Investigating the development of executive functions and their relationship with educational attainment during adolescence: a study of inhibition, shifting and working memory

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Abstract

Background

Research regarding the development of executive functions (EFs) and their association with educational attainment has disproportionately focused on younger ages, mainly pre-schoolers and primary school aged children. Conversely, the period of adolescence and specifically the later stages thereof have been largely overlooked, despite indications suggesting that particular aspects of EFs continue developing throughout adolescence and into young adulthood. Researching EFs during the latter part of adolescence might be particularly informative considering the increasing academic demands that adolescents encounter at school during these ages. In the final years of secondary school, adolescents are called to make critical academic and life decisions and work towards long-term goals (e.g., employment, further education), rendering EFs ever more potent during this period. Furthermore, in multifaceted subjects, such as science, in which attainment relies heavily on a variety of transferable skills, it may be through these skills that EFs affect adolescents' attainment.

Methods

This thesis constitutes a unique contribution to the existing EF literature, in that it addresses questions regarding the development and relation of EFs to educational attainment in the previously overlooked period of late adolescence. Attainment in different disciplines was examined separately and, in the case of science, numeracy and non-verbal reasoning skills were examined as mediators of the relationship between EFs and attainment. A total of 347 adolescents, aged between 14 and 18 (i.e., years 3-5 of secondary school), were administered cognitive tasks that measured three EF components, namely inhibition, shifting and working memory, and completed paper-based assessments of their numeracy and non-verbal reasoning skills. Participants' school grades/performance in national qualifications on a variety of subjects were considered as indicators of their educational attainment.

Results

The results showed that, within the large cross-sectional sample of 14-18 year olds considered, there were significant developmental changes in inhibition, but not shifting or working memory. Furthermore, there was strong evidence of associations between older adolescents' EFs and their attainment in the curriculum areas of English, maths, science, social studies, modern languages and arts. Interestingly, the patterns of association among the three EF components and attainment differed as a function of age cohort. In a separate study, EFs were examined in relation to the oldest (fifth-year) adolescents' performance in national qualifications for entry into university, but EFs were not found to have any significant effect beyond that of socioeconomic status. Finally, it was shown that the relationship between EFs and attainment in science was mediated by numeracy but not non-verbal reasoning skills.

Conclusions

This thesis showcases the significance of studying EFs in adolescence, with the results showing that certain aspects of EF continued maturing during the ages of 14-18 and had an ongoing effect on adolescents' educational attainment. These findings suggest that, even during the later stages of adolescence, EFs may constitute a useful target for educational interventions aimed at improving pupils' attainment. In addition, this thesis highlights the important role of socioeconomic status as a determining factor of adolescents' EFs and their educational attainment.

Lay Summary

Executive functions (EFs) refer to a diverse group of mental control processes that enable people to plan and regulate their behaviour in order to achieve their desired goals, particularly when facing novel or difficult situations. This thesis concerns the study of EFs, more specifically their development and association with educational attainment, during the latter part of adolescence.

To this end, 347 secondary school pupils aged 14-18 years old completed a series of tasks specially developed to measure EF ability. The pupils' performance on these tasks was then examined and compared to their school grades and/or qualification scores, which acted as indicators of their educational attainment.

The results showed that during the ages of 14-18, certain aspects of EF continue to undergo notable developmental changes. In addition, EFs were found to be associated with adolescents' attainment in a variety of subjects, but the exact pattern of associations varied across the ages examined.

These findings suggest that EFs are an important factor that should be considered in education, due to their link with attainment, even in the latter stages of secondary school. EFs, together with socioeconomic status, play a crucial role in determining how well adolescents will perform in terms of their educational attainment.

Signed declaration of independent work

I, Thalia Elizabeth Theodoraki, declare that this thesis is an original report of my research that has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where it states otherwise by reference or acknowledgment, the work presented is entirely my own

One paper, from Chapter 2 has been submitted for publication and is under review at the time of thesis submission:

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List of abbreviations

AWMA Automated Working Memory Assessment

BAS II British Ability Scales Second Edition

BRIEF Behavior Rating Inventory of Executive Function

CFA Confirmatory Factor Analysis

CWI Colour-Word Iinterference (test)

D-KEFS Delis Kaplan Executive Function System

EF(s) Executive Function(s)

ERP Event-Related Potential

FIML Full Information Maximum Likelihood

GPA Grade Point Average

MICE Multiple Imputation by Chained Equations

MRI Magnetic Resonance Imaging

NIH National Institutes of Health

NQ(s) National Qualification(s)

RDB Recall of Digits Backward (task)

RDF Recall of Digits Forward (task)

SAS Supervisory Attentional System

SEM Structural Equation Modeling

SIMD Scottish Index of Multiple Deprivation

SQA Scottish Qualifications Authority

SSLN Scottish Survey of Literacy and Numeracy

ST Sorting Test

TOH Tower of Hanoi (task)

UCAS Universities and Colleges Admissions Service

VIF(s) Variance Inflation Factors

WCST Wisconsin Card Sorting Test

WISC-IV Wechsler Intelligence Scale for Children – Fourth Edition

Chapter 1: Introduction

1.1. Executive functions: definition and research history

Executive functions (EFs) is an umbrella term used to describe a number of higher-order cognitive processes underlying activities such as planning, problem solving, attentional control, and self-regulation. The numerous different processes, that over the years have been included under this umbrella term, makes it very hard to operationally define EFs (Goldstein, Naglieri, Princiotta, & Otero, 2014). It has been postulated that no comprehensive definition fully captures the conceptual scope of EFs (Delis, 2012), and as a result, thus far, there exists no single, unanimous definition of EFs.

However, there are some aspects of EFs which have become commonly accepted and are, thus, frequently reiterated in definitions of executive functioning. Firstly, there is general agreement that the brain area primarily associated and, to a large extent, responsible for executive functioning is the prefrontal cortex within the frontal lobes (Anderson, Jacobs, & Anderson, 2008; Fuster, 2015). In fact, the conceptualisation of EFs has been largely driven by and inevitably linked to research into the functions and role of the frontal lobes in human behaviour (Anderson et al., 2008; Goldstein et al., 2014). Secondly, EFs are more often than not conceptualised as processes implicated in mental control. They are believed to be responsible for regulating and directing humans' cognitive, emotional and motor activity (Corbett, Constantine, Hendren, Rocke, & Ozonoff, 2009; Lezak, 1995). More specifically, there is general consensus that executive functioning concerns the intentional, volitional control of behaviour which is key for engaging in purposeful, goal-directed activity (Lezak, 1995; Stuss & Benson, 1986). Therefore, EFs refer to the skill set that enables humans to organise their thoughts and behaviour in the service of reaching intended goals, especially when overriding immediate demands/rewards is necessary in order to achieve those goals. One final aspect of EFs that is often mentioned in the literature is the fact that they are most pertinent in novel or difficult situations (Banich, 2009; Gioia, Isquith, Guy, & Kenworthy, 2000; Hughes, Graham, & Grayson, 2005), when the management of behaviour in accordance to external demands and stimuli is of paramount importance.

The history of executive functioning research begins much earlier than the first documentation of the term executive functions. Executive functioning research arose from the study of cases of frontal lobe dysfunction dating back to the 19th century. The first case that was influential in the discovery of behaviour changes resulting from damage to the frontal lobes was that of Phineas Gage, documented by Harlow in 1848. After an extreme injury to the head, which left him with severe damage to his prefrontal cortex, Phineas Gage reportedly suffered marked changes to his behaviour (Neylan, 1999). One such behaviour – his constant devising of plans of future operation but inability to carry them out – is particularly associated with the modern concept of executive functioning, rendering him the first example of the impact of frontal lobe damage on EF.

Many more studies investigating the behavioural and psychological profiles of people with frontal lobe damage followed in the 20th century (e.g., Ackerly, 1935; Brickner, 1936; Penfield & Evans, 1935; Rylander, 1939). The frontal lobes were consequently associated with many higher-order processes "from abstract behaviour, foresight, and intellectual synthesis, to capacity for ethical behaviour, control of affect, awareness of self, and recent memory" (Teuber, 2009, p. 26). However, not all studies found evidence of an acute impact of frontal lobe lesions on individuals' cognition (Hebb, 1939, 1945; Mettler, 1949), which resulted in the initiation of a debate regarding frontal lobe function that continued well into the second half of the 20th century. One key contribution to this debate was Luria's work on patients with frontal lobe damage (Luria, 1966; Luria & Tsvetkova, 1964) and his description of 'frontal lobe syndrome', which he described as a syndrome characterised by failure in organizing and regulating one's behaviour in response to complex or symbolic instructions (Luria, 1969; Luria, Pribram, & Homskaya, 1964). Luria's observations led him to the conclusion that problem-solving behaviour is connected to multiple overriding skills, or functions, which were dependent on the frontal lobes (Purdy, 2011).

Towards the end of the 20th century, as a result of the frontal lobe functions debate, the first theories and models of executive functioning emerged. Pribram was amongst the first to intentionally use the term 'executive' when discussing matters of prefrontal functioning (Pribram, 1973). Shortly after, in 1974, Baddeley and Hitch introduced the term 'central executive' to describe the supervisory component in their three part model of working memory (Baddeley & Hitch, 1974). The central executive was not only proposed to be in charge of coordinating its slave systems – the phonological loop, the visuo-spatial sketchpad and the subsequently added episodic buffer – but was envisioned by Baddeley as a system actively involved in dual-task performance, selective attention, switching of retrieval plans and temporary activation of long-term memory (Baddeley, 1996). In 1986, Norman and Shallice introduced the 'supervisory attentional system' (Norman & Shallice, 1986) as part of their model for attentional control of thought and action scripts (schemata). In this model, the supervisory attentional system (SAS) refers to a higher order structure that controls the activation and inhibition of learned schemata under routine circumstances but can also modify existing schemata to adjust to novel, non-routine situations, where planning and problem solving are required. Both these models contain elements that reflect modern views of EFs, however they rely on the idea of a unitary, homogeneous executive module that regulates behaviour, rather like a homunculus in the brain (Baddeley, 1996).

In later years, the notion of executive functioning as a unitary construct was considered too simplistic. Instead, many of the subsequent models of executive functioning included more than one executive domain. In 1997, Barkley developed his self-regulatory model of EFs based on his reports of individuals suffering from ADHD, who, according to him, present deficits that are to a large extent executive (Barkley, 1997). According to this model, behavioural inhibition is a hierarchically higher system that influences four different executive functioning skills, which he termed working memory, internalised speech, self-regulation of affect/motivation/arousal and reconstitution. A similar model, also comprising four general executive domains was developed by Lezak (1995) as a framework for assessing executive functions. Lezak envisaged volition, planning, purposive action, and effective performance as the four separate domains that work together to accomplish global executive functioning needs (Lezak, 1995). The aforementioned models were presented since they are typically mentioned in reviews of EF models, however, there also many other models (including a more recent, revised version of the SAS model; see Stuss, 2011) that support the existence of multiple EF domains (see Goldstein et al., 2014 and Hunter & Sparrow, 2012 for more detailed reviews of EF models).

A particularly prominent theoretical framework in support of multiple aspects of executive functioning was manifested following a study carried out in 2000 by

Miyake and his colleagues (Miyake, Friedman, Emerso, Witzki & Howerter, 2000). They used the progressive, at the time, technique of factor analysis – a statistical (data reduction) method for modelling multiple observed outcomes/variables and their inter-correlations in terms of a smaller set of underlying, unobserved factors. More specifically, Miyake et al. (2000) employed factor analysis to determine the factors that underpinned college students' performance on a variety of tasks considered to tap EFs and found that the variability in performance on all nine EF tasks was best explained by three distinct, albeit correlated factors, which they labelled inhibition, shifting and updating. Moreover, they found that the same three factors (or combinations thereof) contributed to students' performance on a set of more complex tasks. This led to the formulation of a tripartite model for explaining adults' EF performance, according to which executive functions comprise the distinct yet related fundamental components of i) inhibition, referring to the ability to override dominant impulses, ii) updating one's working memory by adding, deleting and monitoring multiple pieces of information and iii) shifting attention between different information and mental states.

One of the strongest advantages of the study carried out by Miyake et al. (2000), was the meticulous approach that the researchers adopted for measuring and acquiring accurate estimates of the EFs in question. Traditionally, EFs are assessed using performance tasks designed to measure the behavioural manifestations of EFs in individuals (Gioia, Isquith, & Kenealy, 2008). Such behavioural tasks, however, have certain limitations that render the valid and reliable assessment of EFs particularly challenging. One major concern is the extent to which performance on these tasks represents actual executive functioning in everyday life (Burgess et al., 2006; Lalonde, Henry, Drouin-Germain, Nolin, & Beauchamp, 2013). This is referred to as tests' ecological validity, which in the case of the behavioural tasks used to measure EFs is inherently limited (Gioia et al., 2008) since these tasks are primarily administered in controlled settings that differ substantially from the everyday environment that individuals normally function in, leading to their predictive value being compromised (Lalonde et al., 2013). In addition to ecological validity issues, many of the tasks used to measure EFs tap more than one EF-related cognitive processes that cannot be easily dissociated, thus prohibiting the assessment of discrete EF components. In her influential review on EFs, Diamond (2013) mentions that the topic of which EF components are tapped by each EF task, remains one of the most hotly debated subjects among researchers studying EFs.

She also discusses working memory and inhibition as examples of two EF components that very rarely occur in isolation as they support one another and are highly intertwined (Diamond, 2013). Furthermore, performance on the behavioural tasks used to measure EFs also draws upon lower-order processes that are not considered to be EFs (Burgess, 1997). The latter is often mentioned in the literature as the ‘task impurity problem’ referring to the fact that these tasks offer an impure measure of EFs.

In order to overcome some of these issues, Miyake et al. (2000) took care to adjust their methodology accordingly. More specifically, instead of using a single task to measure each construct of interest, Miyake et al. (2000) employed a set of three tasks per EF component they wanted to assess. This allowed them to obtain better and ‘purer’ estimates of each EF component by drawing information from all three different tasks used to measure it. Furthermore, Miyake and his colleagues investigated the EF components of interest at the level of latent variables i.e., they created meaningful constructs representing each component based on what was shared among the different tasks used to tap it; subsequently, by examining the interrelations among the resulting constructs, they established the separability of the three EF components of inhibition, shifting and working memory updating. Nowadays, latent variable modelling is commonly accepted as a suitable method to address the “task impurity problem” (Cassidy, 2015; Huizinga, Dolan, & van der Molen, 2006) and is often applied in studies examining EFs (e.g., Brydges, Fox, Reid, & Anderson, 2014; Fuhs & Day, 2011; Huizinga et al., 2006), however, the study by Miyake et al. (2000) was one of the first to introduce it (Huizinga et al., 2006). This methodological innovativeness may perhaps be one of the reasons that led to this study being frequently cited and the tripartite EF model it suggested becoming so widely accepted (Best & Miller, 2010; Diamond, 2013), with the corresponding three EF components being the focus of many studies carried out among adults, as well as children and adolescents.

1.2. Rationale for the present research

Naturally, as is done with many theoretical constructs regarding cognition, EFs quickly became a subject of study in younger age groups as well as adults, and over the years, children’s and adolescents’ EFs have been researched in both a developmental and an educational context. The tripartite model of EF structure that was established for adults began being tested in younger ages in order to determine the maturation process of each of the three EF components (see Garon, Bryson, & Smith, 2008 for a review of EF development during preschool years and Best, Miller, & Jones, 2009; Best & Miller, 2010 for reviews on childhood and adolescence). Different areas of research focused on investigating the links between EFs and other constructs that are influential in development, such as theory of mind (ToM) i.e., the capacity to recognise and attribute mental states to oneself and others, as well as disruptive behaviour and social relationships/problems (Best et al., 2009). Finally, work with older children and adolescents has concentrated on exploring the relationship between EFs and educational attainment within the context of formal schooling.

It is within this developmental and educational context that EFs are investigated in this thesis. In an era characterised by a shift towards more interdisciplinary research and unrestricted communication of information, the interaction between the fields of psychology and education is ever more robust with many discoveries from the discipline of psychology and/or neuroscience being embraced and benefiting education. In this thesis, EFs are considered as another psychological construct with considerable potential within the field of education as tools to assist and/or improve learning. The aim of this thesis is to shed light on particular issues regarding EFs that may be relevant to education and on which current understanding is incomplete. Due to the popularity of the tripartite EF model within the developmental EF literature, the focus throughout the whole thesis is on the three EF components of inhibition, shifting and working memory. The literature on these three EF components was reviewed in order to identify specific areas/issues of interest. Research questions were then formed, and relevant studies were developed and carried out in order to answer these questions.

1.3. Background

1.3.1. Development of EFs

One of the major areas of research into EFs is concerned with the development of EFs through childhood and adolescence and how they mature to reach adult levels.

Early evidence demonstrating the emergence of EFs as early as infancy derived from studies influenced by Piaget's object permanence paradigm. These studies utilised a task known as the AB task (or A not B task), in which the infant initially observes an object being hidden in one of two possible locations (A or B) and has to retrieve/uncover it; after the infant has repeatedly observed and retrieved the object from location A, the contingency is reversed and the object is hidden in location B from where the infant must retrieve it. The AB task is considered to measure the earliest appearance of goal-directed, intentional behaviour, requiring planning and foresight (Diamond & Goldman-Rakic, 1989; Diamond, 1985). Infants' performance on the task is thought to represent both inhibition (inhibition of the proponent response of searching in location A) and working memory (holding in mind novel information about the object's position) (Espy, Kaufmann, McDiarmid, & Glisky, 1999; Russell, 1999). Piaget's initial findings showed that infants 12 months or older reached correctly to location B to retrieve the object (Piaget, 1954), therefore, indicating that early manifestations of EFs (Espy et al., 1999) emerge during the first year of life. Subsequent studies confirmed these results and went on to further examine individual-differences in age-related performance on the AB task among infants and preschoolers, often by manipulating certain aspects of the task (i.e. introducing increasingly longer delays before the child is allowed to search for the object; Diamond & Goldman-Rakic, 1989; Diamond, 1985; Espy et al., 1999). Overall, these preliminary studies set the foundation for ensuing research investigating the development of EFs in younger ages.

Initially, with the exception of the AB task, there was a lack of age-appropriate tasks suitable for measuring EFs in very young children. However, during the last three decades, the scene has effectively changed since many new EF-tasks appropriate for younger ages have been created or adapted from existing adult EF measures (Garon et al., 2008). This led to a sharp increase in the amount of studies investigating EFs during the preschool years, which currently account for the majority of studies concerning EF in childhood (Hughes, 2011). Of course, similar to EF research in adults, establishing a framework for conceptualising the nature/structure of executive functioning in younger ages is challenging. In their influential review of EF development in preschoolers, Garon et al. (2008) adopt an integrative framework that considers EF (and consequently its development) as a unitary construct with partially dissociable components (i.e., inhibition and working memory), similar to the framework suggested for adults by Miyake et al. (2000). At the centre of this framework is the idea of a common, overarching process (potentially related to attention), which forms the foundation for the development of the distinct EF components. In accordance to this view, many recent studies, which used factor analysis to explore the dimensionality of EF in the preschool years, found that preschoolers' performance on a variety of tasks conceptualised as indices of EF could be adequately summarized by a single general EF factor (Fuhs & Day, 2011; Wiebe, Espy, & Charak, 2008; Wiebe et al., 2011; Willoughby, Blair, Wirth, & Greenberg, 2010). This all leads to the conclusion that EFs are hierarchically organised, with the distinct EF components of inhibition, shifting and working memory being built upon simpler cognitive abilities.

According to the findings discussed in the review by Garon et al. (2008), the preschool period is characterised by i) the emergence of elementary cognitive abilities relevant to executive functioning and ii) subsequent rapid improvement of these abilities. This is evident from the results of a multitude of different studies using a large variety of age-appropriate EF tasks (e.g., Alloway, Gathercole, Willis, & Adams, 2004; Diamond, Prevor, Callender, & Druin, 1997; Espy, Kaufmann, & Glisky, 2001; Hongwanishkul, Happaney, Lee, & Zelazo, 2005; Kochanska, Murray, Jacques, Koenig, & Vandegeest, 1996; Scerif, Cornish, Wilding, Driver, & Karmiloff-Smith, 2004). The general pattern arising from all these studies is that adequate performance on the simplest types of tasks (measuring more basic skills) is achieved around the ages of 1-2 years and subsequently, throughout the ages of 2-3 to 5 years, performance continues improving and expanding as preschoolers begin to tackle and solve tasks (or variations of tasks) of increasing difficulty i.e., involving larger degrees of conflict, larger delays or more items to keep track of. Finally, by the end of the preschool period, the findings of certain studies utilising factor analysis demonstrate that performance on EF tasks begins to cluster into distinct factors (Lee, Bull, & Ho, 2013; Van der Ven, Kroesbergen, Boom, & Leseman, 2013), marking the onset of partially dissociable EF components.

The next large body of research regarding the development of EFs focuses on children of primary school age. As was previously mentioned, some studies provide evidence in support of EFs beginning to differentiate during the later stages of preschool and the transition to primary school (Lee et al., 2013; Van der Ven et al., 2013). Studies applying factor analysis on data obtained from samples of primary-school aged children further corroborate the idea of the gradual differentiation of

EFs since many of them show that a two-factor structure in which the working memory component appears separated from inhibition and shifting provided the best fit to the data (Brydges et al., 2014; van der Sluis, de Jong, & van der Leij, 2007; Van der Ven et al., 2013, but also see Latzman & Markon, 2010 and Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003 for contrasting reports of a three-factor structure of EFs among children as young as 8 years old). As far as the development of EFs is concerned, findings of multiple studies using a variety of different EF tasks indicate that EF performance continues to improve throughout the primary-school ages, with stepwise improvements appearing gradually, first on easier tasks and then more complex ones (e.g., Davidson, Amso, Anderson, & Diamond, 2006; Gathercole, Pickering, Ambridge, & Wearing, 2004; Huizinga et al., 2006; Simonds, Kieras, Rueda, & Rothbart, 2007; Somsen, 2007). Thus, EFs appear to steadily develop during the period of middle childhood.

In contrast to the abundance of studies exploring the development of EFs during the preschool and primary-school years, fewer studies have focused on the development of EFs during adolescence (Best et al., 2009; Romine & Reynolds, 2005). This disproportionate focus on younger ages appears to be well grounded considering the fundamental cognitive changes and improvements that take place during the preschool and primary-school ages, as described above. However, research within younger ages has also shown that performance on tasks of different complexity and/or evaluating different EF components improves at different rates (Best & Miller, 2010; Hughes, 2011) and adult levels of performance on some of these tasks has not yet been reached by the beginning of adolescence (Davidson et al., 2006). This indicates that certain aspects of EFs may continue changing after puberty. Moreover, factor analytic studies have shown that the three EF components of inhibition, shifting and working memory become fully-separated during adolescence (Latzman & Markon, 2010; Lee et al., 2013; Li et al., 2015). Although there are some discrepancies among the studies regarding the exact age at which the EF components become fully-differentiated (most studies indicate around 13-14 years), their findings all suggest that the increasing specialisation of EFs continues into adolescence, which is when the tripartite model of EF (Miyake et al., 2000) finally emerges.

Further evidence of the increasing specialisation of EFs during adolescence has derived from neurohistological and neuroimaging studies exploring brain maturation and more specifically the maturation of the prefrontal cortex, which, as previously mentioned, is the brain region most commonly associated with EFs (see page 19 above). Compared to other brain regions (e.g., regions involved in attention, motor and sensory processing etc.) the prefrontal cortex matures at a slower rate, undergoing both progressive (proliferative) and regressive changes well into late adolescence. Progressive changes mainly refer to the myelination of axons – a process known to boost the transmission speed of signals across neurons. Early studies utilising histochemical methods showed that axonal myelination within the prefrontal cortex of human brains continues through adolescence (Yakovlev & Lecours, 1967). These findings have since been corroborated by more recent studies using Magnetic Resonance Imaging (MRI) in which the ongoing myelination is manifested as a linear increase in prefrontal white matter volume during adolescence (Barnea-Goraly et al., 2005; Sowell, Thompson, Holmes, Jernigan, & Toga, 1999). Simultaneously to this increase in white matter, the prefrontal cortex has been shown to undergo significant regressive changes as is evident by the observation of a decrease in prefrontal gray mater during adolescence in MRI studies (Gogtay et al., 2004; Sowell, Thompson, Tessner, & Toga, 2001). The grey matter decrease has been attributed to the synaptic reorganisation that takes place in the prefrontal cortex after puberty (Huttenlocher, 1979). During this synaptic reorganisation – commonly referred to as synaptic pruning- infrequently used synaptic connections are eliminated whilst frequently used ones are strengthened, resulting in a decline in synaptic density but rendering the remaining synaptic circuits more efficient (Blakemore & Choudhury, 2006). Overall, both the progressive and regressive changes described above appear to contribute towards the fine-tuning of the neural networks within the prefrontal cortex, which corresponds well to the idea, implied by the behavioural studies, of continuing specialisation and improvement of EFs during adolescence.

