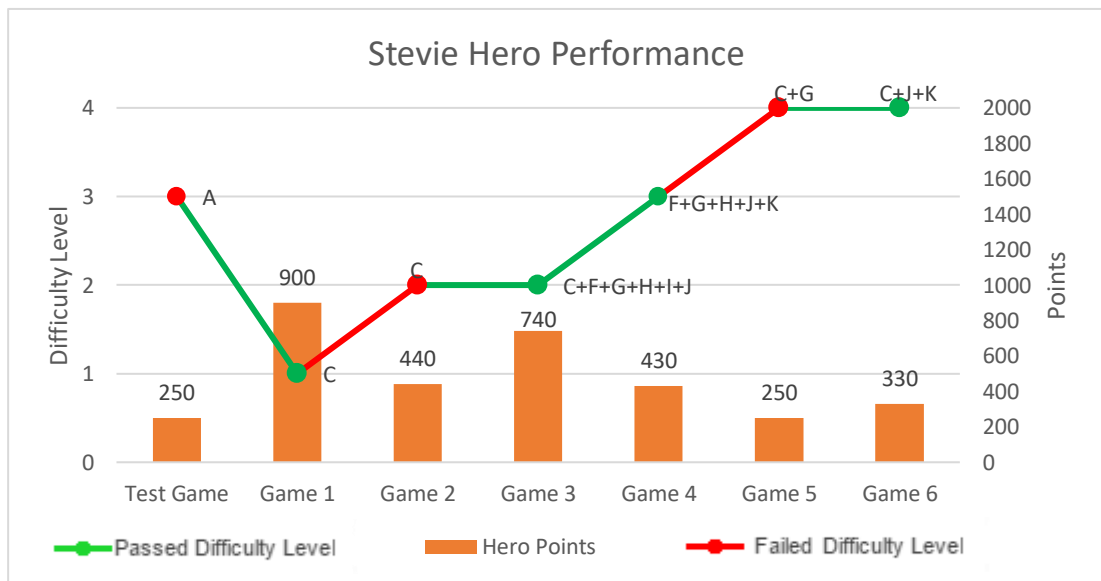


Figure 76: Stevie Hero Performance - Strategy Line

B1.5.3.2 Strategy Evolution

Increase strategic complexity with increasing difficulty – In Games 1 and 2, Stevie followed the rules by simply changing task type at random and not consecutively repeating

the same type (Figure 77). However, he stated using the task support tools prior to help him choose tasks during these games.

In Game 3 Stevie successfully deployed several different strategies at once, many of which complex – he started by selecting a task of each type in cycles of 3 (F) in a repeatable order (H), grouping tasks by animal (G) and choosing tasks from top to bottom (I) before reverting to changing task type in a different order (C) following the completion of the 6 different tasks. Observations suggested Stevie had undertaken a degree of pre-planning because he had sought advice from a researcher regarding how to interpret the in-game feedback. During this interaction, Stevie had stated a correct strategy usable to win a trophy. The data logs also supported this assertion as he used the task history tool for support throughout Games 2 and 3 – 5 times and 6 times respectively.

Compensating for cognitive limitations – Stevie successfully used a similar complex strategy at the next difficulty level (World Class) but this time he stopped doing tasks all together and told the observing researchers that he'd "*just wait...there's only a minute to play*". Stevie then reached Legendary difficulty in Game 5 which incorporates the Task Randomizer and rendered some of his previous strategies redundant, e.g. working top to bottom (I). Faced with this change in task demands Stevie responded by deploying strategy G but did not follow any repeatable order and only completed 5 tasks, thereby failing to follow one of the task ordering rules. Following this in Game 6 Stevie dropped any form of grouping in favour of ad-hoc choices but, again, purposely stopped after he completed 6 tasks to preserve a trophy win. It appeared he found it difficult to generate (generativity – an EF) additional strategies to tackle Legendary difficulty.

Stevie's interview supported many of these assertions regarding strategizing. He stated utilizing a top to bottom and left to right strategy on Profession difficulty:

"you start on the right side or the left side and then you just go down" – Stevie, Interview

However, he had to discontinue this strategy at Legendary-level because “*he couldn’t think of another one*”.