Influenced by the results of both the behavioural and neuroimaging studies that suggest ongoing development and increasing refinement of EFs during adolescence, researchers have accentuated the importance of examining the full developmental trajectory of EFs (Best et al., 2009) and having more research that considers the period of adolescence (Romine & Reynolds, 2005). The results of the few studies that have investigated EF development beyond the ages of 11-12 years, do indeed demonstrate that performance on various measures of EFs improves significantly from early to middle adolescence (Conklin, Luciana, Hooper, & Yarger, 2007; Huizinga et al., 2006; Lee et al., 2013) and, in some cases, even further, up to young adulthood (Boelema et al., 2014; Gur et al., 2012; Leon-Carrion, García-Orza, & Pérez-Santamaría, 2004; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Magar, Phillips, & Hosie, 2010). Although not all results were significant, for example Magar et al. (2010) found no age-related changes in adolescents' performance on a task designed to measure response inhibition, these studies provide important evidence that EFs continue developing throughout adolescence. However, discrepancies among the studies in aspects of their design and methodology make it hard to reach consistent conclusions regarding the developmental trajectories of the three EF components of inhibition, shifting and working memory during adolescence.

Indeed, only certain of the aforementioned studies focused distinctly on the tripartite EF model (Huizinga et al., 2006; Lee et al., 2013; Magar et al., 2010); the rest researched different combinations of EFs (Boelema et al., 2014; Gur et al., 2012; Luna et al., 2004) or even certain EF components in isolation (Conklin et al., 2007; Leon-Carrion et al., 2004). Another notable inconsistency among studies is the age range across which EF development is examined, with differences evident in both the lower and upper age limits studied. In some studies that include adolescent participants, the upper age limit examined is 15 years of age (e.g., Lee et al., 2013; Prencipe et al., 2011; Spielberg et al., 2015) thus, only providing information about the earlier stages of adolescence, whereas less is known about the development of EFs during late adolescence and early adulthood (Taylor, Barker, Heavey, & McHale, 2013). Furthermore, studies investigating the maturation of EFs beyond the age of 15, often rely on examining differences in EF performance between discrete groups with large divergences in age, for example 15 year olds compared to 19-21 year olds (Gur et al., 2012; Huizinga et al., 2006; Luna et al., 2004), therefore, potentially masking the specific changes that EF processes may undergo during late adolescence.

All in all, the development of EFs during adolescent years appears to have received disproportionately less attention compared to younger ages. Furthermore, the few studies that have investigated the development of EFs among adolescents have many limitations, the most important being their focus primarily on early adolescence while neglecting the development of EFs beyond the age of 15. Future studies addressing the development of EFs in adolescence should focus on wide age ranges that include the latter stages of adolescence and would ideally examine the development of all three EF components of the tripartite EF model.

1.3.2. EFs and educational attainment

In addition to the research on the development of EFs throughout childhood and adolescence, EFs have also been at the centre of educational research with regard to their relation to children's and adolescents' educational attainment.

The earliest point at which the relationship between EFs and educational attainment has been explored is among preschoolers, whose attainment is measured in the form of their emergent academic skills and school readiness. There have been studies in which the working memory of children as young as two years old has been examined and found to predict their emergent academic skills at the age of five (Mulder, Verhagen, Van der Ven, Slot, & Leseman, 2017). Typically, however, studies investigating the relationship between preschool EFs and academic abilities involve children aged 3 to 5-6 years and their results have consistently demonstrated that various aspects of EF, most frequently inhibition and working memory, contribute to children's ability and skills in the domains of mathematics, literacy and science (Becker, Miao, Duncan, & McClelland, 2014; Blair & Razza, 2007; R. J. Duncan, McClelland, & Acock, 2017; Gropen, Clark-Chiarelli, Hoisington, & Ehrlich, 2011; Harvey & Miller, 2017; Lan, Legare, Ponitz, Li, & Morrison, 2011; Nayfeld, Fuccillo, & Greenfield, 2013; Purpura, Schmitt, & Ganley, 2017; Verdine, Irwin, Michnick Golinkoff, & Hirsh-Pasek, 2014). Interestingly, in many of these studies, the effect of EFs on attainment was examined in parallel to that of other abilities that develop during these ages, such as visuo-motor skills (Becker et al., 2014; Verdine et al., 2014) and self-regulation (Becker et al., 2014; R. J. Duncan et al., 2017), and most of the studies also controlled for relative aspects of intelligence (Becker et al., 2014; Blair & Razza, 2007; Harvey & Miller, 2017; Purpura et al., 2017). EFs were nevertheless found to make unique contributions to the relevant measures of academic ability, beyond the effects of all the other cognitive variables that were controlled for in the studies, thus showcasing the importance of EFs in shaping children's academic performance during their preschool years.

In addition to the aforementioned studies, in which the relationship between preschool EF and attainment is examined in a cross-sectional manner, a large strand of literature has focused on exploring the role of preschool EFs in the transition to primary school. Typically, these are longitudinal studies which examine pre-schoolers' EFs as predictors of their later educational attainment in primary school. For example, in a 2013 study, Nesbitt, Baker-Ward, and Willoughby used structural equation modelling (SEM) to construct a latent variable representing kindergarteners' inhibition, shifting and working memory and found that this composite index of EF predicted children's maths and reading achievement one year later, in the 1st year of primary school. Two other studies used confirmatory factor analysis (CFA) to demonstrate that, among 5 year old children, EFs are organised into two factors –an inhibition and a mixed working memory-shifting factor- and found that the latter predicted children's overall maths attainment in the 1st and 3rd year of primary school (Viterbori, Usai, Traverso, & De Franchis, 2015), as well as their reading comprehension in 3rd year (De Franchis, Usai, Viterbori, & Traverso, 2017). Furthermore, Vandenbroucke, Verschueren and Baeyens (2017) found that preschool working memory predicted children's performance on maths, reading and spelling assessments they completed in the 1st year of primary school. Two more recent studies (Morgan, Farkas, Hillemeier, Pun, & Maczuga, 2019; Nguyen & Duncan, 2018) have provided evidence that measures of all three EF components during preschool make unique contributions to later achievement in maths, reading and science during the primary school years. Despite slight discrepancies regarding the significance of the respective EF components, the results of all the above studies confirm the importance of preschool EFs as a predicting factor of later attainment during primary school.

Of course, the bulk of literature on the relationship between EFs and educational attainment is focused on primary school aged children, since primary school constitutes the basic stage of formal schooling when children officially begin to acquire knowledge on a variety of academic subjects. Moreover, primary school is typically the period during which children start being assessed on standardised tests of academic achievement, therefore, providing more tangible measures of attainment that can be examined in relation to EFs.

In contrast to the literature relating to attainment in the preschool years, which in the majority of cases regarded multiple EF components being jointly examined, many of the studies on primary school aged children focus on working memory in isolation. More specifically, working memory has been primarily examined in relation to maths attainment in a variety of age groups. The majority of the relevant studies showed that children's working memory uniquely contributes to their achievement in many different aspects of mathematics, as measured either by standardised tests of mathematical abilities (Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Swanson & Kim, 2007) or curriculum-based math tests/exams (De Smedt, et al., 2009; Nyroos & Wiklund-Hornqvist, 2012; Wiklund-Hornqvist, Jonsson, Korhonen, Eklof, & Nyroos, 2016). In addition to maths attainment, working memory has also been found to contribute to children's reading skills (Blankenship, O'Neill, Ross, & Bell, 2015). Moreover, in many of these studies, other variables that can affect attainment, such as non-verbal IQ or processing speed, were controlled for and therefore, their significant results are indicators of the unique contribution of working memory on educational attainment net of the effects of other cognitive factors. However, there are also examples of studies that found that working memory had no further effect on maths attainment beyond that of short-term memory capacity (Alloway & Passolunghi, 2011; Maybery & Do, 2003), thus, underlining the importance of controlling for the non-EF construct of short-term memory capacity.

Despite controlling for the effects of confounding non-EF variables, all the studies mentioned above only inform us about the role of working memory on educational attainment without examining the effects of inhibition and shifting. In general, fewer studies have explored the relative effects of all three EF components on children's educational attainment. In 2017, Aran-Filippetti and Richaud used CFA to establish the three-factor structure of EF among 8-12 year old children, but found that, out of the three EF components, only working memory and shifting had significant independent effects on children's maths achievement (Aran-Filippetti & Richaud, 2017). Similar findings were reached in another 2017 study, which showed that working memory and shifting were the only EF components that uniquely contributed to young children's (6-8 years old) performance on maths and spelling tests (Dekker, Ziermans, Spruijt, & Swaab, 2017). On the other hand, two studies from 2016 provided evidence for unique contributions of all three EF components on attainment: Cantin, Gnaedinger, Gallaway, Hesson-McInnis, & Hund (2016) found that each of the three EF components independently predicted children's reading comprehension, which in turn predicted maths attainment, while Lubin, Regrin, Boulc'h, & Pacton (2016) showed that the three EF components differentially contributed to fourth-graders performance on maths, reading and spelling tests. Therefore, although there are some inconsistencies regarding the role of each EF component, overall the literature indicates that EFs continue influencing children's educational attainment throughout the primary school years and that this is net of the effect of general IQ, which was controlled for in most studies.

It is important to note that the aforementioned studies examined a variety of age groups, which taken together span from 6 to 12 years of age (i.e., the entirety of primary school). However, all but one (De Smedt et al., 2009) of these studies were cross sectional. The transition from primary to secondary school has not been extensively researched using longitudinal studies as was the case for the transition from preschool to primary school. This is an important omission considering that the transition to secondary school is thought to constitute a social and academic turning point for children (Langenkamp, 2009; Smith, Akos, Lim, & Wiley, 2008), as they move to a larger, more heterogeneous school with increased expectations of academic performance and less support from teachers (Hanewald, 2013). This transition also typically coincides with the entry to adolescence, a crucial period of cognitive, psychosocial and emotional transformation (Hines, 2007). According to the previous section of this chapter (section 1.3.1), adolescence is a critical period for the development of EFs, with refinements/specialisation of EFs taking place throughout adolescence and into young adulthood as the prefrontal cortex undergoes some final changes towards maturation. Consequently, since EFs have not reached their mature levels by the beginning of adolescence, which corresponds to the upper age limit in all the previously mentioned studies, it is necessary to study EFs further during secondary school years to get the most complete picture of their effect on educational attainment. Furthermore, EFs might be of particular importance to adolescents' attainment during secondary school, when they are confronted with increasingly taxing academic demands.

Surprisingly, fewer studies have focused on the relationship between EFs and attainment in secondary school compared to the multitude of studies on preschool and primary school attainment. Among the few studies that examine EFs in relation to attainment in secondary school, many focus on a single EF component in isolation; for example, many studies have focused solely on working memory and have found it to be significantly linked with adolescents' attainment primarily in languages, maths and science (Alloway, Banner, & Smith, 2010; Danili & Reid, 2004; Gathercole, Pickering, Knight, & Stegmann, 2004; Kyttala & Lehto, 2008; Lukowski et al., 2014), but also in arts and geography (Lehto, 1995; Riding, Grimley, Dahraei, & Banner, 2003). Although all these studies demonstrate the importance of

EF ability as a predictor of adolescents' attainment in secondary school, they do not provide any insight into the relative effect each EF component may have.

Other studies have investigated all three EF components (inhibition, shifting and working memory) in relation to adolescents' attainment, but only focused on one subject at a time. For example, in a 2017 study, Cragg, Keeble, Richardson, Roome, and Gilmore demonstrated that, in addition to working memory, inhibition also played an important role in predicting adolescents' performance on certain aspects of maths. Two other studies (Aran-Filippetti & Richaud, 2015 and Berninger, Abbott, Cook, & Nagy, 2017) showcased the relative contributions of inhibition, shifting and working memory to adolescents' abilities in regard to different language modules (i.e., writing, reading and speaking). Finally, in studies that examined all three EF components exclusively in relation to science attainment, working memory was found to uniquely predict adolescents' conceptual understanding in the subjects of biology (Rhodes et al., 2014) and chemistry (Rhodes et al., 2016). However, because all these studies were carried out using different samples of various ages and demographic characteristics, their results are not directly comparable. Thus, from these studies alone, it is not possible to assemble a complete picture of the differential effect of EFs on attainment in the variety of subjects available in secondary school.

There are very few studies that examine all three EF components of inhibition, shifting and working memory in relation to attainment across different subjects in the same sample of adolescents. A 2006 study, by St Clair-Thompson and Gathercole was one of the first to examine the partial correlations among the three EF components and young adolescents' attainment on a variety of secondary school subjects. The findings showed that both inhibition and working memory, but not shifting, were associated with English and maths attainment, while inhibition was the only EF component that was independently related to science attainment. A few years later, Latzman, Elkovitch, Young, and Clark (2010) studied the relation between the three EF components and attainment in an even broader range of subjects and once again found differential contributions of each EF component in reading, maths, science and social studies among male adolescents aged 11-16. These studies provided preliminary evidence in support of individual EF components having differential effects on adolescents' attainment in various subjects, however, due to the scarcity of studies that jointly examine all three EF components in relation to attainment in different subjects, more research is needed to confirm these results and draw firm conclusions.

One important limitation of many of the adolescence studies discussed above is that they only examined the relation between EFs and attainment among pupils in a single year of secondary school (e.g., Danili & Reid, 2004; Gathercole et al., 2004; Rhodes et al., 2016; Riding et al., 2003; Zorza, Marino, & Mesas, 2016). Consequently, the age ranges examined in these studies are relatively narrow (1 to 2 years max), which prohibits the generalisability of their results across adolescence. In addition to the narrow age ranges examined, there is a disproportionate focus on early adolescent years, with the majority of studies regarding adolescents between the ages of 11-14 (Alloway et al., 2010; Cragg et al., 2017; Lukowski et al., 2014; Rhodes et al., 2014, 2016; St Clair-Thompson & Gathercole, 2006; Zorza et al., 2016). The latter stages of adolescence have not received adequate attention since the upper age limit examined in studies scarcely exceeds 15 years of age. Of course, there are a few studies that surpass these limitations, but they bear other constraining limitations of their own. For example, the 2010 study by Latzman et al. discussed above considered a relatively wide age range (11-16 year olds) but its sample consisted of solely male adolescents. Furthermore, a study by Best, Miller and Naglieri (2011) using a large sample of 5-17 year olds found significant correlations between EF and performance on assessments of reading and maths, however, the EF construct measured in this study was planning – a complex cognitive process involving multiple EF components – and thus the results do not reveal anything about the relative contribution of each EF component to attainment.

All things considered, the existing literature on the relationship between EFs and attainment during the period of adolescence appears to have substantial gaps and limitations. Perhaps the most important of these limitations is the relative scarcity of studies investigating EFs in relation to attainment during the latter stages of adolescence (roughly from 15 years of age and above). This could potentially be an important omission seeing as this period coincides with the more senior years of secondary school, which can be exceptionally challenging for pupils due to their high academic load. It therefore might be particularly interesting to examine the strength of the association between EFs and attainment during this period of high academic demands.

Furthermore, during the final years of secondary school, pupils are typically at the stage of making decisions, planning and working towards the next stages of their lives. For many, the next step after secondary school is enrolling into higher education, but in order to be eligible to do so, pupils are usually expected to have completed certain qualifications while still at school. Seeing as EFs are essential for the anticipation and achievement of long-term goals (Dawson & Guare, 2018; Gioia & Isquith, 2004; Luria, 1966; Welsh & Pennington, 1988), EFs may govern adolescents' effectiveness in planning their study course, applying self-discipline in studying and ultimately achieving the necessary qualifications for entry into higher education. Interestingly, despite there being studies that examined EFs in relation to adolescents' performance on national, standardised qualifications (e.g., Gathercole et al., 2004; St Clair-Thompson & Gathercole, 2006), this was never in the context of measuring pupils' success in meeting the academic requirements for getting accepted into higher education courses. Once again, this could potentially be an important omission especially when considering the ramifications that a significant finding (i.e., EFs influence performance on qualifications for university entry) may have for educational practice and pupils' preparation for the final exams/assessments that provide access to higher education.

Overall, the literature presented above reveals the need for more research on the relationship between EFs and educational attainment during the latter part of adolescence. Additionally, a more specific subject of interest relative to this age group is adolescents' success in attaining the grades/qualifications necessary for entry into higher education. More studies should thus focus on examining both EFs' relationship to older adolescents' general educational attainment and to their attainment on exams/assessments needed for entry into University/College. Ideally, where appropriate, studies should examine wide age groups that include the latter stages of adolescence and cover attainment in a variety of subject areas.

1.3.3. EFs, transferable skills and educational attainment

The previous section of this chapter (section 1.3.2) introduced the literature concerning the relationship between EFs and academic achievement, with the latter being indicated by school grades or performance on subject-relevant attainment tasks. However, another prominent area of research focuses on investigating the link between EFs and more specific skills and abilities that constitute the building blocks of individuals' academic achievement. Examples of such constructs that have been examined in relation to EFs are literacy and numeracy, problem solving and reasoning abilities. In an educational context, these types of cognitive abilities are often classified as generic or transferable skills due to the fact that they are relevant across different social and professional domains and/or situations (Bridges, 1993). In the 21st century, transferable skills have become increasingly essential and desirable skills to acquire since they underpin competence in many different areas/stages of life, such as school, higher education and employment. Consequently, in recent years, education has been reformed accordingly to incorporate the transmission of transferable skills, with the objective of helping students become independent and effective citizens and individuals, capable of thinking critically.

As a result of the popularity that transferable skills have gained in educational settings during the last century, they have also received a lot of attention as the subject of developmental and educational research. Various types of skills have been studied in a developmental context, in relation to educational attainment or in relation to cognitive abilities, including EFs. Two skills that have been extensively researched are literacy and numeracy, which are acknowledged by many education curricula around the world – including the Scottish Curriculum for Excellence – as the foundational skills necessary for learning and success in everyday life (Lubin et al., 2016; Scottish Government, 2008, 2009). Of course, literacy and numeracy are umbrella terms used to refer to a multitude of more discrete skills pertinent to language and mathematics respectively; consequently, there is a large amount of related studies that focus on different aspects or developmental manifestations of these skills. For example, aspects of literacy that are frequently investigated in studies include reading comprehension, spelling and written expression, whereas letter- sound knowledge, word recognition, vocabulary and phonological awareness are often examined as indicators of emergent literacy in preschoolers (Blair & Razza, 2007; Kegel & Bus, 2014; Purpura et al., 2017). Naturally, these types of (literacy) skills are primarily thought of as indicators or predictors of language learning and achievement (e.g., Monette, Bigras, & Guay, 2011; Berninger et al., 2017), but there is also a growing body of literature that demonstrates links among literacy and EFs. More specifically, studies have provided ample evidence in support of inhibition, shifting and working memory acting as both concurrent (Blair & Razza, 2007; Kegel & Bus, 2014; Lubin et al., 2016; Purpura et al., 2017) and longitudinal (Altemeier, Abbott, & Berninger, 2008; Meixner, Warner, Lensing, Schiefele, & Elsner, 2018) predictors of literacy among pre-schoolers and primary school aged children, while fewer studies have affirmed the relationship between EFs and particular literacy skills among adolescents (Aran-Filippetti & Richaud, 2015; Berninger et al., 2017).

Similar to literacy, the term numeracy incorporates a multitude of different skills related to individuals' ability to understand and use numbers. One characteristic example of a skill considered to be an important component of numeracy is the ability to gauge numerical magnitudes (also referred to as numerical magnitude representation and related to the term subitizing), which has been frequently researched in relation to maths learning and achievement among younger children (Booth & Siegler, 2008; De Smedt, Verschaffel, & Ghesquiere, 2009; Fazio, Bailey, Thompson, & Siegler, 2014; Mazzocco, Feigenson, & Halberda, 2011). Numerical magnitude skills have also been investigated in relation to inhibition, shifting and working memory among both preschoolers (Espy et al., 2004; Kolkman, Hoijtink, Kroesbergen, & Leseman, 2013; Purpura et al., 2017) and primary school-aged children (Lubin et al., 2016), with the results of all the studies indicating significant links between these EF components and numerical magnitude representation. Other math-related skills that have been regarded as indicators of numeracy and have been shown to relate to EFs among young children include number knowledge (Kroesbergen, Luit, Van Lieshout, Van Loosbroek, & Rijt, 2009; Purpura et al., 2017), counting (Espy et al., 2004; Kroesbergen et al., 2009; Purpura et al., 2017) as well as simple calculations, usually only involving basic addition and subtraction (Escolano-Perez, Herrero-Nivela, Blanco-Villasenor, & Anguera, 2017; Espy et al., 2004; Purpura et al., 2017).

In older ages, numeracy is often conceptualised in terms of more complex skills, such as quantitative reasoning and the ability to solve mathematical word problems (Agostino, Johnson, & Pascual-Leone, 2010; Lee, Ng, Ng, & Lim, 2004). Similar to the numeracy skills researched in younger ages, quantitative reasoning and mathematical problem solving have also been found to correlate to children's and adolescents' inhibition, shifting and working memory (Agostino et al., 2010; Lee, Ng, & Ng, 2009; Lubin et al., 2016; Viterbori, Traverso, & Usai, 2017) with particular interest being shown to the relationship between mathematical problem solving ability and the EF component of working memory (Andersson, 2007; Pavlin-Bernardic, Vlahovic-Stetic, & Arambasic, 2008; Swanson, 2011; Zheng, Swanson, & Marcoulides, 2011).

In addition to literacy and numeracy, another set of transferable skills that have received a significant amount of attention are those concerning individuals' reasoning ability. Reasoning is considered a core cognitive skill of humans that allows them to think about something in a logical and sensible way, drawing from facts or premises in order to reach a conclusion. Different types of reasoning have been shown to contribute to various aspects of human intellect such as creativity and innovation (Dunbar, 1997; Markman, Wood, Linsey, Murphy, & Laux, 2009), fluid intelligence (Carroll, 1993) and adaptive learning (Gentner, 2010), while they have also been researched in relation to EFs both during development and in adulthood. The most basic type of reasoning that is not dependent on individuals' real-world knowledge but simply concerns the innate ability to apply logic to known/provided information in order to arrive to a valid (logically certain) conclusion, is typically referred to as deductive reasoning (Goswami, 2002). A particular area of research relating to deductive reasoning focuses on individuals' performance on specific measures of deductive reasoning in which the information that individuals must process to reach a conclusion is incongruent with their prior beliefs or knowledge (e.g., De Neys & Van Gelder, 2008; Handley, Capon, Beveridge, Dennis, & Evans, 2004; Houde & Borst, 2014; Tsujii, Masuda, Akiyama, & Watanabe, 2010) . Results from this line of research unanimously demonstrate that adults' as well as children's and adolescents' ability to apply correct deductive reasoning and reach the right conclusion in these cases is dependent on their inhibition ability (De Neys & Van Gelder, 2008; Handley et al., 2004; Houde & Borst, 2014; Moutier, 2000; Steegen & De Neys, 2012).

EFs have also been (more commonly) researched in relation to more inferential types of reasoning, collectively referred to as inductive reasoning. This type of reasoning concerns the ability to reach a conclusion by making inferences from particular premises, generalising on the basis of a given example or drawing on an analogy (Goswami, 2002). Ever since an early study by Fry and Hale in 1996 revealed significant links between improvements in performance on a measure of inductive reasoning and age-related changes in working memory, inductive reasoning has been frequently examined in relation to the EF component of working memory among both children (Kail, 2007; Nettelbeck & Burns, 2010) and adults (Nettelbeck, Howard, & Wilson, 2009; Nettelbeck & Burns, 2010; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002). The results of these studies, as well as additional studies in which the components of shifting and/or inhibition were considered (Decker, Hill, & Dean, 2007; van der Sluis et al., 2007), have provided abundant evidence of a strong association between EF components and inductive reasoning skills at various ages. Some studies focus on a more specific aspect of inductive reasoning, namely analogical reasoning, which refers to the ability of making analogies (i.e., drawing on the similarities or relationships between concepts/phenomena) in order to arrive at a correct conclusion. Similar to the previous types of reasoning discussed above, analogical reasoning has also been found to be significantly associated with EFs, particularly inhibition and working memory (Morrison, Doumas, & Richland, 2011; Richland & Burchinal, 2013; Simms, Frausel, & Richland, 2018).

The skills related to literacy, numeracy and reasoning presented above represent typical examples of skills that are applicable and relevant across a variety of disciplines. In school, for example, pupils' understanding and competence in virtually any subject relies to a certain extent on their ability to read, write and communicate orally i.e., their literacy. In fact, in recent literature, distinctions are often made between literacy skills specific to each discipline i.e., science (scientific literacy) or mathematics (mathematics literacy) (Stacey, 2010), which lead to the emergence of the term disciplinary-literacy, used to refer to the sets of specialised skills needed to create, communicate and use knowledge within each discipline (Gillis, 2014; Shanahan & Shanahan, 2012). Furthermore, in the majority of school subjects, achievement is typically evaluated using either oral or written assessments and therefore, measures of pupils' achievement are also affected by their level of literacy. Similar to literacy, numeracy skills are also relevant to achievement in more than one subject areas/domains. Obviously, numeracy skills are primarily considered as indicators and/or predictors of math achievement (Best et al., 2011; Blankenship et al., 2015; Bull, Espy, & Wiebe, 2008; De Smedt, Verschaffel, et al., 2009; Latzman et al., 2010). However, they can also influence children's and adolescents' science attainment, since science assessments, particularly in older school years, more often than not require executing numerical calculations and problem solving (see for example past exam papers of the Scottish National qualifications on science subjects[1]). Finally, it should already be apparent from the description of reasoning given above that reasoning skills are an important element for achievement in many subject areas. Indeed, reasoning has repeatedly been found to uniquely predict academic achievement in a variety of subjects and among a wide range of ages (Gómez-Veiga, Vila Chaves, Duque, & García Madruga, 2018; Hofer, Kuhnle, Kilian, & Fries, 2012; Krumm, Ziegler, & Buehner, 2008; Stevenson, Bergwerff, Heiser, & Resing, 2014; Taub, Keith, Floyd, & Mcgrew, 2008). Furthermore, reasoning is particularly closely linked to individuals' problem solving abilities (Chuderski, 2014; Greiff, Krkovic, & Hautamaki, 2016; Greiff et al., 2015) so it is therefore reasonable to assume that reasoning may be particularly pertinent in assessments of maths and science, which often involve solving word problems.

Overall, the information presented in the previous paragraphs reveals the existence of two distinct bodies of research on transferable skills: one that is concerned with the relationship between EFs and skills, such as literacy, numeracy and reasoning, and another that regards the investigation of these skills in relation to academic achievement. Surprisingly, over the years, these two bodies of research have remained fairly separate despite the fact that connections could be easily drawn among the respective elements they involve (i.e., EFs, transferable skills and attainment). When considering the two bodies of research on transferable skills together with the research discussed in the previous section of this chapter (see section 1.3.2), a clear narrative begins to form. More specifically, from section 1.3.2 it is apparent that the EF components of inhibition, shifting and working memory are significant predictors of children's and adolescents' educational attainment. However, the studies presented earlier in the current section also indicate that the three EF components predict children's and adolescents' literacy, numeracy and reasoning skills and in turn those skills influence educational attainment. Therefore, it is possible that transferable skills, such as literacy, numeracy and reasoning skills mediate the relationship between EF components (inhibition, shifting and working memory) and educational attainment. Nevertheless, very few studies have tested this hypothesis, and the ones that have, have only examined one type of skill at a time, while also not jointly considering all three components of the tripartite EF model.

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[1] Past exam papers for Scottish National qualifications on all subjects - including science subjects i.e., Biology, Chemistry, Physics etc. - can be accessed at https://www.sqa.org.uk/pastpapers/findpastpaper.htm

The first such example is a study by Fuhs, Hornburg and McNeil (2016) which demonstrated that certain numeracy skills mediated the relationship between pre-schoolers' EFs and their concurrent, as well as later, math achievement in primary school. However, apart from only focusing on skills and achievement in the context of maths this study considered a composite score of EF based on participants' performance on tasks measuring inhibition and shifting, but not working memory. In a different study, Stevenson et al. (2014) showed that working memory had an incremental effect on children's reading and mathematics attainment above and beyond the effect of reasoning skills and although the mediating hypothesis was not directly tested, these results could be considered as indicative of reasoning skills mediating the relationship between working memory and attainment. More concrete evidence in support of this is provided by Krumm et al. (2008) who in their attempt to investigate the role of working memory and reasoning skills in predicting attainment, tested a hierarchical model in which reasoning skills were treated as the mediator between working memory and school grades in language and science and found that this model had good overall fit. Despite these significant findings, however, this study was still limited in that it only considered a single type of skill in relation to a single EF component. Therefore, although the results of the aforementioned studies provide some preliminary evidence that transferable skills mediate the relationship between EFs and attainment, this line of research appears to be in very early stages and limited in terms of the constructs considered as well as the age groups examined, with the period of adolescence once again having been largely overlooked.

Further research is needed in order to fully discern the potential mediating role of transferable skills in the relationship between EFs and educational attainment. Studies considering multiple different types of transferable skills and examining them in relation to all three components of the tripartite EF model might be particularly helpful for gaining a more detailed picture of the intricate connections among different EF components, transferable skills and attainment. These types of studies would allow the individual examination of the relative contributions that each of the EF components makes to the transferable skills and each of the transferable skills makes to attainment. As far as the transferable skills are concerned, the focus should initially be centred on literacy, numeracy and reasoning skills, which have already been extensively, albeit separately, explored in relation to EFs and educational attainment. One specific context within which it may be particularly interesting to explore these skills is science attainment, since performance on school science assessments, especially in secondary school, typically relies on all three types of transferable skills. Indeed, the skills underlying science achievement have not been researched as systematically as those necessary for success in reading and mathematics, despite the importance attached to science by many national governments (Tolmie, 2012; Tolmie, Ghazali-Mohammed, & Morris, 2016). This renders the exploration of transferable skills and EFs in relation to attainment in science even more pertinent.

1.4. The present research

Overall, from the literature presented above, it appears that there has been less research on EFs during the period of adolescence compared to preschool and primary-school ages. Especially the latter stages of adolescence have been particularly overlooked, both from a developmental i.e., regarding the development of EFs during these stages, and an educational perspective i.e., investigating potential links between EFs and educational attainment at these ages. As mentioned earlier on, this disproportionate focus on younger children is justified since these ages are characterised by the most striking developmental changes and improvements in EFs. Furthermore, research on EFs in relation to attainment in younger ages seems sensible seeing as these ages are the most promising as far as the implementation and success of educational interventions is concerned. However, based on the results of the few studies carried out among adolescents, which provide evidence that EFs continue to develop and have substantial links with attainment until late adolescence, researchers have underlined the importance of having more research on EFs during adolescence (Romine & Reynolds, 2005; Taylor et al., 2013) in order to understand the full developmental trajectory of EFs (Best et al., 2009). In addition, studying EFs in adolescence is important and may prove particularly interesting since adolescence, especially the latter stages thereof, corresponds to the period of transition into adulthood, when individuals gradually become more independent and in charge of their own decisions. Therefore, EFs may constitute stronger predictors of individuals' behaviour and attainment in these ages.

In order to attempt to address the gap that is present in the EF literature due to previous studies overlooking the period of adolescence, the focus of my PhD project and consequently this thesis is on adolescence. More specifically, this thesis concerns the investigation of EFs in adolescents aged 14 to 18 years old. The particular age range was chosen to be relatively wide, rendering it more likely to detect the potentially subtle changes in EF occurring during adolescence, and incorporate the latter stages of adolescence, which were of particular interest since they constitute the period that has been most largely overlooked in the existing literature. Furthermore, in the Scottish educational system, during the ages of 14 to 18, pupils transition from a more broad educational phase to the senior phase of their curriculum, which made this age range interesting to investigate since it would allow the exploration of the development of EFs and their links to attainment in two separate educational phases.

Apart from the lack of studies focusing on the upper part of the developmental spectrum, another obstacle to attaining a more complete picture of the maturation of EFs and their relation to attainment throughout development is the heterogeneity among the relevant studies in terms of the samples and the particular EF components examined. In order to avoid the latter issue, as mentioned earlier on, this thesis focused solely on the tripartite model of EF (Miyake et al., 2000), that is, the same three EF components (inhibition, shifting and working memory) were examined throughout the thesis. Additionally, in the interest of gaining as coherent a picture of adolescents' EFs as possible, this whole thesis was based on a single large sample. More specifically, the data handled in each of the studies presented in this thesis derived from a collective sample of adolescents aged 14-18 years, who were recruited for the project overall. This helped eliminate some of the inconsistencies that may have arisen as a result of recruiting multiple different samples, with potentially different demographic characteristics, for each study.

Four different studies were designed and carried out, each aiming to explore a different issue relative to adolescents' EFs. Due to the scarcity of studies that have examined the development of all three EF components of inhibition, shifting and working memory throughout the latter stages of adolescence, the first objective of this thesis is to study the developmental changes in the three EF components among adolescents aged 14 to 18 years old. As opposed to many previous studies that inspected differences in EF performance among discrete groups of individuals with large divergences in age, the aim is to use cross-sectional data deriving from pupils aged 14-18 to detect whether significant changes in the three EF components of interest occur throughout these ages.

In addition to the development of EFs, another subject of great interest particularly to the discipline of education, is the relationship between EFs and attainment. As previous research, particularly with younger children, has shown significant associations between children's EFs and their attainment in school, the present thesis aimed to examine this relationship within an adolescent population and discover more about how EFs may influence attainment in adolescence, particularly the latter stages thereof, which have been largely overlooked in the existing literature. More specifically, this thesis will examine all three EF components of the tripartite EF model in relation to adolescents' school attainment in a variety of disciplines/subject areas, including the less studied areas of social studies, arts and foreign languages. These relationships will be explored across the relatively wide age range of 14-18 years, in order to obtain a broader picture of the associations between the three EF components and attainment.

Within the context of attainment and academic success, EFs have also not been previously researched in relation to individuals' success in acquiring the necessary qualifications/grades for entry into higher education. Given that the sample of 14-18 year olds recruited for this project included adolescents at school leaving age who completed qualifications that count towards entry into undergraduate programmes, this thesis will examine whether EFs constitute significant predictors of the oldest adolescents' performance on the relevant qualifications.

Finally, if inhibition, shifting and working memory are significant predictors of adolescents' attainment, it is important to question whether transferable skills, such as literacy, numeracy and reasoning skills, play a role in this relationship. Determining whether transferable skills act as a link between EFs and attainment constitutes a particularly appealing subject with potentially important implications from an education point of view, since educational systems and curricula around the world are currently largely focused on the transmission of transferable skills. Led by the literature presented earlier (see section 1.3.3), this thesis set out to test whether transferable skills constitute mediators in the relationship between the three components of the tripartite EF model and adolescents' attainment in science.

Although, the initial plan was to explore three sets of transferable skills that are frequently encountered in the literature – namely literacy, numeracy and reasoning skills – ultimately, literacy could not be examined due to difficulty in finding an inexpensive yet suitable, standardised and group-administered assessment capable of measuring the aspects of literacy that are relevant to adolescents' attainment in science. Therefore, this thesis will investigate whether adolescents' numeracy and reasoning skills constitute significant mediators in the relationship between inhibition, shifting and working memory and attainment in science.

1.5. Research questions

Given the issues identified throughout the literature, this thesis set out to answer the following research questions:

1. Do the EF components of inhibition, shifting and working memory continue to undergo age-related changes during the latter stages of adolescence, specifically during the period of 14-18 years of age?

2. To what extent are the three EF components related to adolescents' educational attainment across a variety of subjects through the ages of 14-18 years?

3. Is there a relationship between these EF components and older adolescents' performance on qualifications necessary for entry into higher education?

4. Do the transferable skills of numeracy and non-verbal reasoning mediate the relationship between the three EF components and adolescents' attainment in science?

1.6. Organisation of the thesis

The entire dataset for this PhD project was obtained from one large session of data collection carried out over the duration of (approximately) one year. The next chapter of this thesis is, thus, dedicated to presenting the methodology followed for the data collection overall (see Chapter 2: General Methods). The chapter begins with a timeline of the recruitment and data collection, before going on to present the tasks used for measuring the cognitive constructs, as well as a rationale for using these particular measures. Finally, a brief overview of the assessments used as indicators of educational attainment is provided and the testing procedure that was followed during data collection is explained.

The following chapters of the thesis are dedicated to presenting the results of the four different studies carried out to answer each of the four research questions of the project (see above). The results of the first study, exploring the development of the three EF components among 14-18 year old adolescents, are presented in Chapter 3. Note that this chapter is in the form of a paper, as it was written for submission to a peer-reviewed journal and is under review at the time of thesis submission.

The second study concerned the investigation of the three EF components in relation to adolescents' educational attainment and the results are presented in Chapter 4. The chapter begins with a general introduction to the subject, is then divided into two separate sets of methods, results and discussions – one for the pupils within the broad general education phase and one for those in the senior phase – before closing with a general discussion of the results across the ages of 14-18.

The third study constituted an attempt to explore the possibility that EFs influence individuals' success in receiving the necessary grades for entering higher education. To this end, this study examined whether inhibition, shifting and working memory predict adolescents' performance on qualifications that count towards points for entry into undergraduate programmes. The results of the study are presented in Chapter 5.

The final study was concerned with investigating the potential mediating role transferable skills may play in the relationship between EFs and science attainment. The results of the study in which numeracy and reasoning were tested as mediators between inhibition, shifting and working memory and adolescents' attainment in science, are presented in Chapter 6.

Finally, an overall discussion of the findings pertaining to each study as well as collectively is provided in Chapter 7. Limitations of the present thesis as well as implications for research and educational practice are also discussed within this final chapter.

Chapter 2: General Methods

2.1. Participants

2.1.1. Recruitment

The focus of this PhD project was the study of EFs in adolescence and consequently the sample consisted of secondary school pupils. More specifically, pupils in their third, fourth and fifth years of secondary school, which typically corresponds to ages 14 through to 18 years, were recruited from schools within the Lothian area of Scotland. The aim was to obtain a total sample of 350-400 pupils deriving from at least two different schools, while having no fewer than 100 pupils per year group. Since the main type of analysis to be carried out in all studies of this thesis was regression, the appropriate sample size was determined using the common rule of thumb that a minimum of 10-15 observations (cases) are needed per predictor in a regression model (Clark-Carter, 2010; Field, Miles, & Field, 2012). Aiming for a total of 100-120 pupils per year group was, therefore, deemed sufficient as it would provide enough power to develop regression models with eight predictors each, which corresponded to the maximum of independent variables considered in any of the analyses.

After designing the study, ethical approval was obtained from the School of Philosophy, Psychology and Language Sciences Ethics Committee at the University of Edinburgh (the relevant ethical approval form can be found in Appendix A). Next, permission was sought to carry out this study in the local authority of the City of Edinburgh's council. Upon receiving the council's consent, a number of schools were approached, initially based on their proximity to the University campus in order to reduce travelling distances for the researcher. The initial email sent out to schools included a brief introduction to the researcher and the project, accompanied by a more detailed letter, addressed to the head teacher, explaining the aim, requirements and potential outcomes of the project (see Appendix B). If no reply was received within two weeks of the schools receiving this email, it was followed up by a phone call to ascertain whether the schools were interested in participating or not.

One out of the seven schools initially approached at the beginning of April 2015 accepted to participate, but due to its small size, it could only contribute around 1/8 of the total sample needed. Therefore, the remaining (16) schools within the City of Edinburgh council's jurisdiction were contacted in waves during the following month. From these contacts, one school expressed potential interest in participating during the following year, but no school firmly accepted to participate. As none of the state-funded schools contacted were able to participate, some of Edinburgh's private secondary schools were also included in the search. However, the five private secondary schools that were approached either did not reply or declined the invitation to participate in the project. Therefore, as a result of the first recruitment session only one school accepted to participate in the project within the 2014/2015 school year. A detailed timeline of the first recruitment session is provided in Table 2.1A.

A second recruitment session was initiated in August 2015 for testing commencing from January 2016[2] onwards (see Table 2.1B for a detailed timeline of the second recruitment section). The school that had previously shown potential interest in the project was among the first to be contacted during this second recruitment session and, after some negotiations regarding when the testing could take place, agreed to participate in the project. This much larger school provided the majority of the participants who took part in the study; however, the target number of participants could still not be fully reached, so recruitment continued in order to find a third school to participate in the project. All the public schools within the City of Edinburgh were re-contacted for participation during the 2015/2016 school year and some further private schools were also contacted. However, none of these schools were willing to participate in the project.

After having exhausted all options in Edinburgh, it was deemed necessary to contact two more councils within the Lothian area: the Midlothian and the West Lothian councils. Approval was obtained from the West Lothian council and ten schools within this council were contacted. One of these schools accepted to participate and contribute the final number of pupils needed for the completion of the sample.

[2] Please note that the second round of testing could not commence any earlier than January 2016 due to a 3 month interruption I took from my PhD studies in order to carry out a full-time internship.

Table 2.1. Timeline of the recruitment process for the project overall.
A) Recruitment session 1 for participation during the school year 2014/2015 and B) Recruitment session 2 for particiaption during the school year 2015/2016

A)

Session 1: Contacting schools for participation during the school year 2014/2015				
Permission to contact schools within the city of Edinburgh council granted in April 2015				
Edinburgh city council	April 2015	16	First seven schools contacted	One school accepted to participate- testing carried out in June 2015
		23	Two further schools contacted	
	May 2015	4	Eleven further schools contacted	
		7	Three further schools contacted	
		11	Five private schools contacted	

B)

Session 2: Contacting schools for participation during the school year 2015/2016				
Edinburgh city council	August 2015	24	Eight schools contacted	Second school accepted to participate- testing carried out in January/February, June and September 2016
		31	Remaining public schools + five private schools contacted	
Permission to contact schools within the West Lothian council granted in September 2015				
West Lothian council	October 2015	4	Four schools contacted	Final school accepted to participate- testing carried out in April and September-October 2016
	February 2016	25	Eight schools contacted	

After receiving consent from the Head Teacher of each of the three secondary schools (see Appendix B for the letters-consent forms that needed to be signed by the schools' Head Teachers), letters of consent were sent out by the schools to the parents/carers of pupils in the third, fourth and fifth years. These letters consisted of a brief description of the study and what participants would be expected to do, followed by an opt-out form[3] that the parents/carers could sign if they did not wish their child to take part in the study (the letter to parents and accompanying opt-out form can be found in Appendix D). Sufficient time (a minimum of 2-3 weeks) was allowed for the parents to send back the opt-out forms, and any pupils for whom opt-out forms were received, were excluded from further consideration. There were no particular selection criteria, so all the pupils whose parents/carers did not return the opt-out form could be considered for participation. Prior to testing, the schools generated lists of pupils (from the respective year groups) who were subsequently invited to participate. Staff were advised that the pupils should be selected at random, as the sample needed to be representative of a typical secondary school class. Each pupil on these lists was then invited to participate and individual assent was also sought prior to administrating the relevant tasks (the assent form for pupils can be found in Appendix E). After completing the testing each pupil was also provided with a debrief form thanking them for their participation (see Appendix F for the debrief form)

2.1.2. The final sample

A total of 349 adolescents across the third, fourth and fifth years of the three participating secondary schools were tested: 33 from the first school, 240 from the second school and 76 from the third school. However, the data of two pupils (one from the second and one from the third school) could not be used. The first pupil whose data were disregarded, was older than 18 years of age, thus could not be considered an adolescent or be reliably assessed by some of the cognitive measures used that were suitable for testing up to the age of seventeen and eleven months. The second pupil's data were deleted because it was uncertain whether their parents/carers had received the letter with information about the project and

[3] Regarding the use of opt-out forms: As a requirement of the School of Philosophy, Psychology and Language Sciences Ethics Committee the participating schools' Head Teachers had to sign a form acknowledging that this research was to be carried out using opt-out forms and stating their willingness to act in loco parentis. The relevant form can be found in Appendix C.

the opt-out form. After removing the two pupils' data, the total overall sample consisted of 347 pupils: 134 third-year, 113 fourth-year and 100 fifth-year pupils. Full information on the final sample broken down by school and year are shown in Table 1 in Appendix G.

2.1.3. Demographic characteristics

Certain demographic characteristics of the pupils who participated were also collected (the demographic characteristics form that was completed for each pupil can be found in Appendix H) and subsequently considered in the analyses. The first important demographic factor considered was pupils' gender. The sample overall consisted of 171 females and 176 males (more information regarding the number of female and male participants across schools and year groups can be found in Table 1 in Appendix G).

Another important demographic characteristic considered was socioeconomic status (SES). Overall, the three secondary schools from which pupils were recruited served children from different socioeconomic backgrounds. At the time testing took place, the percentage of pupils in receipt of free school meals within each school – a statistic often used as an indicator of disadvantage across the UK (McCluskey, 2017) – was 48%, 5% and 13% respectively. The national free meal entitlement rate in the corresponding years was 15% (2015) and 14% (2016).

At an individual level, the Scottish Index of Multiple Deprivation (SIMD; Scottish Government, 2016) was used as an indicator of pupils' SES. The SIMD is an index of disadvantage that is specific to Scotland and is regarded in many official reports published by the Scottish Government, including ones that are relative to education e.g., the publications on attainment, leaver destinations and healthy living (Scottish Government, 2018). The SIMD is a relative measure of deprivation; it ranks small areas within Scotland (called data zones) from most deprived (ranked 1) to least deprived (ranked 6,976). Most importantly, SIMD reflects multiple deprivation; it ranks each data zone in Scotland on the basis of 38 different indicators that describe deprivation in terms of income, employment, education, health, access to services, crime and housing. Therefore, SIMD is not simply an index of wealth, it also describes the resources and opportunities people have in employment, education, health etc.

SIMD is expressed in numerical values that range from 1 for the most deprived area(s) to 6,976, which describes the least deprived areas. Consequently, in all the analyses presented in this thesis, SIMD was handled as a continuous variable, which indicated SES. The postcodes of participating pupils were supplied by the schools and these postcodes were subsequently used to generate the corresponding SIMD values (based on the postcode to SIMD ranks released in 2016). The SIMD range within the whole sample of this project (consisting of 347 pupils) was 116 – 6,807 (M_{SIMD}=4,506, SD=2,050.12, SIMD data not available for 3 pupils). Therefore, the sample included individuals from a relatively wide range of socioeconomic backgrounds. The distribution of SIMD within the sample of pupils from each of the three schools is shown in Figures 1-3 in Appendix G.

Apart from consisting of pupils of varying socioeconomic backgrounds, the aim was for the overall sample to be representative of typical secondary school classes i.e., comprise pupils of varying ability and profiles, including pupils with developmental conditions, learning and/or physical difficulties etc. However, some of these types of conditions and/or difficulties could affect performance on the tasks used to measure the cognitive constructs, so to control for individual differences in performance resulting from such conditions, a binary variable, denoting whether or not participants had a condition, was included in the analyses.

After consulting the exclusion criteria applied in certain studies focusing on EFs in typically developing samples (e.g., Latzman & Markon, 2010) and studying the technical manuals of popular batteries of tests measuring cognitive ability, such as the Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV; Weschler, 2003), a list containing a variety of conditions that are commonly thought to influence performance on cognitive tasks was generated. This list was provided to the schools and a relevant member of staff checked the participating pupils against this list (see Appendix I for a copy of the form given to schools containing the list of conditions). Through this procedure, pupils were categorised into two groups (Condition, No condition); no further distinctions were made, as distinguishing among pupils with different kinds or number of conditions was beyond the scope of this study. A total of 58 (out of 347) pupils were recorded as having a condition that could potentially affect their EF performance. Table 1 in Appendix G provides a more detailed account of the number of female and male pupils with a condition within each year group and school.