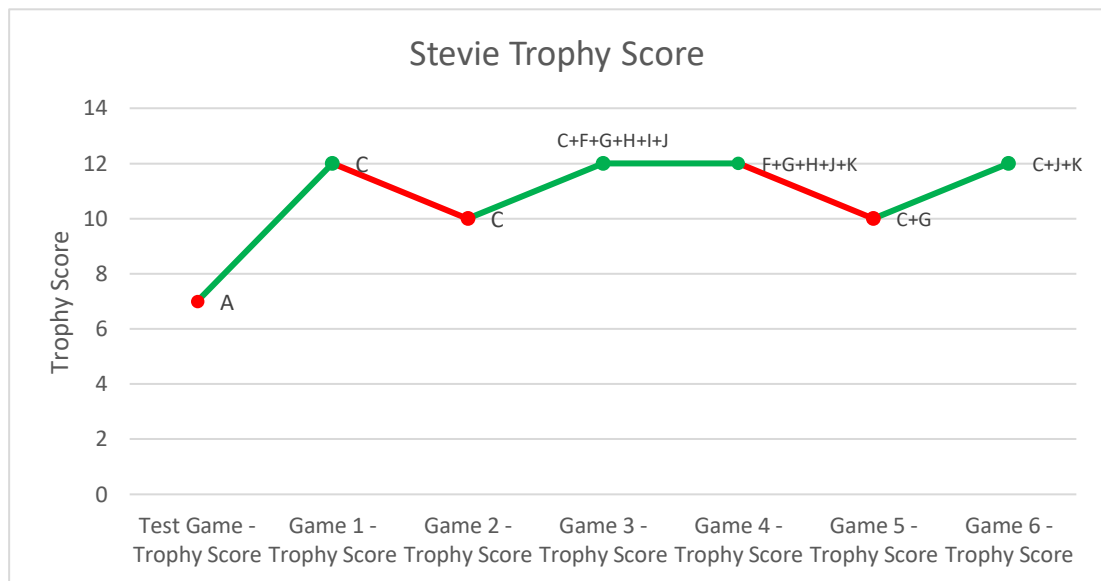


Figure 77: Stevie Trophy Score

B1.5.4 Physical Activity

High physical ability, high BrainQuest performance – Stevie’s physical ability ranked 7th according to the mile rank and bleep test rank measures provided by the PE teacher. In BrainQuest, Stevie ranked low with respect to the HeroPoints/Game measure but his Rustler Points/Game and ShuttleRun/Game measures were much higher – 3rd in the class. This difference in points performance between the two roles suggested a cognitive factor slowing Stevie’s pace in the hero role.

Inconsistent PA before stabilization towards end – Stevie’s Rustler Points and Shuttle Runs (Figure 78 and Figure 79) followed a volatile path throughout, characterized by multiple steep peaks and troughs. Both Stevie’s best and worst Rustler Points and Shuttle Run performances were recorded early in the study and performances fluctuated between high and low until a stabilization from Game 12 until the end of the study – albeit nowhere near his highest performances. Unfortunately, there was limited data to inform the reasons why there was such disparity between different games. Nevertheless, Stevie’s mean rustler runs were 8.7 (SD=4.5) and points were 111.3 (SD=46.7), above the class means – 6.4 and 5.2, respectively.

Moderately perceived exertion but depended on activity – In Stevie’s interview he reported BrainQuest as being a 4 or 5 on the fatigue scale (where 1 is not tiring and 10 is exhausting) but he did say that he found the game tiring when “*you are trying to catch someone really fast*”, fatigue depended “*on what you’re doing*” and catching rustlers was tiring but depended on “*how fast they are*”. Compounding Stevie’s theory, observations captured various PA intensities, most commonly “*running*” but also “*jogging*” and “*walking*”.