2.2. Cognitive measures

2.2.1. Selecting the appropriate cognitive measures for the study

One essential part of EF research is choosing the tests/tasks, which are thought to best tap into the functions desired to be measured. Over the years, many tests/tasks have been developed for assessing EFs; their design being driven by different needs and research questions each time. Some of these tests/tasks became more popular and widely recognisable than others. The Stroop test (Stroop, 1935), the Wisconsin Card Sorting test (WCST) (Heaton, 1981), the Tower of Hanoi (TOH) (Simon, 1975) and its equivalent the Tower of London test (Shallice, 1982) are some of the best known among psychologists.

As research into EF progressed and an increasing number of models supporting the existence of multiple, separable EF components (such as the tripartite EF model studied in this project) began to arise, an additional issue for the development of EF measures emerged: the test/tasks designed to measure EF had to have the ability to distinguish among different EF components. Within this context, some of the original tests, e.g., the aforementioned WCST and TOH, which draw on a combination of different EFs, are considered to measure a more general EF construct, whereas others, e.g., the Stroop test, are regarded to be more specific and therefore, more suitable for taping particular EF components.

Furthermore, the ‘task impurity problem’ that has been previously discussed in section 1.1 (page 23), constitutes another important obstacle in measuring EFs. Indeed, this issue has concerned many of the researchers studying EFs among children and adolescents (Cassidy, 2015; Lee et al., 2013; van der Sluis et al., 2007). As was discussed in section 1.1, one solution to this problem (implemented originally by Miyake et al. in 2000), is to use multiple measures for assessing each EF component of interest and draw the common variance from these tests to obtain a better measure of each EF component (Willoughby, Kupersmidt, & Voegler-Lee, 2012). Another suggested solution for dealing with the “task impurity problem” is to use control tasks. These control tasks do not require the engagement of executive functioning but are otherwise very similar to the initial EF measuring task. EF ability can then be measured by examining the difference in performance between the EF task and its control counterpart (van der Sluis et al., 2007).

The demands and limitations of this specific project guided the choice of the measures utilised. Because of the time limitations when testing in secondary schools, it was not possible to use multiple tasks to measure each construct. Therefore, for the EF assessment, the task impurity problem was tackled by administering additional tasks/conditions that acted as controls. Five cognitive variables were investigated in this project: three EF components (inhibition, shifting and working memory) and two transferable skills (non-verbal reasoning and numeracy). Therefore, five separate measures were required overall; one for each of the five variables. These five measures had to have the ability to dissociate the five constructs (especially the three different EF components) and be suitable and standardised for the age range examined in this study, namely 14 -18 year olds.

When searching for the most appropriate tests to use for this project, attention was drawn to batteries that include multiple tests, each measuring a different construct. Most of these batteries have been widely used and, therefore, are tested and reliable. Furthermore, it is preferable to use multiple tests from the same battery both for financial reasons and because all tests within a battery are scored and standardised in the same way, making the scores from these tests directly comparable.

Many of the available batteries or individual tests that are (or include components that are) suitable for measuring EFs were not appropriate for use in this study due to the age range they applied to. The age range of 14-18 years was difficult to find tests for, as 14-16 years of age often constitute the upper bound of children's tests, while 16-18 years of age constitute the lower bound of adults' tests. Thus, the Test of Everyday Attention (Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994), the Test of Everyday Attention for children (Manly, Robertson, Anderson, & Nimmo-Smith, 1999), the Colour Trails Test (D'Elia, Satz, Uchiyama, & White, 1996), the Children's Colour Trails Test (Llorente, Williams, Satz, & D'Elia, 2003), the Developmental NEuroPSYchological Assessment (Korkman, Kirk, & Kemp, 1998) and the Wechsler Intelligence Scale for Children – Fourth Edition (Weschler, 2003) were automatically rejected because they were not suitable for the entirety of the age range under examination.

After having excluded the aforementioned tests and batteries from further consideration, four remaining batteries were considered: the Delis Kaplan Executive

Function System (D-KEFS) (Delis, Kaplan, & Kramer, 2001), the Automated Working Memory Assessment (AWMA) (Alloway, 2007), the National Institutes of Health (NIH) Toolbox (Gershon et al., 2013) and the British Ability Scales Second Edition (BAS II) (Elliott, Smith, & McCullouch, 1997). None of these batteries included tests for all five constructs considered in this project so a combination of tests from different batteries needed to be used. It was decided that a maximum of two different batteries would be the optimum choice in order to avoid excessive diversity among the tests.

The NIH Toolbox includes Cognition, Emotion, Motor and Sensation domains. Within the Cognition domain of the NIH Toolbox, there are tests for all three of the EF components under examination in this study. More specifically, the Dimensional Change Card Sort Test, which resembles the WCST, is used for measuring shifting ability, the Flanker Inhibitory Control and Attention Test is a classic Flanker type test for measuring inhibition and finally the List Sorting Working Memory Test is a working memory assessment tool that requires immediate recall and sequencing of visually or orally presented stimuli. Despite including individual tests for the three specific EF components of interest, the NIH Toolbox was considered unsuitable for this study because it is not a widely used test and there are not many studies that have utilised it, especially among adolescents. Particularly when examining the relationship between EFs and academic attainment, it is necessary to obtain results that are comparable to information from previous studies in order to improve our knowledge.

The AWMA is a battery consisting of 12 tests used to measure short-term and working memory. The battery's working memory tests include 3 visual working memory measures (Spatial span, Odd one out and Mister X) and 3 verbal working memory measures (Listening recall, Counting recall and Backward digit recall). Despite the AWMA's tests having many advantages, such as being fast to administer, they focus solely on working memory which is just one of the five cognitive constructs being examined in this project. Therefore, the AWMA was considered too limited and was excluded from further consideration.

The D-KEFS consists of 9 individual tests measuring a variety of executive and lower order functions. Latzman and Markon (2010) examined the factor structure of the D-KEFS in the D-KEFS standardisation sample as well as a sample of 11-16 year old male students and concluded with a 3 factor model comprising conceptual flexibility, monitoring and inhibition. Furthermore, a more recent study (Li et al., 2015) examining executive functions in adolescents came to the same 3 factor conclusion regarding the D-KEFS tests. In this case, the research team identified the factors of shifting, fluency and inhibition. Thus, both studies agree that the D-KEFS tests draw on an inhibition and a shifting/flexibility component, however, they appear to differ on the designation of the third factor.

As far as the inhibition component is concerned, the two D-KEFS factor structure studies (Latzman & Markon, 2010; Li et al., 2015) show that, for adolescents, the inhibition factor was most strongly represented by scores on the Colour Word Interference test (factor loadings .69 -.82) and to a lesser extent on the Trail Making test (.38 -.63) and certain scores derived from the Design (.39, .56), Verbal Fluency (.32, .42) and Tower (.34) tests. The Colour Word Interference test had the highest factor loadings on the inhibition factor while also not drawing on any of the other factors proposed in the studies, which suggests that this test provides a clear measure of inhibition. This is also reinforced by other studies that utilised similar Stroop like tests to successfully measure inhibition in samples of adolescents (e.g., Latzman et al., 2010; Leon-Carrion, García-Orza, & Pérez-Santamaría, 2004; St Clair-Thompson & Gathercole, 2006). Therefore, the D-KEFS Colour Word Interference test was selected for assessing the inhibition component in this study.

For the measurement of participants' shifting ability, the Trail Making task from the D-KEFS was initially considered. Trail making tasks are popular and widely used in psychology research, but some studies have shown that these tasks may have some potential disadvantages. Firstly, trail making tasks may draw upon more than one EF component, as shown in the research of van der Sluis et al. in 2007, in which children's performance on a trail making test was found to be indicative of both shifting and working memory updating. In the D-KEFS factor structure studies mentioned above, the Trail Making task of the D-KEFS was shown to draw significantly on inhibition but not shifting (Latzman & Markon, 2010; Li et al., 2015). Another paradox regarding the trail taking task was observed in a study with children (Van der Ven et al., 2013) in which the shifting condition of the task was completed faster than the (easier) control condition, causing the researchers to exclude the task from the final analysis. Influenced by these negative reports, it was concluded that the Trail Making task was not the best option for assessing shifting. Instead, the

Sorting Test from D-KEFS was selected, because it has been shown to be a consistent measure of shifting among adolescents (Latzman & Markon, 2010; Li et al., 2015) while also lacking correlation with any of the other EF components being examined in the study.

At this stage, two of the EF measures had been decided on, leaving only the working memory component from the EFs to find a task for. Unfortunately, the D-KEFS does not include a test intended for working memory and consequently a test from a different battery needed to be used. Initially, the letter memory task was considered as it had been used in many previous studies, including factor structure studies in adults and children, in which it was found to load significantly on the working memory construct (Miyake et al., 2000; St Clair-Thompson & Gathercole, 2006; van der Sluis et al., 2007). However, as this test does not belong to a formal, available for purchase test battery, it would have had to be manually developed. Due to the lack of specific guidelines on how to create such a test, as well as concerns regarding the reliability and validity of a self-developed measure, it was decided that the working memory component should be assessed in another way. In addition, the keep track task, which was also shown to load significantly on a working memory factor in various studies of adults and children (Miyake et al., 2000; St Clair-Thompson & Gathercole, 2006; van der Sluis et al., 2007; Van der Ven et al., 2013), was rejected for the same reason.

The next best option for assessing the working memory component was the Backwards Digit Recall task. This is a very well-known test that has been utilised to measure working memory in many studies of children and adolescents, with the corresponding factor loadings ranging from .57 to .73. (Brydges et al., 2014; Cassidy, 2015; Danili & Reid, 2004; Gathercole et al., 2004; Kroesbergen et al., 2009; Ropovik, 2014; St Clair-Thompson & Gathercole, 2006; Tsaparlis, 2005; Van der Ven, Kroesbergen, Boom, & Leseman, 2012; Van der Ven et al., 2013). Since the Backwards Digit Recall task is so commonly used, different versions of this task exist in many different test batteries. Ultimately, the Recall of Digits Backward task from the BAS II was chosen because the same battery included two other measures, namely the Matrices and Number Skills tests, which could be utilised to measure non-verbal reasoning and numeracy respectively, the two transferable skills under examination in this project. Moreover, the BAS II also includes a Recall of Digits Forward task which could serve as a control task, thus making it possible to assess working memory while minimising task impurity.

In conclusion, the tests used to measure the five key variables of this study derived from two batteries: the D-KEFS and the BAS II. More information on these batteries can be found in Appendix J. The specific tests and the constructs they were used to measure are shown in Table 2.2 and each test is described in further detail in the following sections (sections 2.2.2 and 2.2.3).

Table 2.2. The D-KEFS and BAS II tests used to measure the cognitive variables.

Variable measured	Battery	Task
Inhibition	D-KEFS	Colour Word Interference task (3rd Condition)
Inhibition control (colour naming speed)	D-KEFS	Colour Word Interference task (1st Condition)
Shifting	D-KEFS	Sorting Test
Working memory	BAS II	Recall of Digits-Backward
Working memory control (short-term memory)	BAS II	Recall of Digits- Forward
Non-verbal reasoning	BAS II	Matrices
Numeracy	BAS II	Number skills

2.2.2. EF assessment

D-KEFS Colour Word Interference test

The D-KEFS Colour Word Interference (CWI) test is a variation of the Stroop task and is based on the Stroop effect (Stroop, 1935). In the CWI test, interference is introduced by presenting names of colours (i.e., red, blue, green) in a different colour ink than what they denote (i.e. the name red is printed in blue ink). Therefore, the test measures the individual’s ability to inhibit the easier, more automatic verbal response of reading the printed words in order to generate the more challenging response of naming the dissonant ink colour in which the words are printed.

A novelty of the D-KEFS's version of this test is that it has 4 different conditions. The first two conditions measure fundamental (non-EF) skills needed to perform the higher-order tasks, namely how fast the participant can name patches of colour (Condition1) and how fast they can read the names of colours (Condition 2). The 3rd Condition is the traditional Stroop task where the participant needs to inhibit reading the names of colours in order to name the dissonant ink colour in which they are printed in. Finally, in the 4th condition, the participant is asked to switch back and forth between reading the printed names of colours and naming the dissonant ink colour in which they are printed depending on whether the words are in a rectangle or not.

Only three basic colours (i.e., red, blue and green) are used throughout this task. For each condition, the participant is presented with a page depicting a set of 50 colour names or patches and they are asked to carry out the relevant task (e.g., name all 50 colour patches) as fast as they can without making mistakes. The total time (in seconds) needed to complete each condition is the primary measure derived from the CWI test. The raw scores can be converted into scaled scores (M=10, SD=3), which constitute the standardised (normative) scores that are corrected for each of the 16 age groups. For individuals aged 8-19 years old, the test-retest reliability coefficients for the scaled scores deriving from the CWI test are: .79 for Condition 1, .77 for Condition2, .90 for Condition 3 and .80 for Condition 4. The scaled scores can also be summed or subtracted from one another to produce composite or contrast scores respectively, which can then also be standardised. Optional measures recorded are the number of corrected, uncorrected and total errors made for each condition.

D-KEFS Sorting Test

The D-KEFS Sorting Test (ST) was administered to measure individuals' shifting ability. This measure is based on the same concepts as the WCST and, therefore, relies on sorting a set of cards into groups following various sorting rules that refer to the cards' characteristics. One important innovation of the D-KEFS version of the task is that the cards display both perceptual stimuli and printed words and as a result, individuals can use nonverbal or verbal cues to sort them. In addition, there are two different conditions of the task: Free Sorting and Sort Recognition.

In the Free Sorting condition, the participant is shown six mixed-up cards and is asked to sort these cards into two groups (of three cards each) according to as many different criteria/rules as possible. When making each sort, the participant is also requested to reflect on the rule employed to sort the cards by simply describing each of the two groups generated, e.g., saying “this group consists of cards with boys’ names, whereas this one includes all the cards with girls’ names”. This procedure is carried out with two separate sets of cards. The six cards within each set can be sorted in a maximum of eight different ways; three sorts are generated according to the verbal information from the printed words on the cards and five sorts can be generated based on the perceptual features of the cards.

The two primary measures that derive from this condition are a) the total number of confirmed correct sorts made (maximum of 16 across both card sets) and b) an overall description score, which indicates how well the participant described the sorts they generated (maximum score of 4 for each generated sort; maximum of 64 across both cards sets). The participant’s description of the sorting rule helps ascertain that the participant is not generating sorts by chance, since any correct sort that is not accompanied by an at least partially correct description of the rule employed is not awarded any points. In addition to the two primary measures, other scores referring either to the sorting or the description aspect of this condition can also be calculated. These include the number of repeated sorts/descriptions given, measures of sorting and description accuracy (expressed in percentages) and a measure of the time spent per sort.

In the Sort Recognition condition, the same two sets of cards are used but each set is now sorted into two groups (of three cards each) by the examiner, and then the participant has to describe the rule that the examiner employed to group the cards. This condition yields one primary Sort Description score across both card sets (maximum 64) and optional description measures (number of incorrect or repeated descriptions).

Once again, all the raw scores produced in both conditions of the ST can be converted to corresponding scaled scores (M=10, SD=3), which represent normative scores. The test-retest reliability of the scaled scores deriving from the ST, for the ages of 8-19 years, are: .49 for the score corresponding to the number of confirmed correct sorts made in the Free Sorting condition, .67 for the description score yielded in the Free Sorting condition and .56 for the description score yielded in the Sort Recognition condition. Since the concepts employed to sort the cards in both conditions are the same and due to time limitations when testing pupils in schools, only the first (Free Sorting) condition of this task was utilised. Adolescents' scores on this condition have previously been found to load on factors associated with conceptual flexibility (Latzman & Markon, 2010; Li et al., 2015) confirming that it is suitable for the assessment of shifting.

BAS II Recall of Digits

Two forms of the Recall of Digits task from the BAS II were utilised for this project, each tapping into slightly different processes. In the Recall of Digits Forward (RDF) task, the participant is asked to orally repeat sequences of digits in the same order as they were presented to them. The length of the sequences increases from two to nine digits. Overall, there are 36 sequences to be recalled that are organised in 8 blocks, each block consisting of two to five sequences of a certain length. The Recall of Digits Backward (RDB) also entails increasingly longer sequences of digits being presented orally to the participant. However, for this task the participant is asked to repeat each sequence they heard in the reverse order. The length of the digit sequences presented ranges from two to seven digits. There are 30 sequences overall, organised in six blocks with five sequences of the same length in each block.

Both the digit recall tasks from the BAS II battery utilise a basal and ceiling method of selecting the items (sequences) that each participant completes and is scored on. The participant is administered the first sequence of each block until they make an error, in which case they are administered the items of the previous block and continue backwards until they complete a block with no more than one error. This block constitutes the basal. Once the basal block is established, the participant then completes all the previously unadministered items in ascending order until they reach a block in which they recall no more than one item correctly or until they reach the last item of the scale. The last block, the participant completes, acts as the ceiling block.

One point is awarded for every item in which the participant recalled all digits in the correct sequence. If there are any unadministered items proceeding the basal block, these are all considered as passes and are awarded full points, whereas any unadministered items after the ceiling block are not included in the calculation of the score. Thus, the primary outcome measure for each digit recall task is the number of sequences recalled correctly (up to the ceiling block). This raw score is then converted to an ability score, which indicates the number of items correctly recalled by the participant while also accounting for the difficulty of the items attempted. Finally, the ability score can be further converted to a T-score (M=50, SD=10) which is corrected for each age group. The T-scores, are thus, normative scores that have been established with reference to the score distributions of all children of the same age in the standardisation sample. The test-retest reliability of the RDF is .79 and of the RDB .72.

2.2.3. Transferable skills assessment

BAS II Matrices

The Matrices task is the BAS II battery's variant of the well-known and widely used Raven's Progressive Matrices test (Raven, 1936). This task is typically used to measure participants' reasoning skills by testing their ability to identify and utilise patterns to complete puzzle-like items. It is a non-verbal task, in which each item consists of a series of abstract shapes, arranged in a matrix, with a piece missing. For each item, the participant has to choose, out of six alternatives, the figure that correctly completes the matrix. Unlike the original Raven's Matrices test, which has 60 items, the BAS II adaptation of the task consists of only 33 items, making it faster to administer and less likely to cause fatigue, which is essential when testing children and adolescents.

The BAS II Matrices test has different administration starting and stopping points for different age groups. Each participant begins the task at the suggested starting point for their age and should stop at the designated stopping point, however, administration can be adjusted according to each participant's performance with additional easier items (preceding the designated starting point) being administered when too many errors are made, or additional harder items (beyond the designated stopping point) being administered if very few errors are made. This administration strategy ensures that each participant is administered and scored on the items that are appropriately challenging for them.

The participant is awarded one point for every item they answer correctly and their overall raw score is the total of points they receive from the items they were administered. Since different participants complete different sets of items that span different ranges of difficulty, participants' raw scores are not meaningful and cannot be directly compared with one another. Therefore, raw scores are converted to ability scores, which reflect participants' ability as a function of the number of items correctly answered and the specific set of items completed. Finally, ability scores can be further converted to T-scores (M=50, SD=10) which correspond to normative scores corrected for each age group. The test-retest reliability of the Matrices task is .64.

<u>Bas II Number skills</u>

The Number Skills test of the BAS II battery is used to assess individuals' numeric skills. More specifically, this test is composed of a series of number-based tasks that draw upon knowledge in the domains of number recognition, addition, subtraction, multiplication, division, fractions, decimals, conversion and word problems. There are 46 items in the task in total that range in difficulty from simple sums to more complicated arithmetic operations and problems. The items are grouped in six blocks and the aforementioned basal and ceiling block method (see Recall of Digits tasks description pages 63-64) is applied to determine the items each participant completes and is scored on. Each participant begins at the appropriate block for their age, takes all the items in that block and continues onto the following blocks until they reach a block in which they get no more than three items correct (ceiling) or complete the whole task. The first block administered to the participant acts as the basal block, unless there are less than five items passed in this block in which case the next easier block is administered until the participant completes a block with five or more passes. The number of items correctly answered out of those completed constitutes the raw score for this task. Based on the difficulty of the set of items each participant completed, their raw scores are turned into Ability scores and these are in turn converted to standard scores (M=100, SD=15), which constitute the Number Skills test's version of age-based normative scores. The test-retest reliability of the Number Skills test is .91.

2.3. Educational attainment assessment

The participating schools provided reports of their pupils' performance on the various subjects they attended during their third (S3), fourth (S4) and fifth (S5) year of secondary school. The information included in these reports was utilised to generate appropriate indices of pupils' educational attainment in each of the subjects. The type of information provided by schools on their pupils' performance differed among the year groups, since pupils' attainment is assessed differently in the three school years examined here i.e., the third, fourth and fifth years of secondary school. The most pronounced differences are evident in the third year compared to the fourth and fifth years. This is due to the fact that, in the Scottish education system, these years correspond to different phases of the curriculum; pupils in third year are still in the broad general education phase, which lasts from the first year of primary school up to the third year of secondary school, whereas from the fourth year of secondary school onwards pupils enter the senior phase of their education.

During the third year of secondary school (S3), pupils in Scottish schools do not take exams but are assessed on tests/tasks that are set and marked by their teachers and are subsequently awarded grades at the end of the year. In most subjects, the grades show the level at which each pupil is working (in S3 this would typically be level 3 or 4) as well as how far they have progressed within that level (developing, consolidating or secure). In this project, S3 pupils' grades on all subjects they attended were provided by two of the participating schools. The third participating school did not utilise the same method of grading for S3 pupils and, therefore, no quantitative performance data were obtained for the S3 pupils from this school.

In the senior phase of their education, pupils deepen their knowledge and further develop their skills, through qualifications and/or engagement in personal development. Therefore, once pupils are in the fourth year of secondary school, which marks the beginning of the senior phase, they can begin working towards National Qualifications. There are 7 different levels at which National Qualifications can be achieved: National 1, 2, 3, 4 and 5, Higher and Advanced Higher. Pupils within a certain year can each be working towards different levels of qualifications in different subjects. In fourth year (S4), the majority of pupils work towards National 4 or National 5 qualifications whereas, in their fifth year (S5), most pupils work towards National 5 or Higher qualifications. Qualifications at National 2, National 3 and National 4 levels are assessed internally and pupils are awarded with a pass or fail. At National 5, Higher and Advanced Higher levels pupils are assessed using exams (and/or other types of coursework) that are graded A to D or ‘No award’. For this study, schools provided information on the qualifications their S4 and S5 pupils achieved on all subjects taken.

Further details on the way pupils’ educational attainment data were handled in each analysis can be found in the Methods section of the relevant chapters.

2.4. Testing procedure

The necessary testing for this project, namely the administration of the cognitive tasks, was carried out in two sessions; participants completed the three EF tasks first, and the two skill-assessment tasks were administered during a separate session. All testing took place during term time in designated rooms/classes in the pupils’ schools. The EF assessment always preceded the skill assessment and the interim period was kept as short as possible (M=31 days) in order to minimise the time lag between each individual’s two measurements.

For the EF testing, the tasks measuring the distinct EF components were orally administered by the researcher to each participant individually. All four conditions of the D-KEFS CWI test were administered together, followed by the D-KEFS Sorting task (Free Sorting condition) and finally the two forms of the digit recall tasks from the BAS II. This order was followed with half the participants, whereas for the other half, the tasks were administered in every possible order in similar percentages in order to investigate for potential fatigue effects. All together the three tasks take around 30-40 minutes to complete, so each EF testing session took place within one regular 50-minute school period. As there are seven periods in a school day (with the exception of Friday), a maximum of seven pupils could be individually tested over the course of an average weekday.

During each period, one pupil, eligible to participate, was taken out of class and sent to meet the researcher in a small, quiet room within the school premises. After being introduced to the researcher and the project as a whole, the pupil was asked to read through a consent form explaining the details of the study and what would be expected of them if they agreed to participate. Before giving their consent, the pupil was also reassured that they could withdraw at any point for any reason and were offered the chance to ask any questions about the study. Pupils that agreed to participate were then administered the three EF tasks, whereas any pupils who stated that they did not want to participate were sent back to join their class. All signed consent forms were kept for future reference and stored securely with other study materials.

All the pupils who completed the first (EF) testing session were invited to a second session during which their numeracy and non-verbal reasoning skills would be assessed using the BAS II Number Skills and Matrices tasks respectively. These two measures were administered as written tasks and administered to pupils in groups, consisting of 20-30 pupils each, to save time. This session took place in the pupils' classroom within a regular 50-minute period. During that time, the participating pupils completed both tasks individually, while any remaining pupils (not participating) worked quietly on their homework or another task that their teacher gave them.