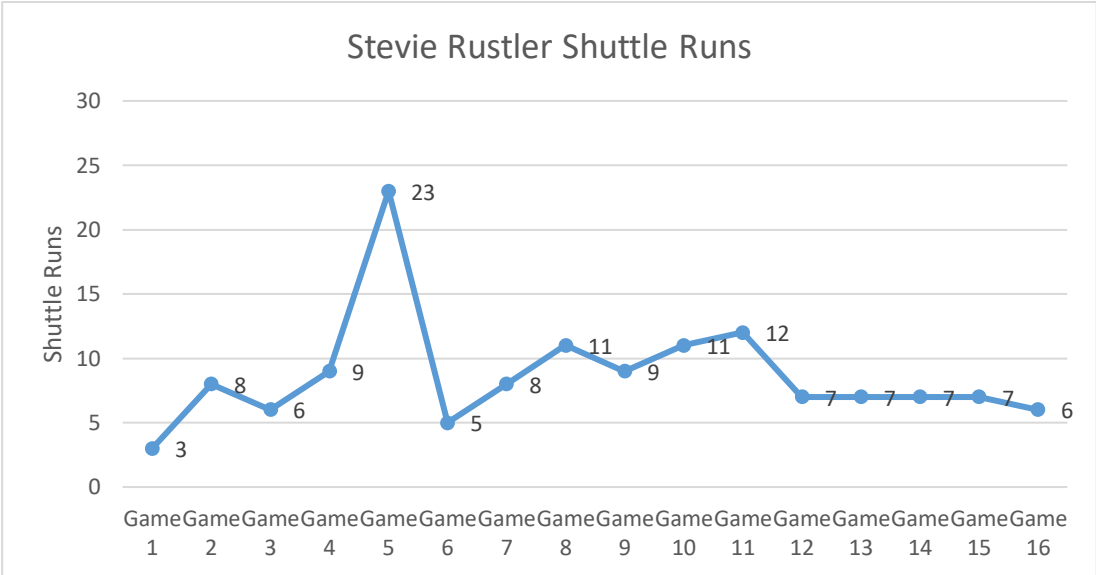


Figure 78: Stevie Rustler Shuttle Runs

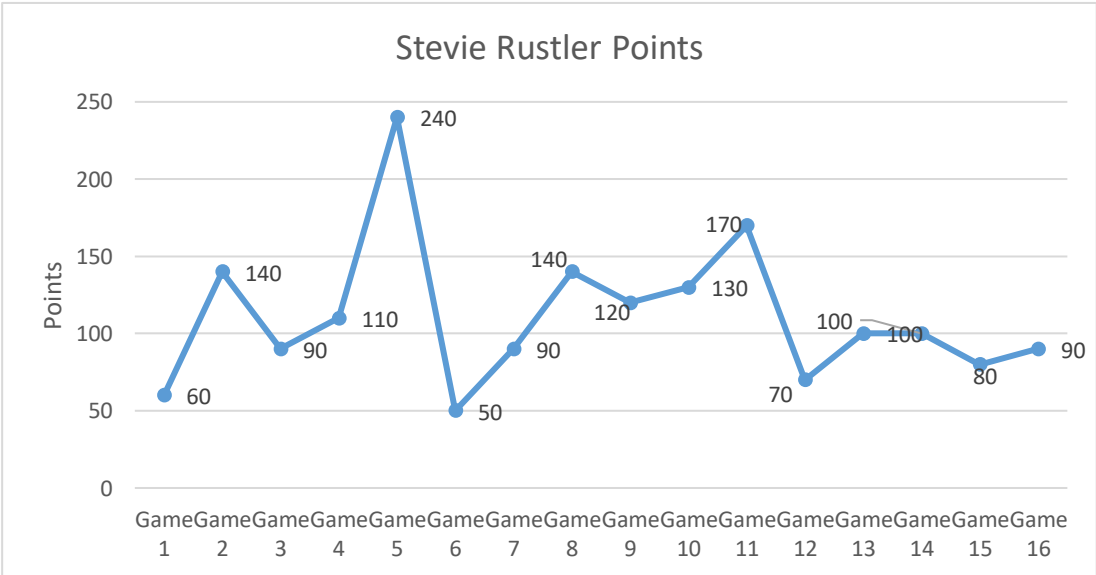


Figure 79: Stevie Rustler Points

B1.5.5 Joy + Pride/Confidence/Self-efficacy

Trophies above all else – All data sources pointed towards the trophy aspect of the reward system as being Stevie’s biggest motivator:

“What motivated you to play BrainQuest?” – Main Researcher, Interview

“When I got a trophy” – Stevie, Interview

As established, his Trophy/Game measure was one of the highest in the class, yet the Hero Points/Game measure was one of the lowest. Furthermore, observations described his disappointment at failing to win a trophy and elation at winning. Stevie also stated that winning the “*harder trophies*” were his proudest achievement during the study.

Trophies as goals – The data suggested Stevie was goal oriented and set himself targets – addressing researchers, “*I want to win my Legenday trophy*” but it seemed he was obsessed with satisfying one particular goal rather than addressing multiple goals simultaneously. For example, it was only after collecting all the trophies he set a new goal:

“I want to try and get as many points as I can” – Stevie, General Observations

There may also have been a social factor underpinning his trophy goals and it appeared he wanted to keep up trophy appearances even if he failed to achieve his goal:

“see if I don’t get trophy for this, can you add one” – Stevie, General Observations

Change of goal based on achievement likelihood – Stevie also stated an interest in the leaderboard during his interview but to a lesser extent. However, observations noted his disappointment during an early session where having been initially top of the leaderboard, he was overtaken following a leave of absence. Hence, this may have influenced his decision to master trophies instead.

Increasing BrainQuest enjoyment – Stevie seemed to enjoy and understand the game progressively more:

“I didn’t really get it at first, that’s why didn’t really like it at first because I didn’t really get it, it was hard and then I understood it a bit more and I liked it better” – Stevie, Interview

This reflected in the observations which described Stevie approaching researchers and other children to broadcast his achievements in the latter sessions. In one word Stevie described BrainQuest as “*amazing*”.

B1.5.6 Social Experience

Competitive rivalries – Despite a greater focus on trophy wins than the leaderboard, Stevie appeared to be very competitive with others and on one occasion a competitive hero-rustler interaction between himself and Rosie went too far. Stevie and Rosie argued over whether or not Stevie had been caught fairly and an observer was forced to step in to de-escalate the situation. Other accounts were more jovial, involving Stevie running out of the game boundaries with Jack and Theo and smiling while interacting with Martin.

Cooperation and strategy sharing – On the other hand, Stevie valued cooperation with others and was seen sharing strategy and game bug response tips with other children on several occasions. Stevie described playing with other classmates as being “*fun*” but also was frustrated when some children “*didn’t really get it and you just wanted to get on with the game*”. However, he conceded that other people in his group had helped him when “*he didn’t really get some of it*”.

B1.5.7 Stevie Summary

Contributions towards RQ1 – Indirect Pathways Summary	Contributions towards RQ2 – Direct Pathways Summary
<p>Joy + Pride/Confidence/Self-efficacy</p> <ul style="list-style-type: none"> • Set a goal of winning all trophies • He would sacrifice alternative goals in order to achieve his goal • His proudest achievement was reaching his trophy goal • Broadcasted results to his peers • Found the game initially hard to understand • Felt more confident regarding the rules by the end • Enjoyed the game more at the end than the start • Described BrainQuest experience as “<i>amazing</i>” 	<p>Pre-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 17th • Achieved 6E score of 8 • Unable to follow either task ordering rules 1 and 2 • No strategy <p>Post-test BADS-C</p> <ul style="list-style-type: none"> • Rank: 4th • Overall age scaled score improved • Achieved 6E score of 12 • Able to follow both task ordering rules 1 and 2

<p>PA</p> <ul style="list-style-type: none"> • Mile Rank: 7th • Bleep Test: 7th • Rustler Shuttle Run Rank: 5th • Mean Rustler Shuttle Runs: 8.7 • Shuttle runs peaked in Games 5/14 • Number of rustler runs varied throughout but appeared to become more consistent in the final 5 games • Number of runs in the final 5 games were slightly below his mean • Fatigue scale: 4 or 5/10 • The level of fatigue depended upon the opponent • The level of fatigue also depended upon the task type 	<ul style="list-style-type: none"> • Only did 6 tasks within the time limit, the same as he did in BrainQuest <p>BrainQuest Performance Evolution</p> <ul style="list-style-type: none"> • Complex strategies were developed by the midpoint of the study and continued until the final session • Moderate use of task history tool • Deployed strategies of low, moderate, high and very high complexity • Maintenance strategies used • Deployed 7 different feasible strategies • Deployed 5 different strategy combinations • Highest Difficulty Level Completed: 4 • Trophies/Games: 4/7 • Highest Hero Points Score: 900 • Difficulty Level (Win/Lose) <ul style="list-style-type: none"> ○ Rookie: 1/0 ○ Professional: 1/1 ○ World Class: 1/0 ○ Legendary: 1/1
<p>Social Experience</p> <ul style="list-style-type: none"> • Cooperative: <ul style="list-style-type: none"> ○ Stevie shared strategy advice with other players and also helped others with respect to game bugs ○ Stevie also recognised receiving help from others when he didn't understand • Competitive: <ul style="list-style-type: none"> ○ Stevie argued with Rosie during hero-rustler interaction with respect to whether or not he was caught ○ Stevie ran out of the game boundaries while chasing other players 	

Table 40: Stevie Summary

Appendix C – BADS-C Subtests Overview

C1 Modified 6 Elements Test (6E)

This is a test of planning, task scheduling, cognitive flexibility and performance monitoring which requires both attention and use of WM. Children are given three different colour-coded tasks to do: a green task (simple arithmetic), a blue task (picture naming), and a red task (sorting). Each of these tasks has two parts, part 1 and part 2, so there are two piles of cards for the green task and two piles for the blue task. Both parts of both tasks are graded in difficulty so as to be suitable for children from age 8 years upwards. The third task, the red task, consists of two boxes of objects, one containing multi-coloured and multi-shaped beads, and the other a mixture of nuts, bolts, and washers. Children have to schedule their time to attempt something from all six parts over a five-minute period with restrictions on the order in which parts can be attempted. A key requirement of this test involved generating strategies (Emslie et al., 2003).

Below is an overview of the 6E task structure:

1. Each task contains two parts (A and B), where only one may be undertaken at a time. Furthermore, once one task type is completed, the same task may not be re-chosen until the user has completed a further task of a different type, e.g. If Task 1A is chosen and then completed, then the user may not choose any part of Task 1 until a part of Task 2 or Task 3 are completed.
2. Within the 5-minute time limit, the user must make sure that they have attempted all 6 subtasks while following Rule 1.

The task and subtasks involved in the 6E test are named, structured and described below:

1. How many? – in these tasks the user must perform some sums written on a series of cards before writing the answer down on paper
 - a. How many? Part 1
 - b. How many? Part 2
2. What is it? – in these tasks the user must write down on paper which object that they see on each card
 - a. What is it? Part 1
 - b. What is it? Part 2

3. Sort it – in these tasks the user must sort items into their box lids, according to a picture drawn on the inside of each box lid:
 - a. Sort it Part 1
 - b. Sort it Part 2

Note: though the undertaking of both parts (A and B) of each task are identical, the content is different e.g. in ‘Sort it Part 1’, the user sorts bolts, while in ‘Sort it Part 2’, the user sorts beads.