At the beginning of the session, the researcher reminded the pupils about the research study and then went on to explain some details of the tasks i.e., that although they resembled school tests, they were not related to their school grades and could not influence them in any way. Next, the answer sheets for the first task were distributed, the necessary instructions were provided, and the pupils were given enough time to complete the test before they had to hand in their sheets and the procedure was repeated for the second test. The pupils were given 24 minutes to complete the Number Skills test and 16 minutes to complete the Matrices test and, as much as possible, the order in which the two tasks were administered was counterbalanced in order to control for fatigue effects.

2.5. Data handling and analysis

For reasons of confidentiality, each pupil was assigned a unique code, which was thereby used instead of their names, to represent them on all the original hard-copy transcripts and digital spreadsheets. At all times, the original answer sheets were stored securely in a locking cabinet in the researcher's office and any digital files containing confidential information were password protected.

Pupils' raw scores on all tasks (and their Ability scores for the BAS II measures) were manually calculated and then entered into spreadsheets. The respective normative scores for each task were produced electronically using appropriately developed functions in R studio. This was done by building special commands which incorporated all the possible rules specified in the D-KEFS and BAS II score transformation tables into a particular R function. The functions consisted of multiple statements of the type "if the individual is older than 15 years old and their raw score on this condition is 8 then replace this score with the value 7". Subsequently these functions were applied on the corresponding variables and the raw scores were instantly replaced with the equivalent normative scores. Carrying out these transformations electronically was deemed much more time effective, especially with the large sample size of this project, while also being less prone to human error.

Deppending on the study, either the raw or the normative scores from the cognitive tasks were used in the analyses. More specifically, for the first study, which investigated the development of the three EF components, the raw scores were used since the objective was to determine the effect of age on pupils' EF performance and therefore, it was essential that the cognitive scores used were not corrected for age. In all the rest of the studies presented in this thesis, however, the normative scores were used. For these studies, which all considered pupils' EF performance in relation to their attainment data, it was preferable to use scores corrected for age, so as to not have to include age as an additional covariate in the analyses and thereby establishing more statistical power.

Chapter 3: Developmental changes in executive functions during adolescence: a study of inhibition, shifting and working memory.[4]

3.1. Background

During the last few decades, executive functions (EFs) have gained increasing attention in educational and developmental research. Despite there being no single, universal definition that fully captures the conceptual scope of EFs, it is predominantly agreed that the term covers a range of complex cognitive skills, which help people regulate their cognitive, emotional and motor activity and enable them to engage in purposeful, goal-directed behaviour, especially when faced with novel or difficult situations. EFs are associated with many different activities such as planning, problem solving, attentional control, self-regulation, and therefore, most researchers conceptualise EF as being multifaceted, comprising a set of at least partially dissociable processes (Baddeley, 1996; Miyake et al., 2000; Robbins, 1998; Shallice & Burgess, 1998) rather than a single underlying unitary construct (J. Duncan, Emslie, Williams, Johnson, & Freer, 1996; J. Duncan, Johnson, Swales, & Freer, 1997).

In recent years, the distinction has frequently been made between three EF components: i) inhibition, which refers to the ability to override dominant impulses/responses, ii) shifting, which reflects the ability to shift attention between different information and mental states and iii) updating, the ability to update one's working memory by adding, deleting and monitoring pieces of information. This tripartite EF model, was first proposed by Miyake and his colleagues, who found that these three EF components were related, yet separable, in a sample of undergraduate students (Miyake et al., 2000). Many researchers have since explored the extent to which the components of inhibition, shifting and working memory/updating are evident and discernible in children and adolescents. Some studies have confirmed the existence of these three separate EF components in children as young as 8 years old (Latzman & Markon, 2010; Lehto et al., 2003), but the general pattern accruing from the majority of research is that EFs differentiate with age. In preschool-aged children, cognitive performance can be adequately

[4] Please note that this chapter is written and presented in the form of a paper submitted for publication in the British Journal of Developmental Psychology

explained by a unitary model, consisting of a single general EF factor (Fuhs & Day, 2011; Wiebe et al., 2008, 2011; Willoughby et al., 2010), whereas among primary school-aged children, a two factor model of EF in which the working memory component is separated from inhibition and shifting is regularly found to provide the best fit (Brydges et al., 2014; van der Sluis et al., 2007; Van der Ven et al., 2013) and finally, during adolescence, a fully-separated three-factor structure is evident (Latzman & Markon, 2010; Lee et al., 2013; Li et al., 2015). Despite some discrepancies regarding the ages at which the transitions in EF structure take place, these studies suggest that there is an increasing specialisation of EFs with age, with the tripartite model of EF emerging during early adolescence, around the age of 13-14 years.

Further evidence in support of the specialisation of EFs derives from studies of brain maturation, which demonstrate that the prefrontal cortex – the brain region associated with EFs – continues to undergo substantial changes during adolescence. In the prefrontal cortex, the myelination of axons, a process known to boost the transmission speed of signals across neurons, continues well into adolescence (Yakovlev & Lecours, 1967). In MRI studies, this ongoing axonal myelination is manifested as a linear increase in prefrontal white matter volume during adolescence (Barnea-Goraly et al., 2005; Sowell et al., 1999). In addition to the increase in white matter, MRI studies show that adolescence is characterised by a decrease in prefrontal grey matter volume (Gogtay et al., 2004; Sowell et al., 2001). This has been attributed to the synaptic reorganisation that takes place in the prefrontal cortex after puberty (Huttenlocher, 1979), during which infrequently used synaptic connections are eliminated whilst frequently used ones are strengthened, resulting in a decline in synaptic density but rendering the remaining synaptic circuits more efficient (Blakemore & Choudhury, 2006).

In accordance with the factor analytic and neuropsychological studies that suggest ongoing development and increasing refinement of EFs with age, researchers have accentuated the importance of examining the full developmental trajectory of EFs. Nevertheless, the majority of research has focused on pre-schoolers and, secondarily, primary school-aged children, while fewer studies have investigated EFs' development during adolescence (Best et al., 2009; Romine & Reynolds, 2005). The disproportionate focus on younger ages is well grounded, since the preschool and early school years are characterised by fundamental changes in cognition, as reflected in the reports of rapid improvements in behavioural tasks tapping into EF components (particularly inhibition) during these ages (Best & Miller, 2010). However, research within younger ages has also shown that performance on tasks of different complexity and/or evaluating different EF components improves at different rates (Best & Miller, 2010; Hughes, 2011) and adult levels of performance on some of these tasks has not yet been reached by the beginning of adolescence (Davidson et al., 2006), thus, indicating that certain aspects of EFs may continue changing after puberty.

Behavioural studies investigating EF development beyond the ages of 11-12 years, provide some important evidence that EFs continue developing throughout adolescence and into adulthood (e.g. Boelema et al., 2014; Gur et al., 2012; Luna, Garver, Urban, Lazar, & Sweeney, 2004) and that the different EF components assessed follow somewhat discrete development pathways (e.g. Luna et al., 2004; Magar, Phillips, & Hosie, 2010). The most robust findings concern the protracted development of working memory, since multiple studies using a variety of measures (e.g., digit/letter span, n-back, search and oculomotor tasks) have found significant changes in performance transpiring from early to middle adolescence (Conklin, Luciana, Hooper, & Yarger, 2007; Huizinga et al., 2006; Lee et al., 2013; but see also some contradicting accounts by Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001 and Prencipe et al., 2011) and, in some cases, extending beyond the age of 18 (Boelema et al., 2014; Gur et al., 2012; Luna et al., 2004). The shifting component of EF also appears to continue developing after puberty, as is evident from the findings of studies investigating adolescents' performance on tasks that require switching between different rules or response sets. More specifically, studies investigating age-group differences have found that performance on shifting tasks levelled off around the ages of 14-15 years (Anderson et al., 2001; Huizinga et al., 2006), while other studies have demonstrated a linear relationship between age and shifting ability extending from early adolescence into young adulthood (Boelema et al., 2014; Magar et al., 2010). Findings are less consistent for the ongoing development of the inhibition component during adolescence, with some results even suggesting no further improvement of response inhibition beyond the age of 11 (Magar et al., 2010). However, most studies show that performance on inhibition tasks continues improving up to the age of 15 (Huizinga et al., 2006; Lee et al., 2013; Luna et al., 2004), with the exception of Stroop tasks (Stroop, 1935), in which functional gains in efficiency continue to emerge after 15 years of age and into early adulthood (Huizinga et al., 2006; Leon-Carrion et al., 2004).

It is important to note that individual studies vary considerably on many different aspects of their design and methodology. One of the most notable inconsistencies regards the age range across which EF development is examined, with differences evident in both the lower and upper age limits studied. In fact, in some studies with adolescent participants, the upper age limit examined is 15 years of age (e.g., Lee et al., 2013; Prencipe et al., 2011; Spielberg et al., 2015); thus, only providing information about the earlier stages of adolescence, whereas less is known about the development of EF during late adolescence and early adulthood (Taylor et al., 2013). Furthermore, studies investigating the maturation of EFs beyond the age of 15, often rely on examining differences in EF performance between discrete groups with large divergences in age, for example 15 year olds compared to 19-21 year olds (Gur et al., 2012; Huizinga et al., 2006; Luna et al., 2004), therefore, potentially masking the specific changes that EF processes may undergo during late adolescence. Finally, there is a large amount of diversity among studies regarding the EF components under examination. Only three of the aforementioned studies (Huizinga et al., 2006; Lee et al., 2013; Magar et al., 2010) examined the development of all three components of inhibition, shifting and working memory; the others research different combinations of EFs or even certain EF components in isolation (Conklin et al., 2007; Leon-Carrion et al., 2004). In conclusion, more research is needed to further elucidate and disentangle the developmental trajectories of the three EF components, particularly in late adolescence where the existing literature is scarce.

This study aimed to investigate the development of each of the components comprising the tripartite EF model during the latter part of adolescence. Three aspects of EF – inhibition, shifting and working memory – were examined in relation to age in a large sample of 14-18 year olds. Based on the findings of the existing studies discussed above, it was expected that each of these EFs should show some change during the period of 14-18 years of age, but the exact pattern and magnitude of these changes is equivocal due to inconsistencies in the literature. An important objective of this study was to examine the independent effect of age on EFs, whilst controlling for any other factors that may affect individuals' EF abilities, such as individuals' socioeconomic status and the presence of developmental conditions or learning difficulties. Most importantly, because the behavioural tasks used to assess EFs do not constitute pure measures of EFs but also tap other lower-order processes (Burgess, 1997; Miyake et al., 2000), this study aimed to control for the non-executive processes implicated in performing the EF tasks. Many studies examining age related changes in EFs do not address the task impurity problem, making it difficult to determine whether their findings of improved EF performance over time reflect actual changes in the EF components or arise from changes in other lower-order processes (e.g., processing speed). In this study, we accounted for this by using control tasks/conditions wherever possible. These are conditions that resemble the EF tasks but do not place any significant demand on executive functions, thus, allowing us to measure relevant lower-order processes and subsequently partial out performance on these control tasks in the examination of the development of EFs with age (Denckla, 1996; van der Sluis et al., 2007).

3.2. Method

3.2.1. Participants

The sample for this study comprised of 347 adolescents (171 females, 176 males) recruited from three different secondary schools in and around the city of Edinburgh, Scotland UK. The participants were drawn from the third (N=134), fourth (N=113) and fifth (N=100) years of the schools (M_{age}=15.74 years, SD=1.07, range=13.83-17.83) and the majority were British (88%) and right handed (87%). The three secondary schools served children from different socioeconomic backgrounds. The schools' free meal entitlement rates at the time testing took place were 5%, 13% and 48%, while the national rate in these years was 15% (2015) and 14% (2016).

The study received ethical approval from the School of Philosophy, Psychology and Language Sciences Ethics Committee within the university and permission to contact the schools was obtained from the City of Edinburgh and West Lothian councils in Scotland, UK. Information forms were sent out to the pupils' parents/carers providing them with the opportunity to opt their child out from participating in the study. Assent was also obtained, from each pupil individually, prior to them being tested.

3.2.2. Materials

The tasks used to measure the three EF components of interest derived from two cognitive assessment batteries: the Delis Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kramer, 2001) and the British Ability Scales Second Edition (BAS II; Elliott, Smith, & McCullouch, 1997).

Inhibition - The Colour Word Interference (CWI) test from the D-KEFS was used to measure inhibition. For the inhibition condition, the participants were presented with 50 colour names (i.e., “green”, “red” and “blue”) printed on a page in a colour that is incompatible with each word’s meaning (e.g., the word green printed in red ink). The participants had to inhibit their prepotent response to read out the words and instead name the ink colour in which the words were printed. The colour naming condition of the CWI test was also used in this study; this measures the speed with which participants name colours i.e., the non-EF process that influences performance on the inhibition condition. Participants were shown a page depicting 50 colour patches and were asked to name the colour of these patches as fast as possible. The time needed for the participants to complete each condition was recorded.

Shifting - The Sorting test from the D-KEFS battery – more specifically the Free sorting condition of the test – was administered as a measure of shifting, since scores on this condition have previously been found to load on factors associated with conceptual flexibility (Latzman & Markon, 2010; Li et al., 2015). Participants were presented with a set of six cards that each displayed a printed word and discernible perceptual stimuli. The participants’ task was to sort the cards into two groups of three cards each according to as many different categorisation rules as they could identify (e.g., according to the shape of the cards – angular or curvy – or the words displayed on them – animals or means of transportation). The six cards could be grouped into a maximum of eight sorts, and the procedure was carried out with two different sets of cards, yielding a maximum of 16 sorting rules to be identified. For each sort generated, participants were expected to provide a verbal description of the rule/concept they used to sort the cards and only those sorts that were accompanied by an at least partially accurate description of the sorting rule were awarded points. Descriptions were also awarded up to four points each, according to their quality. The total number of correct sorts generated across the two sets of cards (maximum = 16) and the overall score for the corresponding descriptions (maximum = 64) were recorded for each participant.

Working memory - The Recall of Digits Backward scale of the BAS II was administered as a measure of verbal working memory. For this task, participants were read sequences of digits at a rate of two digits per second and were asked to repeat the digits in the reverse order. In total, there were 30 sequences arranged in blocks of increasing length (from two to seven digits). The number of sequences (maximum = 30) which the participant recalled correctly (with all digits recalled in the correct reverse order) was recorded. The Recall of Digits Forward scale was also administered as a control condition that measures verbal short-term memory. In this version, the participants have to repeat sequences of digits that are read to them in the same order. The sequences are presented at a rate of two digits per second and increase in length from two to nine digits. Similar to the Recall of Digits Backward scale, the number of sequences (maximum = 36) correctly recalled was recorded.

3.2.3. Procedure

Pupils were individually tested in a quiet room within their school premises. Each participant completed the cognitive tasks during a single session lasting approximately 40 minutes. For the tasks comprising more than one condition, the control conditions were administered first followed by the EF ones, in line with the D-KEFS and BAS II manual guidelines.

3.2.4. Covariates

Certain demographic variables were considered potential confounders in the relationship between EFs and age, and were thus included as covariates in the analyses. Socioeconomic status was indicated by the Scottish Index of Multiple Deprivation (SIMD; Scottish Government, 2016), which is used to rank small areas within Scotland from most to least deprived (ranked 1 to 6,976 respectively). In this study's sample, the SIMD values ranged from 116 to 6807 (M_{SIMD}=4506, SD=2050.12, SIMD data not available for 3 pupils). Because the participants for this study were recruited as part of a project aiming to investigate the relationship among EFs and the educational attainment of pupils within a typical secondary school classroom, our sample included individuals with developmental conditions, learning and/or physical difficulties that could affect performance on the cognitive tasks. In order to control for individual differences in performance resulting from this, a binary variable, denoting whether or not participants had a condition, was included in the analyses. A list containing a variety of conditions that influence performance on the cognitive tasks of the D-KEFS and BAS II batteries (e.g., learning difficulties, hearing, speech or visual impairment, head injury requiring hospitalisation/traumatic brain injury, autism spectrum disorder etc.) was provided to the schools and a relevant member of staff checked the participating pupils against this list. Pupils were categorised into two groups (Condition, No condition) with no further distinctions made, since distinguishing among pupils with different kinds or number of conditions was beyond the scope of this study. A total of 58 pupils were recorded as having a condition that may affect their EF performance.

3.2.5. Data preparation

Raw scores on each of the cognitive measures were examined for univariate outliers resulting in four scores on the CWI colour naming condition and one score on the CWI inhibition condition being recoded as missing, because they constituted major outliers[5]. Together with missing data accruing from procedural and/or administration errors, only 57 values were missing on the cognitive measures, which corresponded to approximately 3% of the data.

3.2.6. Statistical analyses

Statistical analyses were performed in R, version 3.4.4 (R Development Core Team, 2018). Firstly, the relationship among pupils' performance on each of the measures and their age was examined by calculating the zero-order correlations between these variables. Following the correlational analysis, multiple linear regression models were developed in which performance on each one of the EF measures was regressed on pupils' age, gender, their level of deprivation (SIMD), their condition status (binary variable indicating whether or not they had a condition) and their performance on the respective non-EF condition of each task.

The Full Information Maximum Likelihood (FIML) method was utilised for handling missing data across all analyses. As opposed to other techniques, where missing

[5] Major outliers were determined based on the Inter Quartile Range (IQR) rule for extreme outliers. Any value that was more than 3xIQR beyond the Upper (Q3) or Lower Quartile (Q1) was considered a major outlier.

data are deleted or imputed, the FIML estimator uses all the available information from all cases (including the partially observed cases) and incorporates it into the estimation process. The FIML method is, therefore, considered superior to other ad hoc missing data techniques (i.e., listwise deletion, pairwise deletion and mean imputation) and has been found to produce regression coefficients and R^2 estimates with little or no bias in simulation studies (Enders, 2001). For this study, FIML estimation was implemented through the lavaan package for latent variable analysis in R Studio, version 1.1.453.

3.3. Results

Descriptive statistics for the raw scores on all the cognitive measures after the removal of extreme values are shown in Table 3.1 (for the whole sample) and Table 3.2 (for each age-group separately). Skewness and kurtosis were both below 1 for all measures. Higher scores indicate better performance for all measures apart from the scores on the inhibition task (CWI), which correspond to completion times.

Table 3.1. Descriptive statistics (sample size, mean and standard deviation) for all cognitive variables, after removing extreme values.

	N	M	SD
Inhibition, CWI INH time (s)	340	48.95	11.86
Colour naming speed, CWI CN time (s)	337	29.17	5.66
Shifting, ST correct sorts (max.16)	345	8.94	2.14
Shifting, ST description score (max. 64)	345	30.61	7.80
Working memory, RDB score (max. 36)	338	26.27	4.36
Short-term memory, RDF score (max. 30)	320	17.95	4.66

Note.

CWI INH: Colour Word Interference Inhibition condition, CWI CN: Colour Word Interference Colour Naming condition, ST: Sorting Test, RDB: Recall of Digits Backward, RDF: Recall of Digits Forward

Table 3.2. Descriptive statistics (sample size, mean and standard deviation) for all cognitive variables, after removing extreme values presented separately for each age group.

	Age 13			Age 14			Age 15			Age 16			Age 17		
	N	M	SD	N	M	SD	N	M	SD	N	M	SD	N	M	SD
Inhibition, CWI INH time (s)	3	57.67	16.5	106	51.33	11.60	81	49.04	10.75	89	49.38	13.03	61	43.66	10.22
Colour naming speed, CWI CN time (s)	3	31.00	4.36	105	30.42	5.47	80	29.75	5.65	88	28.32	5.78	61	27.38	5.39
Shifting, ST correct sorts (max.16)	3	8.33	2.31	108	8.88	2.19	83	9.08	2.21	90	9.07	2.07	61	8.69	2.07
Shifting, ST description score (max. 64)	3	28.00	9.64	108	30.22	7.98	83	31.30	7.76	90	31.06	7.92	61	29.80	7.36
Working memory, RDB score (max. 36)	2	17.50	4.95	93	16.85	4.39	78	17.94	4.48	88	18.86	4.98	59	18.34	4.63
Short-term memory, RDF score (max. 30)	3	25.67	2.52	99	24.96	3.89	83	26.07	3.88	92	27.15	4.88	61	27.34	4.46

Notes.

CWI INH: Colour Word Interference Inhibition condition, CWI CN: Colour Word Interference Colour Naming condition, ST: Sorting Test, RDB: Recall of Digits Backward, RDF: Recall of Digits Forward

The total number of pupils within each age group was N=3 for Age 13; N=108 for Age 14; N=83 for Age 15; N=92 for Age 16 and N=61 for Age 17

The correlations among performance on the cognitive measures and age are shown in Table 3.3. For these analyses, the time scores from the two conditions of the CWI test were inverted so that, similarly to all other measures, higher scores indicated better performance. Pupils' age was found to be significantly correlated to their inhibition ($r=.20$, $p<.001$) and working memory scores ($r=.12$, $p<.05$), as well as their scores on the control conditions measuring colour naming speed and short-term memory ($r=.20$, and $r=.18$ respectively, both $p_s<.001$). However, neither of the two measures obtained from the Sorting test were found to correlate with age (number of correct sorts, $r= -.02$, $p=.74$ or description score, $r= -.01$, $p=.81$).

Table 3.3. Correlations among cognitive variables and age.

	1.	2.	3.	4.	5.	6.
1. Inhibition, CWI INH	-					
2. Colour naming speed, CWI CN	.68***	-				
3. Shifting, ST correct sorts	.26***	.19**	-			
4. Shifting, ST description score	.26***	.19**	.94***	-		
5. Working memory, RDB	.46***	.42***	.24***	.24***	-	
6. Short-term memory, RDF	.38***	.32***	.25***	.24***	.61***	-
7. Age	.20***	.20***	-.02	-.01	.12*	.18***

Notes.

CWI INH: Colour Word Interference Inhibition condition, CWI CN: Colour Word Interference Colour Naming condition, ST: Sorting Test, RDB: Recall of Digits Backward, RDF: Recall of Digits Forward

*p<.05, **p<.01, ***p<.001

In regard to the relations among the EF components, the highest correlation was observed between pupils' inhibition and working memory scores ($r=.46$, $p<.001$). Conversely, pupils' shifting scores were only weakly associated with their inhibition and working memory scores ($r=.26$ and $r=.24$ respectively, $p_s<.001$ for both correct sorts and description scores). As expected, pupils' colour naming speed and short-term memory scores were strongly correlated to the corresponding EF scores, i.e., inhibition and working memory ($r=.68$ and $r=.61$ respectively, all $p_s<.001$). Finally, the two types of scores for shifting were very highly related to each other (r=.94, p<.001) and presented the same pattern of correlations with the other EF scores. On this account, only the number of correct sorts generated was chosen to be included in the regression models as a measure of shifting.

In the next step, three regression models were developed, in order to examine the independent effect of age on each of the three EF components whilst controlling for the other variables of interest. Pupils' inhibition (performance on the CWI inhibition condition), shifting (number of correct sorts generated in the Sorting test) and working memory (performance on Recall of Digits Backward task) were set as the outcomes in each model respectively. In addition to pupils' age, their gender, SIMD and condition status were included as predictors in each model. Furthermore, the non-EF processes of colour naming speed and short-term memory were considered in the respective EFs models.

The full models are presented in Table 3.4. In the inhibition model, pupils' SIMD, condition status, age and colour naming speed were all significant predictors of pupils' inhibition scores and accounted for approximately 50% of the variance. Only gender was not a significant predictor of adolescents' inhibition. In the shifting model, and in line with the correlational analyses, age was not found to be a significant predictor of pupils' shifting scores. The model only accounted for 6% of the variance in shifting scores and pupils' SIMD was the only significant predictor. Finally, in the working memory model, 39% of the variance in performance was explained, with pupils' condition status, SIMD and short-term memory as significant predictors. Pupils' age and gender were not significant predictors of their working memory scores.

Table 3.4. Regression models: Information on the individual predictors and overall variance explained in the models predicting a) inhibition, b) shifting and c) working memory.