In the scoring system for the 6E test, the user earns 2 points per unique task attempted (e.g. 4 different tasks = 8 points) with a maximum of 12 points available. The user loses a mark for every unique task type in which they break the rules (e.g. ‘What is it? Part 1’, followed by ‘What is it? Part 2’ = -1 points) with a maximum of 3 penalty points. Finally, the user can earn extra points for using a discernible strategy, such as task ordering or time management strategies, while they may also lose an extra point for persistent rule breaking.

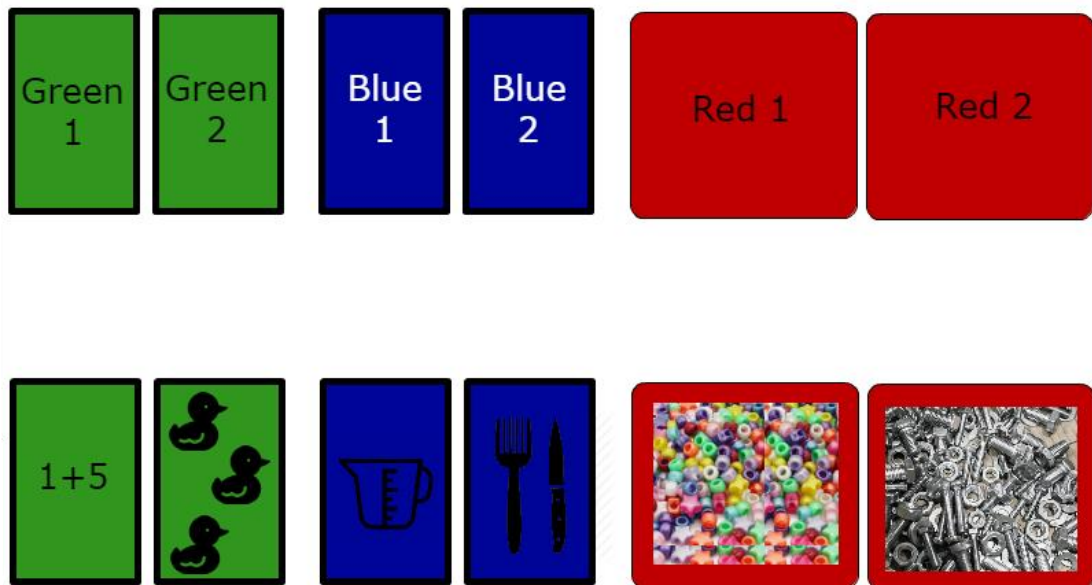


Figure 80: 6E Test (Example)

C2 Key Search Test

This test examines a child’s ability to plan an efficient, systematic, implementable plan of action, monitor their own performance, and take into account factors which are not explicitly stated. Children are presented with an A4 piece of paper with a 100mm square in the middle and a black dot 50mm below the square. They are asked to imagine that the square is a large

field in which they have lost their keys. Starting from the dot they are to draw a line with a pen to show how they would search the field in order to find their keys (Emslie et al., 2003).



● Start here

Figure 81: Key Search (Example)

C3 Playing Cards Test

The Playing Cards Test requires the child to respond according to one rule and then change strategy in accordance with a new rule. The test provides a measure of cognitive flexibility as the child shifts from one rule to another and also assesses the child's ability to keep track of the colour of the previous card and the current rule (Emslie et al., 2003). In the test, the child is first ask to respond 'yes' when red cards are shown and 'no' when black cards are shown. After completing the deck, the rule changes and the child is asked to only respond 'yes' when the card is the same colour as the one before as they run through the deck for a second time.

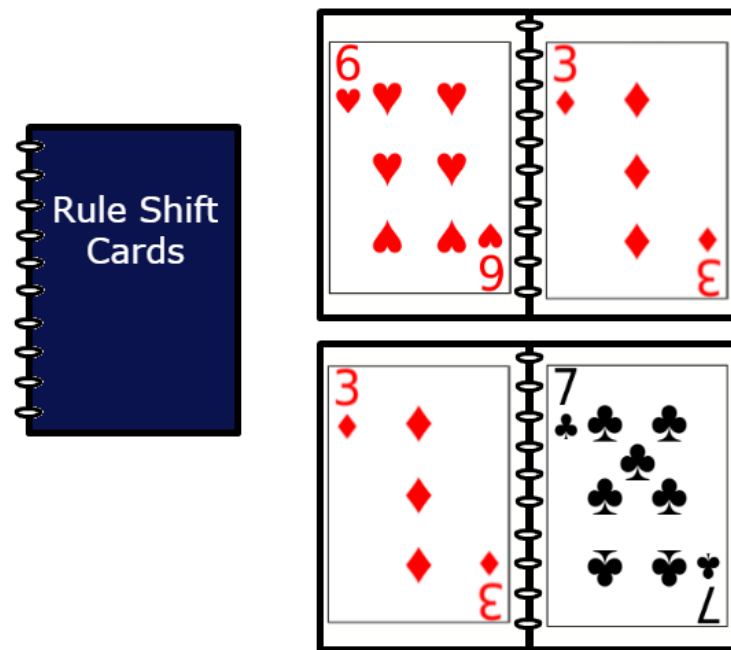


Figure 82: Playing Cards (Example)

C4 Water Test

This is a novel, practical task, originally devised by Klosowska (1976), which requires the development of a plan of action in order to solve a problem. Rather than requiring a pencil and paper solution it requires the physical manipulation of a variety of materials:

- A water beaker with a small hole in its lid
- A plastic tub
- A screw top lid
- A metal hook
- A test tube in which lies a cork

The child must solve a practical problem – removing the cork from the plastic tube using only the implements provided and without touching any implements apart from the tub, lid, cork, and hook with their hands. The Water Test requires five steps to its solution, each of which involves simple skills that are in everyone’s repertoire (Emslie et al., 2003):

1. Screw the lid onto the tub
2. Use the hook to remove the water beaker's lid
3. Use the tub to collect water from the beaker
4. Pour a tub's worth of water into the test tube
5. Repeat steps 3 and 4 until cork can be removed from test tube

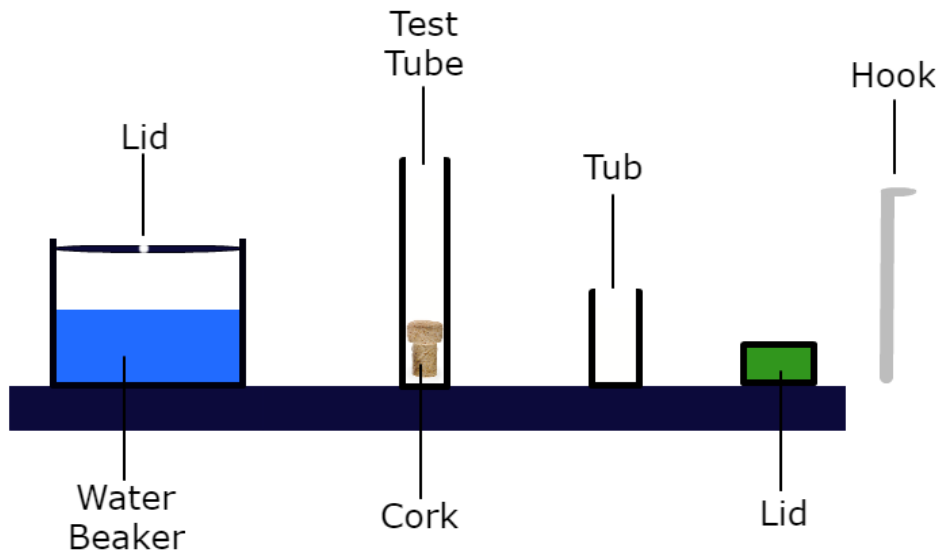


Figure 83: Water Test (Example)

C5 Zoo Map

These are two tests of planning. They provide information about a child's ability to plan a route in order to visit six out of 12 possible locations in a zoo when there are restrictions on the number of times certain paths can be used and the starting and finishing point are specified. The map has been constructed so that there are only four variations on the route that can be followed if no errors are to be made, and the use of different coloured pens between locations provides feedback for the children so they can modify their performance when a rule is broken. Comparison of performance on the two Zoo Map Tests will allow quantitative evaluation of a child's spontaneous planning ability when structure is minimal versus his or her ability to follow a concrete, externally-imposed strategy when test structure is high (Emslie et al., 2003).