		B	SE(B)	β	p	R^2
a) Inhibition	Gender	-1.403	0.909	-0.059	.123	0.495
	Condition status	-3.940	1.501	-0.124	<.01	
	SIMD	0.057	0.028	0.098	<.05	
	Age	0.851	0.414	0.077	<.05	
	Colour naming speed	1.331	0.087	0.648	<.001	
b) Shifting	Gender	-0.035	0.220	-0.008	0.875	0.058
	Condition status	-0.399	0.308	-0.070	0.195	
	SIMD	0.024	0.005	0.231	<.001	
	Age	-0.000	0.105	-0.000	0.998	
c) Working memory	Gender	-0.375	0.412	-0.040	.364	0.385
	Condition status	-1.442	0.568	-0.116	<.05	
	SIMD	0.020	0.010	0.088	<.05	
	Age	0.092	0.201	0.021	.649	
	Short-term memory	0.600	0.048	0.561	<.001	

3.4. Discussion

The main objective of this study was to investigate the development of three different aspects of EF, namely inhibition, shifting and working memory, during the late stages of adolescence. The results showed that within a large cross-sectional sample of 14 to 18 year olds, there is no evidence of developmental differences in working memory and shifting, but notable differences in inhibition.

Initially, the correlational analyses showed that scores on the inhibition and working memory tasks were significantly and positively correlated with pupils' age but scores on the shifting task were not. It is noteworthy that even in the case of inhibition and working memory, the correlations with age albeit significant, were small, suggesting only tenuous changes in performance across these ages. The next step was to examine whether the effect of age remained after controlling for gender, socioeconomic status, and the presence of any learning/developmental condition that may affect EF performance. Importantly, adolescents' performance on the control conditions used to measure the non-EF processes implicated in performing the EF tasks was also included in the relative regression models. After controlling for all these variables, age only remained a significant predictor of performance on the inhibition task.

Initially, this finding seems inconsistent with the majority of the literature which indicates no further improvements in inhibition after early adolescence (Lee et al., 2013; Luna et al., 2004; Magar et al., 2010). However, when considering only those studies that assess inhibition using Stroop-like tasks, similar to the one used in this study, the results unanimously demonstrate continued improvement of inhibitory control during late adolescence (Huizinga et al., 2006; Leon-Carrion et al., 2004). In their review, Best and Miller (2010) make a case for different inhibition tasks showing different ages of mastery as a result of their different cognitive demands. Perhaps then, compared to other inhibition tasks, Stroop-like tasks tap into more complex inhibitory processes which continue developing after the ages of 14-15.

A relatively surprising finding of this study was that shifting appeared not to change within the age period under study. Previous studies have demonstrated ongoing improvements in shifting up to the age of 15 (Anderson et al., 2001; Huizinga et al., 2006) or linear improvements up to young adulthood (Boelema et al., 2014; Magar et al., 2010); however, these findings are not directly comparable to ours, due to dissimilarity in the tasks used to assess shifting. These studies often measured shifting using computerised tasks in which participants have to switch between different kinds of responses based on the stimuli presented to them. In addition to shifting, these tasks rely on individuals' ability to hold different rules in mind and inhibit one response in favour of another, which renders them more complex than the Sorting test used in this study, and may therefore, explain why performance on these tasks is shown to improve at a slower pace.

The third EF component – working memory – was found to correlate with age, but this effect was grossly attenuated after controlling for demographic variables and the non-EF process of short-term memory. Findings from other studies utilising the backwards digit recall task are mixed, with performance showing no further improvement beyond early adolescence in some studies (Anderson et al., 2001; Prencipe et al., 2011), while in others, 16-17 year olds were found to perform better than younger adolescents (Conklin et al., 2007). It is noteworthy, however, that in contrast to our study and despite having found differences between older and younger adolescents' short-term memory capacity, Conklin et al. (2007) did not control for these differences when examining age-related changes in working memory, which might explain their contrasting results. All things considered, changes in performance on backwards digit recall tasks observed during late adolescence may not result from changes in working memory efficiency as such, but rather reflect the expansion of short-term memory capacity.

Among the covariates examined in this study, socioeconomic status (indicated by SIMD) was found to consistently explain unique variance in performance on all three EF tasks. Thus, individual differences in adolescents' inhibition, shifting and working memory appear to be influenced by their home background, with lower socioeconomic status being associated with poorer EF performance. This is in agreement with several other behavioural studies that detected socioeconomic disparities in EF performance in younger samples of infants (Lipina, Martelli, Vuelta, & Colombo, 2005), preschoolers and school-aged children (Arán-Filippetti & Richaud De Minzi, 2012; Noble, McCandliss, & Farah, 2007; Sarsour et al., 2011 and see Lawson, Hook, & Farah, 2018 for a meta-analysis of mutliple studies), but fewer studies have focused on socioeconomic disparities in EF performance among adolescents. Two studies that examined the development of adolescents' EFs in relation to socioeconomic status longitudinally, found that socioeconomic status is significantly related to changes in certain aspects of EF over time (Boelema et al., 2014; Spielberg et al., 2015). In the case of inhibition, in particular, Boelema et al. (2014) found that the socioeconomic gap in performance was not only maintained but magnified during adolescence, as inhibition was found to mature at a faster rate among the adolescents with higher socioeconomic status compared to their less affluent counterparts. Although our study was not longitudinal and thus, no inferences could be made about the role of socioeconomic status in the maturation of EF, the fact that socioeconomic status was found to uniquely contribute to adolescents' EF performance, even after controlling for age, confirms that it is an important predictor of EF across the ages of 14-18.

In addition, the variable indicating pupils' condition status was found to explain unique variance in performance on the inhibition and working memory tasks. Although, the selective effect of different conditions on EF performance was beyond the scope of the current study, the inclusion of this binary variable distinguishing between individuals with and without conditions allowed us to control for some of the variability in EF performance that results from pupils having a condition.

Most importantly perhaps, the non-executive processes measured in this study were very strong and significant predictors of their EF counterparts. Indeed, in the case of working memory, controlling for the non-EF process of short-term memory and other variables rendered the individual effect of age non-significant, despite the initial zero-order correlation between age and working memory scores reaching significance. These results highlight the importance of controlling for lower order, non-executive processes when studying EFs. Failing to do so is likely to lead to biased conclusions.

One limitation of our study was that it was cross-sectional. Studies with a longitudinal design that allow within-person comparisons of performance on EF tasks constitute a better way to control for effects of external variables and reliably detect developmental changes. Another limitation was that only one task was used to assess each EF component. Administering multiple tasks would allow us to use latent variable modelling to extract shared variance across these tasks and yield a purer measure of each EF (Cassidy, 2015; Lehto et al., 2003; van der Sluis et al., 2007).

Despite these limitations, this study attempted to minimise the noise in the results by controlling for pupils' demographic characteristics and non-executive abilities – variables that are often overlooked – thus, allowing us to obtain a clearer picture of the independent effect of age on EF performance. Our results indeed confirmed the importance of controlling for these confounding variables when examining age-related differences in EFs within cross-sectional samples. Most importantly, since we found a selective age effect on inhibition but not the other EF components, this study contributes further evidence in support of the ongoing development of EFs during late adolescence and the different developmental trajectories of the inhibition, shifting and working memory components of EF.

Chapter 4: Relationships between executive functions and educational attainment in 14-18 year old adolescents: inhibition, shifting and working memory in relation to attainment in a variety of subject areas.

4.1. Introduction

After examining the developmental differences in inhibition, shifting and working memory across the ages of 14-18 years, the next main goal of this PhD was to investigate the relationship between these EF components and educational attainment. As previously mentioned in the Introduction of this thesis the majority of the existing literature on the association of EFs with educational attainment focuses on preschoolers and primary school aged children. Relatively fewer studies examine this issue in samples of adolescents, and research on adolescents above 15 years of age, in particular, is scarce. Therefore, in the following chapter, the EF components of inhibition, shifting and working memory were explored in relation to educational attainment within a sample of 14 to 18-year-old adolescents.

Among the studies that have investigated EFs in relation to attainment in adolescence, many focus solely on a single rather than multiple EF components. Among the three EF components considered in this thesis, working memory has received the most attention; different aspects of working memory, i.e., verbal and visuo-spatial, have been examined in relation to attainment on a variety of school subjects, including native and foreign languages, maths, science, arts, technology and social subjects (Alloway et al., 2010; Danili & Reid, 2004; Gathercole et al., 2004; Kyttala & Lehto, 2008; Lehto, 1995; Riding et al., 2003). Despite discrepancies in the subject areas examined, the samples' characteristics or the measures of attainment (standardised/National assessments or teachers' ratings of achievement) used in all the aforementioned studies, their results uniformly demonstrate a significant association between working memory and adolescents' attainment in a multitude of subjects. Furthermore, a recent longitudinal study which followed individuals from preschool to adolescence, showed that working memory measured at 54 months of age, was the only significant EF predictor of math and literacy achievement at 15 years of age; thus, further showcasing the important role of working memory in predicting academic outcomes across development (Ahmed, Tang, Waters, & Davis-Kean, 2018). However, despite their significant results, studies in which working memory is examined in isolation cannot provide a clear picture of its relative contribution to adolescents' educational attainment (i.e., beyond the contribution of inhibition and shifting). Therefore, more research is needed that explores all three EF components of inhibition, shifting and working memory in relation to adolescents' educational attainment.

Another limitation of some of the existing studies on EFs and adolescents' attainment is that they only examine attainment relating to one particular subject/area. One of the subjects most frequently investigated in relation to EFs is mathematics, with studies having found links between various EF components and adolescents' academic outcomes relating to general math performance (Kyttala & Lehto, 2008; Oberle & Schonert-Reichl, 2013) or more specific domains of mathematics, such as geometry (Giofre, Mammarella, Ronconi, & Cornoldi, 2013) or algebra (Lee et al., 2009). Furthermore, in a 2015 study, Gilmore, Keeble, Richardson and Cragg examined three distinct components of mathematics, namely factual knowledge, procedural skill and conceptual understanding in relation to inhibition and only found significant correlations between procedural skill and inhibition among 11-14 year old adolescents (Gilmore et al., 2015). In a later study, the same three components of mathematics were investigated in relation to inhibition, but also shifting and working memory, with the findings revealing that inhibition and working memory but not shifting uniquely contributed to at least one of the mathematics components (Cragg et al., 2017).

In addition to mathematics, adolescents' performance in their native language has often been the focus of studies examining EFs, with associations having been found between various domains of language and specific EF components. In their 2015 study, Aran-Filippetti and Richaud showed that measures of working memory, inhibition and verbal fluency explained unique variance in children's and adolescents writing composition, over and above the variance explained by age, reading comprehension and verbal IQ (Aran-Filippetti & Richaud, 2015). A comprehensive study by Berninger et al., (2017) investigated several EF components in relation to children's and adolescents' composite scores on three different language systems – oral language, reading and writing skills. Furthermore, the EF measures comprised both behavioural ratings, which were independent of participants' language processing, and performance on cognitive tasks that required language processing. The total amount of variance explained, as well as the EF components that were unique contributors in regression models predicting the composite scores, varied across the writing, reading and oral language systems and associations were generally more significant in the case of the EF measures involving language processing. In contradiction to the Aran-Filippetti and Richaud study (2015), only shifting, not inhibition or working memory, uniquely predicted writing skills; inhibition was a significant independent predictor of oral language, whereas shifting, inhibition and a working memory (behavioural rating) all made unique contributions to reading.

One final subject that has been separately examined in relation to EF in adolescence is science. The three EF components of inhibition, shifting and working memory have been studied together in relation to adolescents' factual knowledge and conceptual understanding in the fields of both biology (Rhodes et al., 2014) and chemistry (Rhodes et al., 2016). Factual knowledge and conceptual understanding were measured using a set of questions relating to a popular topic of biology/chemistry that pupils had been taught and received a practical on. Both these studies showed that none of the three EF components were significantly correlated or predicted factual knowledge in either biology or chemistry. However, working memory was found to uniquely contribute to adolescents' conceptual learning in both science subjects after controlling for covariates, such as age and vocabulary ability, thus leading to the conclusion that EFs may be critical when adolescents have to understand and apply information they were taught about science (Rhodes et al., 2014, 2016).

By exploring one EF component and/or (attainment in) one subject at a time, the studies discussed above only reveal part of the complicated picture that is the relationship between EFs and educational attainment. For example, considering only one EF component in isolation, does not allow drawing conclusions in regard to the relative influence of each EF component on attainment, and therefore, any significant results need to be interpreted with caution. Likewise, using composite scores of EF performance or measuring complex EFs that tap into many EF components also does not provide useful insights. For example, a recent longitudinal study looking at adolescents' EF in relation to their attainment throughout the ages of 12 to 15, found that adolescents' scores on the Behaviour Rating Inventory of Executive Function (BRIEF) constituted a strong and consistent predictor of their annual grade point averages (GPAs) in a variety of subjects (Samuels, Tournaki, Blackman, & Zilinski, 2016). However, these results concerned the General Executive Composite score from the BRIEF, rather than the sub-domain scores that refer to specific aspects of EF, thus, no conclusions can be drawn from this study in regard to the relative contributions of individual EF components on adolescents' attainment. With regard to the subjects in which attainment has been examined in relation to EFs, once again many studies have focused on one subject at a time and also, the existing literature has disproportionally focused on some subjects, mainly language and maths, while largely overlooking others, such as social studies, foreign languages and arts.

There are very few studies that have attempted to look at all three EF components of inhibition, shifting and working memory in relation to attainment in a variety of subjects among adolescents. One influential study, carried out by St Clair-Thompson and Gathercole in 2006, investigated all three EF components in relation to attainment on National curriculum assessments of English, maths and science. Multiple measures were used to assess each EF component in a sample of 11-12 year old young adolescents. The initial zero-order correlations indicated significant associations between performance on certain EF tasks and attainment, however, in order to control for interrelations between the EF tasks, a principal component analysis was carried out and only two factors - one corresponding to inhibition and another to working memory- were identified. Partial correlations between these two factors and attainment in each subject revealed that working memory was uniquely associated with English and maths attainment, while inhibition was independently associated with attainment in all three subjects. In 2010, Latzman et al., extended this further by studying the three EF components in relation to attainment across an even wider range of subjects (reading, maths, science and social studies) in a sample of adolescents spanning a wider age range (11-16 year olds). Once again, the three EF components appeared to be differentially associated with adolescents' attainment in each of the subjects: after controlling for general intellectual ability, inhibition was a unique contributor in explaining maths and science attainment, shifting made unique contributions to reading and science, whilst working memory uniquely contributed to attainment in reading and social studies. These two studies both yielded significant results that shaped researchers' understanding of the relative effects of EF components on attainment in different subjects. However, it should be noted that the age-range examined in the first study was limited to one year in early adolescence and that the sample of the latter study was made up exclusively by male adolescents, therefore these studies' results arguably cannot be generalised to the entire adolescent population.

In an attempt to address some of the limitations in the previous literature, the current study was designed to investigate all three components of the tripartite EF model- inhibition, shifting and working memory- in relation to attainment in a variety of subjects among adolescents aged 14-18 years old. The age range was chosen to include the latter stages of adolescence which have been disproportionately overlooked in the literature and be sufficiently wide to allow for the exploration of potential age-related differences in the relationship between the three EF components and attainment in the various subjects. Furthermore, the age range examined in this study includes the transition from the broad general education phase (up to S3) to the senior phase (S4 and onwards) of the Curriculum for Excellence - the Scottish education curriculum. Seeing as the two phases differ in regard to their requirements, the present study sought to investigate the role of EF's in these two phases.

The goal was to obtain an accurate view of the relative contributions of the EF components on attainment, beyond the effect of other influencing factors; therefore, I aimed to control for the effects of factors, such as socioeconomic status or gender. Furthermore, many previous studies investigating the relationship between EF performance and measures of educational attainment, did not control for non-executive, lower-order processes that individuals rely on when performing the EF tasks; therefore, any significant results they may have found cannot be interpreted as representing pure effects of the EF components on attainment. In order to deal with this "task impurity" issue, I aimed to control for the effects of as many non-EF processes that may be implicated in the relationship between EFs and attainment as possible.

To conclude, the following chapter presents the results of a study aiming to investigate the relative contributions of the three EF components to attainment in a variety of subjects for which the 14-18 year old adolescents comprising the sample had attainment data, while controlling for the effects of demographic variables and non-EF processes. The total sample comprised of third-year pupils still in the broad general education phase, as well as fourth- and fifth-year pupils in the senior phase of their education. The disparities between the two phases e.g., the different ways in which pupils' attainment is assessed, naturally divided the sample in two. Consequently, the methods and results pertaining to the younger (third-year) and the older (fourth- and fifth-year) pupils are presented and discussed separately and are then followed by a more general discussion that incorporates the results from all the age groups.

4.2. Third-year (S3) pupils

4.2.1. Methods

Participants

The sample for this study was a subset of the total 134 third-year pupils that were tested as part of the overall project. More specifically, the sample consisted of 114 third-year pupils (55 females, 59 males) for whom educational attainment data were available. The mean age of the pupils at the time of testing was 14.58 years (SD=0.41, range 13.83 to 15.91) and the majority of them were British (95, data missing for 2 pupils) and right handed (97, data missing for 2 pupils). It is important to note, that because one of the three participating schools was not able to provide quantitative data of pupils' attainment at the end of their third year, this study's sample is composed entirely of pupils from the remaining two schools that participated in the research project. The free meal entitlement rates in these two schools for the years during which testing took place were 48% and 5%, when the corresponding national rates were 15% and 14%.

Cognitive measures

The tasks from the D-KEFS and BAS II batteries that were used to assess inhibition, shifting and working memory in this project and the scores that derive from them have been described in detail in previous chapters and, therefore, are only briefly recounted here.

Inhibition - Pupils' scores on the third (Inhibition) condition of the CWI test from the D-KEFS were utilised as measures of their inhibition. In order to control for lower-order, non-executive processes implicated in performing this task, the scores from the first (Colour naming) condition of the CWI test were also utilised. The normative scores corresponding to the time needed for completing each of the two conditions were used in the analyses (see pages 60-61 for more information regarding the D-KEFS CWI test and the scores produced from it).

Shifting - The Free Sorting condition of the Sorting test from the D-KEFS battery was used to measure pupils' shifting ability. More specifically, two different scores from this task were considered in the analyses: the normative scores corresponding to the number of correct sorts generated and the normative scores calculated from pupils' descriptions of the sorts (see pages 61-63 for more information regarding the D-KEFS Sorting test and the scores produced from it).

Working memory - Pupils' normative scores on the Recall of Digits Backward task from the BAS II battery were used in the analyses as measures of their working memory. In addition, normative scores on the Recall of Digits Forward task of the BAS II were used as measures of pupils' baseline levels of short-term verbal memory (see pages 63-64 for more information on the BAS II Recall of Digits tasks and the scores produced from them).

<u>Educational attainment assessment</u>

For the sample of third-year pupils, educational attainment was indicated by the grades the pupils received from their teachers at the end of their third year. These grades reflected pupils' achievement and progress during the year, as measured by internal assessments administered and marked by teachers to national standards. The schools supplied grades on all the subjects that pupils attended in their third year, however, for the subjects of Physical Education, Religious/Moral Education and Science there were inconsistencies in the grades resulting from different marking schemes used in the two schools. The grades of the majority of pupils on these three subjects were not in an appropriate format and could not be used as indices of pupils' performance, therefore, these three subjects were not considered when examining the relation between educational attainment and EFs.

For the rest of the subjects, the grades supplied by the two schools indicated the level of the Scottish National Curriculum that pupils were working in and their status - Developing (D), Consolidating (C) or Secure (S) - within that level. There were two pupils in the sample who each had one grade indicating performance at level 2 of the National Curriculum, but the remaining pupils were working at levels 3-4 of the National Curriculum, as is expected among third-year pupils. Since there were only two grades corresponding to performance at level 2, they were disregarded and consequently, pupils' educational attainment was treated as an ordinal variable with a total of six grade categories (status D, C and S within level 3 and 4 respectively).

With the exception of English and Mathematics, which are compulsory subjects that all pupils must attend, the number of pupils who attended and, therefore, had grades on each subject varied greatly. Moreover, the number of pupils with grades on some subjects such as Spanish, Music and Drama, was prohibitively low (≤30 cases) for carrying out the relevant analyses for each subject separately. In order to overcome this issue, subjects that fell under the same general curriculum area e.g., social studies, were grouped together and grades in these subjects were merged. Figure 4.1 shows the subjects for which grades were combined and the resulting curriculum areas that were subsequently considered in the analysis.

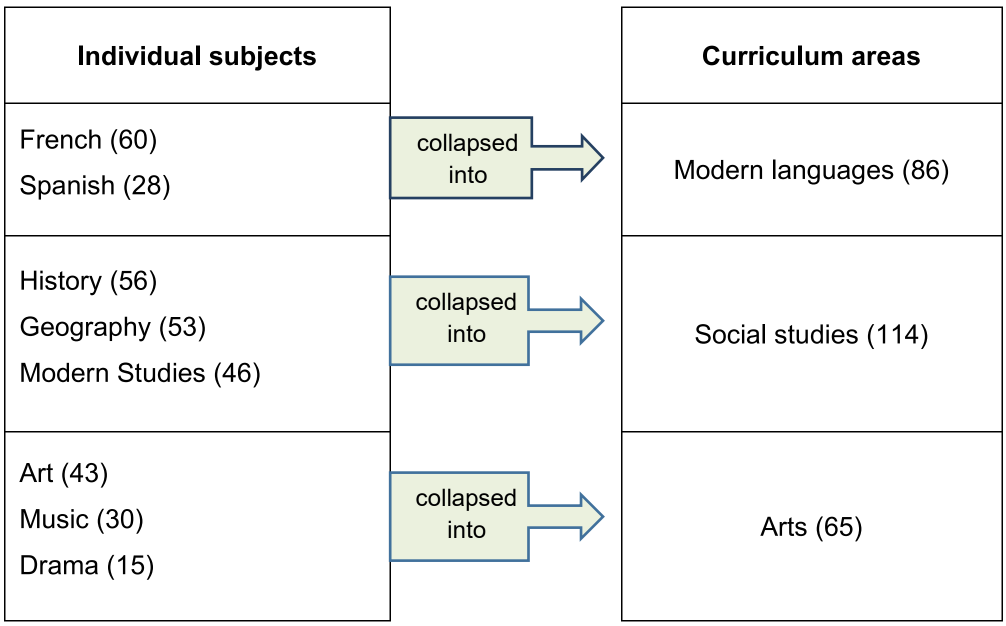

Figure 4.1. Depiction of the individual subjects that were combined to form the general curriculum areas in which attainment was subsequently examined for third-year pupils. The number of pupils within the sample with qualifications in each individual subject and curriculum area is presented in brackets.

Pupils' grades in each of the curriculum areas presented in Figure 4.1 were generated by integrating their grades on the respective individual subjects. This procedure was relatively straightforward for pupils who had identical grades on the subjects that needed to be combined, whereupon their attainment in the overall curriculum area was represented by the same grade they had on all the component subjects. However, if pupils had different grades on subjects that fell under the same curriculum area, the highest grade they received across these subjects was used to indicate their attainment in the curriculum area overall. This approach was deemed the most appropriate since taking the mean of pupils' grades across subjects was not possible due to grades not having numerical values but rather representing different levels of an ordinal variable. There were also many pupils who had only attended one of the individual subjects that made up a curriculum area and in this case their grade on that single subject served as an indicator of their attainment in the overall curriculum area. Lastly, if pupils had not attended any of the individual subjects belonging to a certain curriculum area, they were perceived as not having a grade and were not included in the analysis of attainment in that curriculum area in relation to EFs.

Covariates

Pupils' gender was included in all analyses as a covariate. In an attempt to control for socioeconomic status, the SIMD, an index which constitutes a measure of deprivation (for more information see pages 53-54) was included as a covariate in the analyses. Within the sample of 114 third-year pupils, the SIMD ranged from 116 to 6807 (M_{SIMD}=4726.09, SD=2114.81). Furthermore, the binary variable denoting whether or not each pupil had a condition (for more information on this see page 54) was also included as a covariate. Among the S3 pupils, 16 were reported to have such a condition.

Statistical analyses

Educational attainment in the five curriculum areas of English, maths, social studies, modern languages, and arts, was examined in relation to the three EF components (inhibition, shifting and working memory). Analyses were carried out separately for attainment in each of the curriculum areas, based on the appropriate sample of third-year pupils each time, i.e., only pupils who had attainment data in each curriculum area were considered in the relevant analyses.