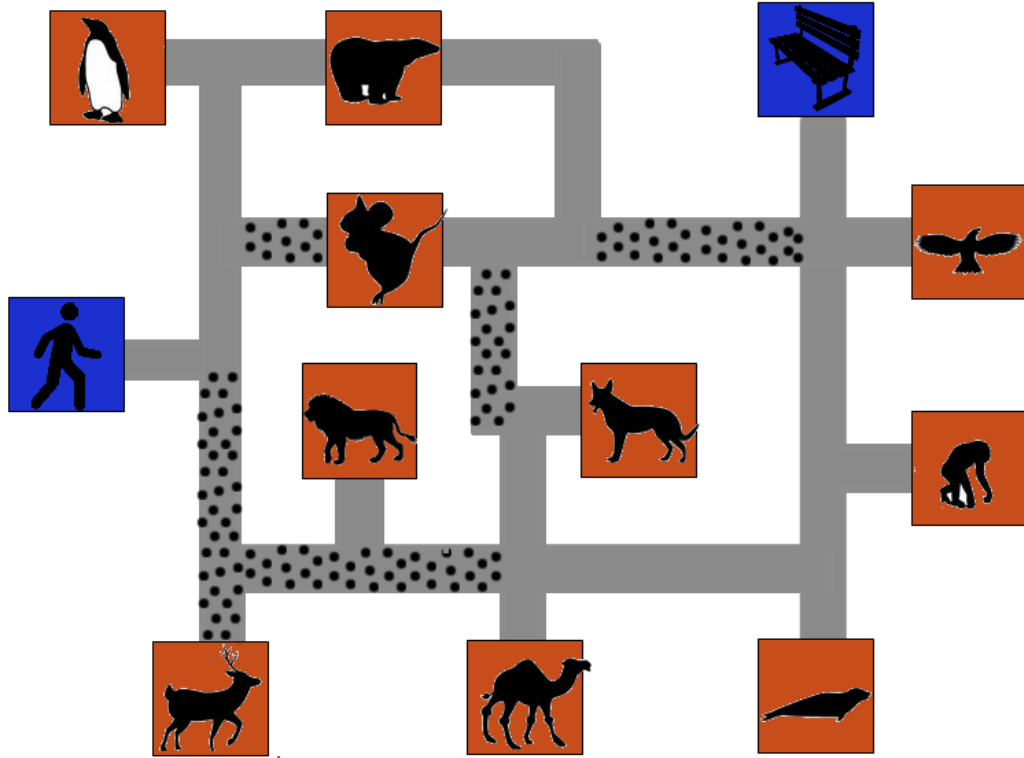


Figure 84: Zoo Map (Example)

Appendix D – PHP Source

D1 BqgameLog.php

This php script is used to log game performance following the end of a BrainQuest game.

```
<?php
```

```
$query = $conn->prepare("INSERT INTO BQ_GameLog (Username, GameDate,
GameTime, Difficulty, HeroGames, HeroPoints, ComboScore, TasksCompleted,
CorrectTasks,
RuleBreaks, AVGTaskChoiceTime, CRustlerGames, CRustlerPoints, SRustlerGames,
SRustlerPoints, TotalGamePoints, TotalGameDuration, CRustlerShuttleRuns,
SRustlerShuttleRuns, ViewedLeaderBoard, ViewedTaskHistory, All6Raw, RawErrors)
VALUES (:username, :gameDate, :gameTime, :difficulty, :heroGames, :heroPoints,
:comboScore, :tasksCompleted, :correctTasks, :ruleBreaks, :aVGTaskChoiceTime,
:cRustlerGames, :cRustlerPoints, :sRustlerGames, :sRustlerPoints, :totalGamePoints,
:totalGameDuration, :cRustlerShuttleRuns, :sRustlerShuttleRuns, :viewedLeaderBoard,
:viewedTaskHistory, :all6raw, :rawerrors)");

$result = $query->execute( array(':username' =>$_POST['Username'],'gameDate'=>
$_POST['GameDate'],'gameTime'=> $_POST['GameTime'],'difficulty'=>
$_POST['Difficulty'],'heroGames'=> $_POST['HeroGames'],'heroPoints'=>
$_POST['HeroPoints'],'comboScore'=> $_POST['ComboScore'],'tasksCompleted'=>
$_POST['TasksCompleted'],'correctTasks'=> $_POST['CorrectTasks'],'ruleBreaks'=>
$_POST['RuleBreaks'],'aVGTaskChoiceTime'=>
$_POST['AVGTaskChoiceTime'],'cRustlerGames'=>
$_POST['CRustlerGames'],'cRustlerPoints'=> $_POST['CRustlerPoints'],'sRustlerGames'=>
$_POST['SRustlerGames'],'sRustlerPoints'=> $_POST['SRustlerPoints'],'totalGamePoints'=>
$_POST['TotalGamePoints'],'totalGameDuration'=>
$_POST['TotalGameDuration'],'cRustlerShuttleRuns'=>
$_POST['CRustlerShuttleRuns'],'sRustlerShuttleRuns'=>
$_POST['SRustlerShuttleRuns'],'viewedLeaderBoard'=>
$_POST['ViewedLeaderBoard'],'viewedTaskHistory'=>
$_POST['ViewedTaskHistory'],'all6raw'=> $_POST['All6Raw'],'rawerrors'=>
$_POST['RawErrors']));
```

```
echo json_encode($results);
```

```
?>
```

D2 Bqgetallfromdatabase.php

This php script is used to fetch game points performance in the BrainQuest score centre.

```
<?php
```

```
$query = $conn->prepare('SELECT * FROM BQ_Points WHERE Username = :user');
```

```
$query->execute(array( 'user' => $_POST['Username'] ));
```

```
$results = $query->fetchAll(PDO::FETCH_ASSOC);
```

```
echo json_encode($results);
```

```
?>
```