In the first step, the relationship among each of the three EF components and attainment in each of the 5 curriculum areas was examined by calculating the zero-order correlations between the relevant variables. Potential relationships among demographic variables and educational attainment in the 5 curriculum areas were also investigated by calculating the zero-order correlations among pupils' educational attainment and their gender, SIMD and condition status[6]. The next step was to build multiple regression models, in which educational attainment in each of the curriculum areas was regressed on the relevant EF scores and covariates. The EF scores and covariates that were included in each regression model were determined on the basis of the previously calculated zero-order correlations i.e., only the variables with significant zero-order correlations to attainment in each of the 5 curriculum areas were included as predictors in the corresponding models. This was done in order to maximise the statistical power in the regression analyses by reducing the number of variables included in each model. Once the regression models were developed, they were checked for multicolinearity, by inspecting the relevant Variance Inflation Factors (VIFs) i.e., indices that show whether each predictor in a model has a strong linear relationship with any of the other predictors. The VIFs of each predictor within all the models were calculated and multicolinearity was gauged according to the common rule of thumb that a VIF value of 10 or above indicates serious multicollinearity issues. (Clark-Carter, 2010; Field et al., 2012).

All statistical analyses were carried out using R studio. Missing data were present for some of the predictor variables considered in the analyses, but also for the attainment in English variable, due to the fact that the grades provided for 20% of the sample were not in the acceptable form described above. Missing data on these variables could not be dealt with using the FIML method (described in the previous chapter, section 3.2.6.), since there is currently no R package that allows implementing FIML in analyses with ordinal outcome variables, such as the

[6] Please note that the software used to estimate the correlation coefficients in this study automatically adjusts to the type of variables considered, making it possible to estimate correlations between categorical and binary variables, as in the case of the correlations between educational attainment and gender or condition status in this study. The estimation in this case is done using polychoric/tetrachoric correlations, which, essentially, estimate a latent continuous variable based on the observed categorical variable. For reasons of coherence, all types of correlation referred to throughout this chapter are simply reported using the general symbol r.

educational attainment variables in the analyses carried out in this study. An alternative to FIML estimation, namely multiple imputation, was used to deal with missing data in these analyses instead.

Like FIML estimation, multiple imputation is a state-of-the-art missing data technique and makes some of the same assumptions i.e., missing at random (MAR) data and multivariate normality; however, it differs in one important aspect: it actually fills in the missing values in the dataset prior to the analyses (Enders, 2010). More specifically, in the imputation phase of multiple imputation, the missing data are imputed, not once, but several times, generating multiple copies of the dataset, each containing somewhat different imputed values of the missing data. The imputed values are generated by estimating plausible values for the missing data based on the observed data, and then adding a random residual to each estimated value to reflect their uncertainty. In the next step, called the analysis phase, each of the filled-in datasets generated in the previous step is analysed separately, ultimately yielding a set of parameter estimates (i.e., correlation or regression coefficients) and standard errors for each dataset. The final step of a multiple imputation analysis is the pooling phase, in which the results from all the datasets are combined into a single set of results, using the formulas proposed by Rubin (1987). Because multiple imputation involves generating multiple predictions for each missing value and averaging across them, rather than relying on any single set of imputations, it accounts for the uncertainty associated with the missing data, which renders this missing data technique superior to any single imputation method.

For the analyses presented below, the ‘mice’ package was used to impute missing data in R. This package was used to implement multivariate imputation by chained equations (mice), a version of multiple imputation that is suitable for large datasets with numerous variables and missing data on more than one variable (Azur, Stuart, Frangakis, & Leaf, 2011). Unlike other multiple imputation procedures that impute data assuming a joint model across all variables, the chained equation approach allows each variable with missing data to be modelled separately conditional upon the other variables in the dataset. Imputing data on a variable-by-variable basis renders the mice method more flexible and capable of handling variables of varying types, e.g., continuous or binary, with each of these types of variables being modelled accordingly, e.g., using linear and logistic regression respectively (Azur et al., 2011). Thus, mice was deemed the most appropriate method for imputing data in this case, since the dataset included demographic information and educational attainment data that were treated as binary and/or ordinal variables, in addition to performance on cognitive tasks which were handled as continuous variables.

One very important element to decide upon when applying multiple imputation is the number of imputed datasets to be generated. Early research indicated that, unless rates of missing information are really high, 5–10 imputed datasets is sufficient (Schafer, 1999); however, more recent research suggests that more imputations are usually needed depending on the percentage of missing data (Bodner, 2008; Olchowski, & Gilreath, 2007; White, Royston, & Wood, 2010). Based on simulations, Graham, Olchowski and Gilreath (2007) suggested that, in order to get stable estimates of standard errors and p-values for regression coefficients while tolerating up to 1% loss of power, 20 imputations are needed when there is 10% to 30% missing data, whereas 40 imputations are needed for 50% missing information. Following this suggestion, I carried out 20 imputations since the dataset under study had 8.2% missing data, which is relatively close to 10%.

As far as the cognitive measures are concerned, imputations were carried out on the normative scores. Seeing as the normative scores did not differ in their normality from the raw scores (Azur et al., 2011), imputing the normative scores was much more preferable as it meant that no further transformations of the scores would be necessary after the imputation phase; instead, the generated datasets could be directly used in the analysis phase. Finally, in order to satisfy the MAR assumption, all the variables that were going to be part of the subsequent analyses, as well as variables that were predictive of the missing values (Azur et al., 2011; White et al., 2010), were included in the imputation model. After the data were imputed, the R lavaan package for Latent Variable Analysis was used in conjunction with the R semTools package in order to carry out the analysis and pool the results across datasets.

4.2.2. Results

The main variables considered in the analyses of this study were pupils' normative scores on the CWI, Sorting[7] and Recall of Digits tasks, which represented pupils' EF abilities, and their school grades in five different curriculum areas - English, mathematics, social studies, modern languages and arts - as proxies of their educational attainment. The descriptive statistics of pupil's normative scores on the cognitive tasks, as calculated using the available data before the imputations were carried out, are shown in Table 4.1.

Table 4.1. Descriptive statistics for the third-year pupils' cognitive measures based on the original data, before imputations were carried out; the first column shows the number of pupils (N) with normative scores on each measure and the remaining columns present the mean (M), standard deviation (SD), value range, skewness and kurtosis of the scores for those pupils.

	N	M	SD	Range	Skewness	Kurtosis
Inhibition, CWI INH	113	10.70	2.65	1-15	-0.93	1.16
Colour naming speed, CWI CN	113	9.41	2.79	1-14	-0.93	0.63
Shifting, ST correct sorts	114	8.68	2.50	3-15	-0.15	-0.71
Working memory, DRB	95	50.20	9.04	23-69	-0.52	0.43
Short-term memory, DRF	106	49.75	7.84	30-71	0.25	0.29

Note. CWI INH: Colour Word Interference Inhibition condition, CWI CN: Colour Word Interference Colour Naming condition, ST: Sorting Test, RDB: Recall of Digits Backward, RDF: Recall of Digits Forward

[7] It should be noted that between the two types of normative scores deriving from the Sorting test i.e., scores referring to the number of sorts generated and the description given to justify sorting, only the former was considered as an indicator of shifting in the analyses and results discussed below because only the former was included in the imputation model when the missing data were being imputed. This was done because the two types of scores were very highly correlated (r=.94, p<.001) among the third-year pupils, so including both of them would not really add to the model and could in fact cause multicolinearity issues when predicting the values to be imputed.

For educational attainment, which was treated as an ordinal variable, the number of pupils within each grade category, for each of the five curriculum areas is shown in Table 4.2. It is important to note that, in order to carry out analyses with an ordinal variable, there must be a sufficient number of cases within each category of the variable. For this reason, in the case of the educational attainment variable, categories with very few cases (n<5) needed to be combined with adjacent categories to yield an acceptable number of cases per category. As shown in Table 4.2, this was done for the curriculum areas of mathematics, social studies and modern languages, in which the level 3 developing, consolidating and secure categories were collapsed into an overall Level 3 category and additionally, in modern languages, the level 4 secure category was combined with level 4 consolidating.

Table 4.2. Number (and percentage) of third-year pupils with grades in each of the curriculum areas broken down by attainment level.

		English	Maths	Social studies	Modern languages	Arts
Level 3	developing	7 (6%)				5 (8%)
	consolidating	8 (7%)	8 (7%)	10 (9%)	12 (14%)	11 (17%)
	secure	22 (20%)				11 (17%)
Level 4	developing	35 (31%)	15 (13%)	19 (17%)	25 (29%)	19 (29%)
	consolidating	8 (7%)	21 (18%)	21 (18%)	49 (57%)	11 (17%)
	secure	10 (9%)	70 (62%)	64 (56%)		8 (12%)
grades not available		23 (20%)	NA	NA	NA	NA
	Total	113	114	114	86	65

Table 4.2 also shows that English grades were not available for 23 pupils. This was due to the fact that their teacher(s) had not graded their performance using the common grading scheme described above. These pupils all came from the same school, were all male and there was a slightly higher percentage of pupils with a

condition among them (22%) compared to the rest of the sample (12%). Consequently, it was decided not to disregard these cases in the analyses of English attainment since this could bias the sample and subsequently the results. Instead the grades for these 23 pupils were imputed during the multiple imputation phase.

Table 4.3 shows the correlations between pupils' normative scores on the cognitive tasks and their attainment in the five curriculum areas. All three EF components were significantly correlated with attainment in English, maths, social studies and modern languages (correlation coefficients ranging from r=.23 to r=.53, all p_s<.05), but only shifting was significantly correlated with attainment in arts (r=.45, p<.001). In regard to the strength of the correlations between the three EFs and educational attainment, there appeared to be a trend: correlations between attainment and the inhibition component were the smallest for most curriculum areas (correlation coefficients ranging from r=.14 to r=.47) whilst the correlations with shifting were always the strongest (coefficients ranging from r=.42 to r=.53). Moreover, inhibition and working memory were each significantly correlated with their respective non-EF processes i.e., colour naming speed and short-term memory (r=.72 and r=.46 respectively, p_s<.001). As a result of their strong association with the two EF components, colour naming speed and short-term memory were also significantly correlated with attainment in some of the curriculum areas and were, therefore, included as predictors in the relevant regression models.

As far as the demographic variables are concerned, gender was found to be correlated to attainment in English (r= -.35, p<.001), social studies (r= -.20, p<.05) and modern languages (r= -.58, p<.001), with females outperforming males in all cases. Having a condition that may affect EF performance was found to be associated with lower attainment in modern languages (r= -.24, p<.05), but not any of the other curriculum areas. Finally, SIMD, was correlated strongly with pupils' attainment in all curriculum areas (correlation coefficients ranging from r=.51 to r=.61, p<.001) apart from modern languages (r=.11, p>.05).

Table 4.3. Correlations among third-year pupils' performance on the cognitive measures and their attainment in English, maths, social studies, modern languages and arts

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Inhibition	-									
2. Colour naming speed	.72*** [a]	-								
3. Shifting, correct sorts	.32** [a]	.16 [a]	-							
4. Working memory	.47*** [a]	.35** [a]	.33** [a]	-						
5. Short-term memory	.22* [a]	.19 [a]	.17 [a]	.46*** [a]	-					
6. English	.23** [b]	.08 [b]	.42*** [b]	.38** [b]	.28** [b]	-				
7. Maths	.34** [b]	.21* [b]	.53*** [b]	.47*** [b]	.40*** [b]	.78*** [c]	-			
8. Social studies	.27** [b]	.20* [b]	.51*** [b]	.46*** [b]	.26* [b]	.82*** [c]	.79*** [c]	-		
9. Modern languages	.47*** [b]	.25* [b]	.49*** [b]	.33** [b]	.06 [b]	.53*** [c]	.47*** [c]	.57*** [c]	-	
10. Arts	.14 [b]	.14 [b]	.45*** [b]	.21 [b]	.21 [b]	.68*** [c]	.62*** [c]	.58*** [c]	.40** [c]	-

[a] based on the whole sample of 114 pupils

[b] based on the total of pupils with grades in each curriculum area; 113 for English, 114 for mathematics, 114 for social studies, 86 for modern languages and 65 for arts

[c] based on samples of pupils with grades in each of the two curriculum areas.

*p<.05, **p<.01, ***p<.001

In the next step, regression models predicting attainment in each curriculum area were developed and fitted to the data. There were five models in total, one for each curriculum area, and each model included the demographic variables and cognitive measures that were significantly correlated to attainment in the relevant curriculum area as predictors. The models were built using Structural Equation Modelling (SEM) in the R lavaan package, but because in SEM it is not possible to get accurate estimates of each predictor's unique contribution to the outcome by inserting the predictors in a stepwise manner, all the relevant predictors (demographic and cognitive) for each model were inserted simultaneously, in one step. The details of the five (full) models are shown in Table 4.4.

Attainment in English was regressed on all three EF components, short-term memory, SIMD and gender, which all together explained around 48% of the variance in English attainment. The p values corresponding to each individual predictor indicated that shifting was a significant predictor ($\beta=.244$, $p<.05$) whereas the effects of inhibition and working memory were not statistically significant ($\beta=.037$ and $\beta=.088$ respectively, both $p_s>.05$). Among the other variables, gender and SIMD were significant predictors of attainment ($\beta=-.265$, $p<.01$ and $\beta=.420$, $p<.001$ respectively) while short-term memory was not found to have a significant effect ($\beta=.090$, $p>.05$).

The next two models, predicting attainment in maths and social studies respectively, were relatively similar in that they contained all three EF components, as well as the two lower-order processes and SIMD as predictors; the only difference was that the model for social studies additionally included gender. Overall, the six predictors in the maths model explained 55% of the variance in pupils' grades and the seven predictors in the social studies model explained approximately 58% of the variance in social studies grades. In both models, SIMD and shifting were the most significant predictors with regression coefficients in the range of 0.3-0.5 (all $p_s<.001$). Short-term memory was found to have a significant albeit weaker effect ($\beta=.189$, $p<.01$) on maths attainment and working memory approached significance as a predictor in the social studies model ($\beta=.199$, $p=.05$), but no other variables within each model were found to have significant effects.

Table 4.4. Regression models predicting third-year pupils' educational attainment; information on the individual predictors and overall variance explained for attainment in a) English, b) maths, c) social studies, d) modern languages and e) arts.

		B	SE(B)	β	p	R^2
a) English	Gender	-0.528	0.150	-0.265	<.01	0.484
	SIMD	0.202	0.038	0.420	<.001	
	Inhibition	0.014	0.031	0.037	.658	
	Shifting	0.097	0.038	0.244	<.05	
	Working memory	0.010	0.014	0.088	.499	
	Short-term memory	0.011	0.012	0.090	.354	
b) Maths	SIMD	0.179	0.043	0.379	<.001	0.552
	Inhibition	0.053	0.052	0.138	.308	
	Colour naming speed	-0.006	0.042	-0.017	.884	
	Shifting	0.135	0.030	0.336	<.001	
	Working memory	0.013	0.009	0.115	.174	
	Short-term memory	0.024	0.009	0.189	<.01	
c) Social studies	Gender	-0.229	0.138	-0.115	.096	0.576
	SIMD	0.228	0.032	0.482	<.001	
	Inhibition	-0.015	0.041	-0.039	.716	
	Colour naming speed	0.041	0.035	0.114	.241	
	Shifting	0.126	0.034	0.314	<.001	
	Working memory	0.022	0.011	0.199	.05	
	Short-term memory	-0.001	0.011	-0.009	.913	
d) Modern languages	Gender	-0.899	0.164	-0.450	<.001	0.553
	Condition status	-0.250	0.295	-0.084	.395	
	Inhibition	0.087	0.064	0.198	.170	
	Colour naming speed	0.004	0.055	0.010	.940	
	Shifting	0.139	0.035	0.315	<.001	
	Working memory	0.009	0.010	0.080	.374	
e) Arts	SIMD	0.171	0.044	0.405	<.001.	0.347
	Shifting	0.125	0.039	0.315	<.01	

In the fourth model, pupils' attainment in modern languages was regressed on all three EF components, colour naming speed, gender and the variable denoting pupils' condition status. All together, these variables explained 55% of the variance in pupils' grades. Pupils' gender was the most significant predictor of attainment in modern languages with a standardised regression coefficient of $\beta=-.450$ (where the negative sign indicated that female pupils outperformed males). Shifting was the only other variable with a significant effect ($\beta=.315$, $p<.001$) although, it is worth noting that the effect of inhibition was also relatively large ($\beta=.198$) but did not reach significance. All the other variables included in the model were not found to be significant predictors[8].

The final regression model showed that SIMD and shifting explained approximately 35% of the variance in pupils' art grades. Both variables were significant predictors of attainment in arts, but the effect of SIMD ($\beta=.405$, $p<.001$) was relatively larger than the effect of shifting ($\beta=.315$, $p<.01$)[9].

In regard to multicolinearity, although the regression models presented above often included predictors that were highly correlated to each other, the VIFs of each predictor within the models were calculated and found to be within acceptable ranges. More specifically, all VIFs were lower than 3.00 (VIF range was 1.05-1.68 for English; 1.13-2.45 for maths; 1.10-2.58 for social studies; 1.13-2.20 for modern languages and all VIFs=1.12 for arts).

4.2.3. Discussion

This section (section 4.2) of the chapter concerned the investigation of the relationship between EFs and the educational attainment of the youngest pupils of the overall sample i.e., the third-year pupils. Overall, the three EF components of inhibition, shifting and working memory were examined in relation to pupils'

[8] Due to the relatively small sample size that this regression model was based on, additional analyses of covariance were carried out to explore whether pupils belonging in the different grade groups differed in their EFs whilst controlling for the relevant covariates. The results of the corresponding ANCOVAs confirmed that pupils with different levels of attainment in modern languages differed in regard to their shifting ($F(2,80)=26.02$, $p<.001$), as well as their inhibition ($F=(2,80)=9.55$, $p<.001$) and working memory ($F(2,80)= 4.80$, $p<.05$).

[9] Once again, due to the small sample size that this model was based on, an additional analysis of covariance was carried out, which confirmed the regression results, that pupils with different levels of attainment in arts differed in regard to their shifting ability, $F(5,58)=4.8$, $p<.001$.

attainment in five curriculum areas - English, maths, social studies, modern languages and arts - in an attempt to get the most complete picture of the relationship between EFs and educational attainment possible.

Guided by the zero-order correlations among the variables under study, multiple linear regression models were developed, in which attainment in each curriculum area was regressed on the relevant variables, in order to inspect their relative contributions. The sample sizes in each of these analyses were different as a result of the varying number of pupils with attainment data in each curriculum area. In the case of modern languages and arts in particular, the number of pupils with attainment data was relatively small for the regression models that were developed, and therefore, the results relating to attainment in these curriculum areas should be considered with caution.

When all the relevant EF components, non-EF processes and demographic variables were considered together as predictors of attainment, SIMD was found to be the most significant predictor of attainment in all the models apart from the one for modern languages, in which it was not included as a predictor. This is in keeping with the existing literature which indicates a significant role of socioeconomic status in predicting both adolescents' EF ability (Boelema et al., 2014; Spielberg et al., 2015) and their educational attainment (McCluskey, 2017; Scottish Government, 2016b, 2017).

In the model predicting modern languages, which did not include SIMD as a predictor, gender was the most significant predictor of attainment instead. In addition, gender was a strong predictor of attainment in English but did not have a significant effect on attainment in any of the other curriculum areas. In both English and modern languages, female pupils were found to outperform their male counterparts. Very similar results in regard to observed gender differences in English and language attainment were found by Riding et al. (2003) in a sample of British secondary school pupils of a similar age (13 years old), indicating that there might be a more general trend for girls outperforming boys in these subjects in the UK. However, the Riding et al. (2003) study also observed gender differences in attainment in History, Music and Art, which was not the case in our study. Apart from differences between the samples of the two studies (age, recruitment region etc.), the fact that the present study considered attainment across broader curriculum areas rather than in each school subject, such as History or Music, separately might warrant the somewhat different findings.

Shifting was the variable with the next biggest effect on attainment in all curriculum areas. In models where shifting was considered in concert to inhibition and/or working memory as predictors of pupils' attainment, shifting was found to have a relatively larger effect and, in fact, was the only EF component that constituted a significant predictor of attainment. Therefore, the results overall, indicate that shifting was the EF component most strongly associated with attainment across all five of the curriculum areas examined. These results are slightly counterintuitive considering the disproportionate amount of studies which focus solely on working memory (Alloway et al., 2010; Gathercole et al., 2004; Riding et al., 2003) or inhibition (Gilmore et al., 2015) as predictors of educational attainment in the earlier stages of adolescence. Furthermore, in studies that examined all three EF components together, shifting was often shown to not independently contribute to young adolescents' attainment (Cragg et al., 2017; St Clair-Thompson & Gathercole, 2006) or to only selectively predict attainment in some subject areas but not others (Latzman et al., 2010). The only exception was a study by Zorza et al. (2016), which found that shifting was the only independent predictor of pupils' GPA across all subjects taken during their first year of secondary school. However, it should be noted that Zorza et al. (2016) only considered shifting in combination with inhibition and verbal fluency, therefore, demonstrating the independent effect of shifting on attainment beyond that of inhibition, but not providing any information about the relative role of shifting in comparison to working memory.

Interestingly, similar to the current study, the Zorza et al. (2016) study was one of the few that controlled for lower-order processes implicated in performing the EF tasks and this might, to some extent, explain its similar findings. Indeed, in many cases in my study, both EFs and the corresponding non-EF processes were found to be significantly correlated to attainment but, when considered simultaneously in the regression models, their independent effects on attainment did not reach significance. Taking into consideration that the non-EF processes (colour naming speed and short-term memory) were strongly correlated to the corresponding EFs (inhibition and working memory respectively), it is likely that they were partly driving the significant correlations between the EFs and attainment, and once they were controlled for the remaining associations (between EFs and attainment) were not significant. Therefore, once again, the current results highlight the importance of controlling for lower-order, non-EF processes implicated in performing the tasks used to measure EFs. However, it is important to note that whilst I assessed and subsequently controlled for the non-EF processes implicated in the inhibition and working memory tasks, I did not assess the non-EF processes implicated in the shifting task, as there was no control condition provided by the D-KEFS for the Sorting test. It is likely that my results would be different if the non-EF process(es) implicated in performing the Sorting test had been controlled for and possibly the significant effect of shifting on attainment would have been attenuated. Consequently, future research intending to reproduce the current results should aim to control for lower-order processes corresponding to each of the EF components measured.

4.3. Fourth- (S4) and fifth- (S5) year pupils

4.3.1 Methods

Participants

The fourth-year (S4) and fifth-year (S5) pupils who were tested as part of the overall PhD project constituted the two samples. The sample of the younger (S4) pupils consisted of 113 individuals (59 females, 54 males) with a mean age of 15.90 years (SD=0.33, range 15.08 to 17.08) and the majority of them were British (97) and right handed (96). The sample of the older (S5) pupils consisted of 99 individuals (47 females, 52 males) with a mean age of 17.07 years (SD=0.34, range 16.25 to 17.83), who in their majority were British (89) and right handed (83), although ethnicity and handedness data were not available for two pupils.

Cognitive measures

The same scores resulting from the D-KEFS and BAS II tasks that were presented in the previous section of this chapter (section 4.2) were used as indicators of pupils' inhibition, shifting, working memory and the two non-EF processes (colour naming speed and short-term memory). Normative scores that had been standardised for age were used in all cases.

Educational attainment assessment

In the fourth and fifth year of high school, pupils select the subjects in which they want to earn National Qualifications (NQs) as well as the level of qualification they want to work at in each subject. The pupils in this study's samples were working towards NQs at different levels and in a variety of subjects; educational attainment for these pupils was, therefore, indicated by the level of qualification they acquired in each subject. Schools provided information on the qualifications the S4 and S5 pupils completed in all the subjects they attended during their fourth and fifth year respectively and, where appropriate, they provided pupils' exam and/or coursework grades as well.

Overall, across both samples (fourth- and fifth-year pupils) examined in this section, pupils had achieved qualifications at National 3, National 4, National 5 and Higher levels. The different levels of qualifications mainly correspond to varying degree of difficulty, but there are also some discrepancies in the way the different levels of qualifications are organised and assessed. Qualifications at National 3 or National 4 level are internally assessed (by the teachers within each school) on a pass or fail basis, depending on whether the pupil completed all the necessary units that make up the qualification. Qualifications at National 5 level and above are also composed of individual units that pupils must complete, but in addition pupils are assessed on a question paper (exam) and/or coursework (assignment, portfolio, practical activities etc.), which is usually marked externally by the Scottish Qualification Authority (SQA). Pupils' performance on the exams and/or coursework, ultimately determines whether or not they are awarded the relevant qualification as well as the grade they receive; consequently, qualifications at National 5 or Higher levels are graded A to D or "No Award".