D3 Bqleaderboard.php

This php script is used to fetch usernames and game point scores in order of the highest score in the BrainQuest score centre leaderboard.

```
<?php
```

```
$query = $conn->prepare('SELECT * FROM BQ_Points GROUP BY Points ASC');
```

```
$query->execute();
```

```
$results = $query->fetchAll(PDO::FETCH_ASSOC);
```

```
echo json_encode($results);
```

```
?>
```

D4 Register.php

This php script is used to register a new user in BrainQuest.

```
<?php
```

```
$query = $conn->prepare("INSERT INTO Register (Username, ID, Password) VALUES (:username, :id, :password)");
```

```

$result = $query->execute( array(

    ':username' => $_POST['Username'], ':id' => $_POST['ID'], ':password' =>
    $_POST['Password'], ));

echo json_encode($results);

?>

```

D5 Bqstats.php

This php script is used to gather a user's historical performance data to be displayed in the BrainQuest score centre.

```

<?php

$query = $conn->prepare('SELECT MAX(Difficulty), SUM(HeroGames),
SUM(HeroPoints), MAX(ComboScore), SUM(TasksCompleted),

MAX(CorrectTasks), MAX(RuleBreaks), MAX(AVGTaskChoiceTime),
SUM(CRustlerGames), SUM(CRustlerPoints), SUM(SRustlerGames),

SUM(SRustlerPoints), SUM(TotalGamePoints), SUM(TotalGameDuration),
SUM(CRustlerShuttleRuns), SUM(SRustlerShuttleRuns),

MAX(CRustlerShuttleRuns), MAX(SRustlerShuttleRuns)

FROM BQ_GameLog WHERE Username = :user');

$query->execute(array(':user' => $_POST['Username'] ));

$results = $query->fetchAll(PDO::FETCH_ASSOC);

echo json_encode($results);

?>

```

D6 Bqupdatepoints.php

This php script is used to insert game points into a user's BrainQuest account.

```

<?php

```

```
$query = $conn->prepare('UPDATE BQ_Points SET Points = :points WHERE Username = :username');

$query->execute(array(':points' => $_POST['Points'], ':username' => POST['Username']));

$results = $query->fetchAll(PDO::FETCH_ASSOC);

echo json_encode($results[0]);

?>
```

D7 Login.php

This php script handles the username and password login authentication in BrainQuest.

```
<?php

$query = $conn->prepare('SELECT * FROM Register WHERE Username = :user AND Password = :pass');

$query->execute(array( ':user' => $_POST['Username'], ':pass' => $_POST['Password'] ));

$results = $query->fetchAll(PDO::FETCH_ASSOC);

echo json_encode($results);

?>
```

Appendix E – Child Consent Form Example



BrainQuest Consent Form

You have been invited to take part in a project for my university course to give your opinion about a new mobile phone game for problem solving and exercise.

What is the project about?

I have made a smart phone game called BrainQuest to help children take exercise and improve their problem solving and I would like to use this game at your school over the course of 6 weeks to see if it works.

What will I be doing?

You will take part in two 10 minute tests – one on the week before playing BrainQuest for the first time and another during the week following your final session with the game. In each 10-minute test you will have to do several tasks that challenge your brain. You will play the game for 30 minutes twice a week for 5 weeks during class time. The session will be video recorded. We will store the video on university computers and it will not be on the Internet. We might show the video to other people who work at the university to get their feedback too.

If you have any questions, please ask the researcher. If you do not want to take part that is OK, as your teacher will give you another activity. If you want to stop part way through the session, that is also fine. Tell your teacher and he or she will give you something else to do.

Stuart Gray

Please delete as applicable

I do/do **NOT** give consent to take part in the study.

Appendix F – Parent Consent Form Example



BrainQuest Consent Form

Your child's class will be taking part in a research project where they use a smartphone game called BrainQuest during PE and class time. The game is designed to help children's problem solving abilities as well as increase their physical activity. The class will use the game for two hours per week for 6 weeks in sessions during February and March.

Your child will use the game on the school AstroTurf in teams of three. They can choose to stop at any point and return to an alternative class activity. Afterwards we will ask their opinions about the game. We would like to video record them throughout the sessions to help us with our research.

The video files will be held securely on the university servers for a period of 5 years. The video footage may be shown at teaching or research seminars, but if so we will blur the children's faces so they are not identifiable. The videos will not be publically available on the Internet.

Your child will also have to complete two 10 minute tests, measuring some levels of their cognition. The tests involve a series of paper-based tasks to be completed within a time limit. Again, they can choose to stop at any point.

Please complete and return the consent form to your child's teacher. If you have any questions, please contact me below.

Stuart Gray

Please delete as applicable

I do/do **NOT** give consent to take part in the study.

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