In both the fourth- and fifth-year pupil samples, there were no cases with a D grade on any qualification and cases with a "No Award" grade were not considered in the analyses because this grade corresponds to failing the relevant qualification. Therefore, pupils with qualifications at National 5 or Higher level were distinguished into three categories according to their grades (A, B or C). Furthermore, there were only four pupils with qualifications at the National 3 level: among the fourth-year pupils there was one pupil with a National 3 qualification in English and two with National 3 qualifications in Maths and among the fifth-year pupils, there was one pupil with a National 3 qualification in English. Seeing as there were very few cases of pupils achieving National 3 qualifications and that these cases were limited to two subjects (English and Maths), it was decided to disregard these cases and not include them in the analyses. Ultimately, educational attainment was treated as an ordinal variable with the following possible levels: National 4, National 5 grade C, National 5 grade B, National 5 grade A, Higher grade C, Higher grade B and Higher grade A. Of course, it is important to note that because fourth-year pupils typically only work towards qualifications at National 5 level or below, in the current sample of fourth-year pupils, only the first four levels of educational attainment were encountered and, subsequently, considered in the analyses.

As mentioned above, the schools provided information about the qualifications on all the subjects that the pupils had attended/studied for. There were over 10 subjects, but not all pupils had worked towards qualifications in each of these subjects. In addition, there was a number of pupils who did not complete or failed their qualifications in some subjects. As a result, the number of pupils with qualifications varied greatly from one subject to another in both the S4 and S5 samples and for certain subjects it was very low e.g., there were fewer than 20 fourth-year pupils and fewer than 15 fifth-year pupils who had achieved qualifications in Music, Drama, Art & Design and Modern Studies. Therefore, the relationship between EFs and educational attainment could not be examined for each subject separately. Instead, certain individual subjects were combined to form broader curriculum areas and pupils' EFs were then examined in relation to attainment in these broad curriculum areas. Figure 4.2 depicts the individual subjects that were combined and the resulting curriculum areas.

Pupils' level of attainment in each of the broader curriculum areas was generated by combining their attainment on the relevant individual subjects in a similar way to that implemented for the third-year pupils in the previous section of this chapter (section 4.2). For pupils with qualifications on only one of the individual subjects composing a curriculum area, the level and/or grade of that qualification was considered as their attainment level for the curriculum area overall. When pupils had achieved qualifications on more than one of the subjects that fell under the same curriculum area, if the level/grade of the qualifications was the same across the subjects, then that constituted their attainment level in that curriculum area, whereas if pupils had achieved qualifications at different levels and/or with different grades, the highest level or grade was considered as their overall attainment level. Lastly, pupils who had not achieved qualifications (this included those who failed the qualifications they set out for) on the subjects belonging to a certain curriculum area, were not included in the analyses pertaining to attainment in that area.

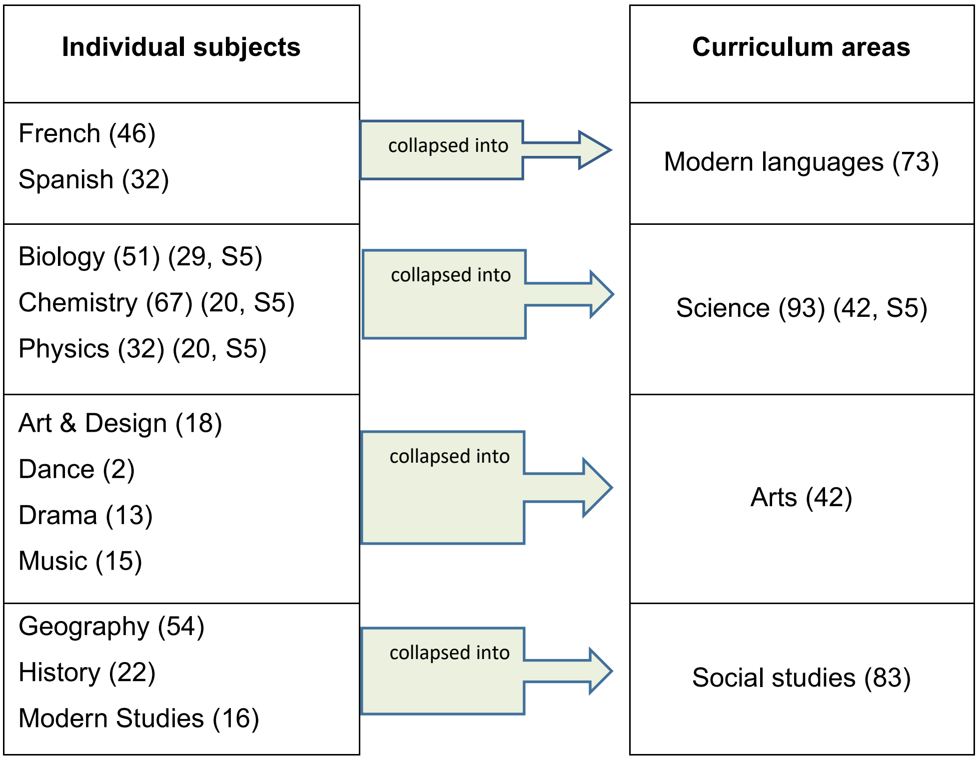

Figure 4.2. Depiction of the individual subjects that were combined to form the general curriculum areas in which attainment was subsequently examined for fourt- and fifth-year pupils. The number of pupils in the S4 and S5 samples with qualifications in each individual subject and curriculum area is reported in brackets.

Covariates

In accordance to what was done in section 4.2, pupils' gender, SIMD rank and the condition status variable were included as covariates in all analyses. In the sample of S4 pupils, SIMD ranged from 116 to 6807 (M_{SIMD}=4680.5, SD=1920.47) and there were 17 pupils who were recorded as having a condition that may affect their EF performance. Among the S5 pupils, SIMD ranged from 116 to 6807 (M_{SIMD}=4267.96, SD=2055.34) and 16 pupils were reported to have a condition.

Statistical analyses

Statistical analyses were carried out separately for the S4 and S5 pupils. This was necessary since there are limitations on the level of NQs that pupils within different years can work towards and consequently the outcome variable (educational attainment) had a different range in each sample.

The same steps as those described in section 4.2 for the S3 pupils were followed for both samples, i.e. first zero order correlations were calculated to gauge the relationships among each of the three EF components, the two non-EF processes, the demographic variables and attainment in each of the curriculum areas and then regression models predicting attainment in each curriculum area were developed with the relevant (significantly correlated) variables as predictors. Once again, the full models i.e., containing all relevant predictors were developed in a single step, whereupon all the necessary predictors were inserted in each model simultaneously.

All statistical analyses were carried out using R studio. Missing data were present on the predictor variables in both the S4 and S5 samples, so multiple imputation was carried out separately on each sample to address this issue. The procedure was identical to that undertaken for the S3 pupils, presented in section 4.2; imputations were carried out directly on pupils' normative scores for the cognitive measures, all relevant variables were included in the imputation models in order to satisfy the MAR assumption and 20 datasets were imputed for each sample since the percentage of missing data within each dataset was close to 10% (12% missing data for S4 and 11% missing data for S5 pupils). Imputations were carried out using the mice package in R and after the data had been imputed, the R lavaan package was used in conjunction with the R semTools package in order to carry out the analysis and pool the results across datasets.

4.3.2. Results

The descriptive statistics of pupils' normative scores on the cognitive measures are presented in Table 4.5A for the S4 pupils and Table 4.5B for the S5 pupils[10].

[10] Once again, due to the high correlations between the two types of normative scores deriving from the Sorting test (r=.91 for the fourth-year pupils and r=.92 for the fifth-year pupils, all p_s<.001), only the score reflecting the number of sorts generated was included in the relevant imputation models and thus considered as an indicator of shifting in the analyses and results discussed below.

Table 4.5. Descriptive statistics for the cognitive measures based on the original data before imputations; shown separately for the A) fourth-year and B) fifth-year pupils. The first column shows the number of pupils (N) with normative scores on each measure and the remaining columns present the mean (M), standard deviation (SD), value range, skewness and kurtosis of the scores for those pupils.

A)

	N	M	SD	Range	Skewness	Kurtosis
Inhibition, CWI INH	109	10.94	2.53	1-15	-1.19	2.04
Colour naming speed, CWI CN	110	9.75	2.84	1-15	-0.96	0.62
Shifting, ST correct sorts	112	8.21	2.47	1-15	0.28	0.48
Working memory, RDB	111	51.01	9.70	21-72	-0.60	0.27
Short-term memory, RDF	113	52.84	9.98	25-78	-0.04	-0.28

B)

	N	M	SD	Range	Skewness	Kurtosis
Inhibition, CWI INH	99	11.21	2.61	1-17	-0.87	1.71
Colour naming speed, CWI CN	98	9.87	2.57	1-13	-1.08	1.44
Shifting, ST correct sorts	98	7.92	2.11	1-13	-0.09	0.48
Working memory, RDB	94	49.68	9.55	27-72	-0.05	-0.58
Short-term memory, RDF	99	51.49	10.11	33-77	0.51	-0.30

Notes.
CWI INH: Colour Word Interference Inhibition condition, CWI CN: Colour Word Interference Colour Naming condition, ST: Sorting Test, RDB: Recall of Digits Backward, RDF: Recall of Digits Forward

The number of pupils within the S4 and S5 samples with qualifications in each of the curriculum areas and their distribution across the different attainment levels is shown in Table 4.6A and 4.6B respectively. Among the S4 pupils, there were very few who had achieved National 5 qualifications in arts with a B or C grade so these two levels were collapsed into one, resulting in arts attainment being treated as an ordinal variable with three levels. In all other subjects, S4 pupils' educational attainment was treated as an ordinal variable with four different levels. In the S5 sample, the majority of pupils worked towards Higher qualifications, as is generally expected by pupils in their fifth year of high school. There were relatively few pupils with National 4 or National 5 qualifications and, in many cases, there were fewer than five individuals per category within the National 4 and 5 levels. For this reason, the four levels corresponding to National 4 and National 5 qualifications were collapsed into one and consequently, S5 pupils' educational attainment in all curriculum areas was treated as an ordinal variable with four levels.

Table 4.6. Number (and percentage) of A) fourth-year and B) fifth-year pupils with qualifications in each of the curriculum areas broken down by attainment level.

A)

<table>
<tr><th></th><th>English</th><th>Maths</th><th>Science</th><th>Social studies</th><th>Modern languages</th><th>Arts</th></tr>
<tr><td>National 4</td><td>17 (15%)</td><td>27 (32%)</td><td>25 (27%)</td><td>14 (17%)</td><td>17 (23%)</td><td>8 (19%)</td></tr>
<tr><td>National 5, grade C</td><td>13 (12%)</td><td>12 (14%)</td><td>15 (16%)</td><td>8 (9%)</td><td>8 (11%)</td><td rowspan="2">5 (12%)</td></tr>
<tr><td>National 5, grade B</td><td>27 (24%)</td><td>13 (15%)</td><td>24 (26%)</td><td>29 (35%)</td><td>12 (17%)</td></tr>
<tr><td>National 5, grade A</td><td>55 (49%)</td><td>33 (39%)</td><td>29 (31%)</td><td>32 (39%)</td><td>36 (49%)</td><td>29 (69%)</td></tr>
<tr><td>Total:</td><td>112</td><td>85</td><td>93</td><td>83</td><td>73</td><td>42</td></tr>
</table>

B)

<table>
<tr><th></th><th>English</th><th>Maths</th><th>Science</th></tr>
<tr><td>National 4</td><td rowspan="4">19 (24%)</td><td rowspan="4">24 (41%)</td><td rowspan="4">9 (21%)</td></tr>
<tr><td>National 5, grade C</td></tr>
<tr><td>National 5, grade B</td></tr>
<tr><td>National 5, grade A</td></tr>
<tr><td>Higher, grade C</td><td>18 (22%)</td><td>11 (19%)</td><td>10 (24%)</td></tr>
<tr><td>Higher, grade B</td><td>19 (24%)</td><td>5 (8%)</td><td>10 (24%)</td></tr>
<tr><td>Higher, grade A</td><td>24 (30%)</td><td>19 (32%)</td><td>13 (31%)</td></tr>
<tr><td>Total:</td><td>80</td><td>59</td><td>42</td></tr>
</table>

The zero-order correlations between the S4 pupils' normative scores on the cognitive measures and their attainment in each of the six curriculum areas are shown in Table 4.7. Working memory appeared to be significantly correlated to attainment in all six curriculum areas (correlation coefficients ranging from r=.21 to r=.45, all p_s<.05), inhibition was significantly correlated to attainment in all areas (coefficients ranging from r=.23 to r=.45, all p_s<.05) apart from modern languages (r=.14, p>.05) and shifting was significantly correlated to attainment in all areas (coefficients ranging from r=.27 to r=.49 , all p_s<.05) apart from arts (r=.33, p>.05). Among the three EF components, inhibition displayed the weakest correlations to attainment in most curriculum areas, whereas shifting or working memory (depending on the curriculum area) displayed the strongest correlations. An exception to this rule was observed in the case of arts in which attainment was most strongly correlated to inhibition (r=.45, p<.01).

The non-EF processes of colour naming speed and short-term memory were strongly correlated to inhibition and working memory respectively (r=.65 and r=.67 respectively, both p_s<.001) and consequently the correlations between these non-EF processes and attainment in the six curriculum areas were analogous, albeit weaker, to those between the corresponding EF components and attainment. Subsequently, colour naming speed and short-term memory were included as predictors in the regression models for attainment in the curriculum areas that they were significantly correlated with.

As far as the demographic variables are concerned, a significant correlation was found between gender and attainment in English with females having higher level of qualifications than males (r= -.24, p<.05) so gender was included as a covariate in the regression model predicting English attainment. SIMD rankings, were found to be correlated to attainment in English (r=.41, p<.001), maths (r=.43, p<.01), social studies (r=.27, p<.05) and arts (r=.43, p<.05) so it was included in the regression models for these four curriculum areas. Finally, the condition status variable was found to be significantly associated with attainment in English (r=-.26, p<.01), science (r=-.37, p<.001) and social studies (r=-.28, p<.05), so it was included in the relevant regression models to control for the fact that pupils with a certain condition achieved lower levels of qualifications compared to pupils without any conditions.

Table 4.7. Correlations among fourth-year pupils' performance on the cognitive measures and their attainment in English, maths, science, social studies, modern languages and arts.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
1. Inhibition	-										
2. Colour naming speed	.65***[a]	-									
3. Shifting	.24*[a]	.20[a]	-								
4. Working memory	.56***[a]	.58***[a]	.18[a]	-							
5. Short-term memory	.43**[a]	.42***[a]	.23*[a]	.67***[a]	-						
6. English	.34***[b]	.27**[b]	.34**[b]	.37***[b]	.24*[b]	-					
7. Maths	.33**[b]	.25*[b]	.49***[b]	.43***[b]	.41***[b]	.61***[c]	-				
8. Science	.23*[b]	.23*[b]	.36**[b]	.45***[b]	.42***[b]	.58***[c]	.74***[c]	-			
9. Social studies	.35**[b]	.25*[b]	.45***[b]	.21*[b]	.17[b]	.61***[c]	.55***[c]	.60***[c]	-		
10. Modern languages	.14[b]	.00[b]	.27*[b]	.40**[b]	.34**[b]	.64***[c]	.65***[c]	.65***[c]	.48***[c]	-	
11. Arts	.45**[b]	.23[b]	.33[b]	.41*[b]	.13[b]	.75***[c]	.67***[c]	.45**[c]	.22[c]	.46*[c]	-

[a] based on the whole sample of 113 pupils

[b] based on the total of pupils with qualifications in each curriculum area; 112 for English, 85 for mathematics, 93 for science, 83 for social studies, 73 for modern languages and 42 for arts

[c] based on samples of pupils with qualifications on each of the two curriculum areas.

*p<.05, **p<.01, ***p<.001

Based on the aforementioned zero-order correlations, regression models predicting attainment in each of the six curriculum areas of interest were developed; the details of the full models are presented below in Table 4.8.

Table 4.8. Regression models predicting fourth-year pupils' educational attainment; information on the individual predictors and overall variance explained for attainment in a) English, b) maths, c) science, d) social studies, e) modern languages and f) arts.

		B	SE(B)	β	p	R^2
a) English	Gender	-0.429	0.163	-0.214	<.01	0.426
	Condition status	-0.655	0.261	-0.229	<.05	
	SIMD	0.177	0.047	0.332	<.001	
	Inhibition	0.041	0.053	0.096	.436	
	Colour naming speed	-0.010	0.040	-0.029	.795	
	Shifting	0.079	0.034	0.190	<.05	
	Working memory	0.026	0.012	0.248	<.05	
	Short-term memory	-0.001	0.010	-0.006	.949	
b) Maths	SIMD	0.137	0.055	0.255	<.05	0.484
	Inhibition	0.064	0.057	0.152	.258	
	Colour naming speed	-0.066	0.043	-0.187	.125	
	Shifting	0.156	0.032	0.387	<.001	
	Working memory	0.029	0.013	0.269	<.05	
	Short-term memory	0.014	0.010	0.133	.195	
c) Science	Condition status	-0.869	0.218	-0.311	<.001	0.413
	Inhibition	-0.031	0.056	-0.065	.577	
	Colour naming speed	-0.039	0.039	-0.107	.325	
	Shifting	0.117	0.044	0.295	<.01	
	Working memory	0.036	0.012	0.339	<.01	
	Short-term memory	0.020	0.010	0.189	<.05	
d) Social studies	SIMD	0.151	0.072	0.240	<.05	0.303
	Inhibition	0.087	0.059	0.189	.144	
	Colour naming speed	-0.011	0.046	-0.029	.812	
	Shifting	0.155	0.041	0.376	<.001	
	Working memory	0.009	0.013	0.084	.467	
e) Modern languages	Shifting	0.108	0.051	0.256	<.05	0.240
	Working memory	0.037	0.016	0.317	<.05	
	Short-term memory	0.015	0.014	0.128	.292	
f) Arts	SIMD	0.130	0.087	0.265	.137	0.290
	Inhibition	0.080	0.077	0.228	.299	
	Working memory	0.022	0.022	0.188	.324	

Attainment in English was regressed on all three demographic variables, the three EF components and the two non-EF processes, which all together explained approximately 43% of the variance in pupils' attainment. Among these variables, SIMD was the most significant predictor of English attainment (β=.332, p<.001) followed by gender, condition status and working memory and finally shifting with standardized regression coefficients around β=0.2. Inhibition and the two non-EF processes were not significant predictors of English attainment (standardized coefficients ranging from β=-.006 to β=.096, all p_s>.05).

All three EF components and the two non-EF processes were also included as predictors in the models for maths and science. These two models, however, each included a different demographic variable as the final predictor, namely SIMD for maths and the condition status variable for science. Overall, 48% of the variance in pupils' maths attainment and 41% of the variance in science attainment was explained by the models. The EF components of shifting and working memory along with the relevant demographic variable in each model were found to be the most significant predictors of attainment in maths and science. Short-term memory was found to be a significant predictor of science (β=.189, p<.05) but not maths (β=.133, p>.05), whereas inhibition and colour-naming speed were not found to be significant predictors in either model.

Pupils' attainment in the curriculum area of social studies was regressed on all three EF components, colour naming speed and SIMD, which together explained 30% of the variance in attainment. Despite being significantly correlated to social studies attainment, the condition status variable could not be included in the model because it caused the model to not converge. Among the variables included in the model, only SIMD and shifting were individually significant predictors (β=.240, p<.05 and β=.376, p<.001 respectively). Although inhibition was not shown to be a significant predictor, it had a relatively large regression coefficient (β=.189, p>.05) compared to working memory (β=.084) and colour-naming speed (β=-.029).

The next two models included three predictors each and explained 24% of the variance in pupils' attainment in modern languages and 29% of the variance in their attainment in arts. In the case of modern languages, pupils' attainment was significantly predicted by the EF components of shifting and working memory (β=.256 and β=.317 respectively, both p_s<.05 whereas the effect of short-term memory was smaller and non-significant (β=.128, p>.05). In regard to pupils' attainment in arts, SIMD appeared to have the largest effect (β=.265) followed by inhibition (β=.228) and lastly working memory (β=.188), but none of these effects reached significance[11].

The VIFs for each predictor within all of the models mentioned above were inspected to check for multicollinearity, but they were all found to be smaller than 2.50 (VIF range was 1.01-2.24 for English; 1.11-2.05 for maths; 1.06-2.18 for science; 1.03-2.06 for social studies; 1.02-1.56 for modern languages and 1.29-1.59 for arts).

For the S5 pupils, the correlations between their normative scores on the cognitive measures and their attainment in English, maths and science are shown in Table 4.9. As can be seen in Table 4.9, inhibition was significantly correlated to attainment in all curriculum areas, although the correlations were stronger in the case of maths and science (r=.57, p<.001 and r=.56, p<.01 respectively) compared to English (r=.34, p<.01). The shifting component was found to be significantly albeit weakly associated with maths attainment (r=.33, p<.01), while working memory was not significantly associated with attainment in any of the curriculum areas (correlation coefficients ranging from r=.18 to r=.30, all p_s>.05).

Once again, the non–EF processes of colour naming speed and short-term memory were strongly correlated to inhibition and working memory (r=.73 and r=.54 respectively, p_s<.001) and were also significantly associated with attainment in certain curriculum areas. Interestingly, short-term memory, was more strongly correlated to attainment in English and maths (r=.25 and r=.32 respectively, both p_s<.05) than the corresponding EF component of working memory (r=.19 and r=.18 respectively, both p_s>.05). In fact, the correlations between short-term memory and English and maths attainment were significant and, therefore, it was subsequently included as a predictor in the relevant regression models, whereas working memory was not.

[11] For the regression models predicting fourth-year pupils' attainment in modern languages and arts, which were based on relatively small sample sizes (considering the amount of predictors included), analyses of covariance were also carried out to explore whether pupils who completed different levels of qualifications differ in regard to their EFs. The results of the ANCOVAS corresponding to attainment in modern languages confirmed that pupils with different level qualifications differ in regard to their working memory, F(3,68)=5.07, p<.01; however, no significant differences were found in their shifting performance, F(3,68)=2.27, p=.088. For arts, the ANCOVAs showed that there were significant differences among pupils with different levels of attainment in regard to both their inhibition, F(2,38)=4.61, p<.05 and working memory F(2,38)=4.53, p<.05.

Table 4.9. Correlations among fifth-year pupils' performance on the cognitive measures and their attainment in English, maths and science.

	1.	2.	3.	4.	5.	6.	7.	8.
1. Inhibition	-							
2. Colour naming speed	.73***[a]	-						
3. Shifting	.32**[a]	.37**[a]	-					
4. Working memory	.31**[a]	.26*[a]	.26*[a]	-				
5. Short-term memory	.28*[a]	.23[a]	.26*[a]	.54***[a]	-			
6. English	.34**[b]	.22[b]	.08[b]	.19[b]	.25*[b]	-		
7. Maths	.57***[b]	.33*[b]	.33**[b]	.18[b]	.32*[b]	.65***[c]	-	
8. Science	.56**[b]	.42*[b]	.18[b]	.30[b]	.30[b]	.73***[c]	.78***[c]	-

[a] based on the whole sample of 99 pupils

[b] based on the total of pupils with qualifications in each curriculum area; 80 for English, 59 for mathematics and 42 for science

[c] based on samples of pupils with qualifications on each of the two curriculum areas.

*p<.05, **p<.01, ***p<.00

As far as the demographic variables are concerned, pupil's gender was only significantly associated with attainment in English ($r=-.33$, $p<.01$), in which females outperformed males, while SIMD was significantly related to attainment in English ($r=.50$, $p=.001$) and maths ($r=.40$, $p<.05$). Therefore, gender and SIMD were included in the relevant regression models. In contrast, the binary variable denoting pupils' condition status was not included in any of the regression models since it was not significantly correlated to attainment in either of the three curriculum areas (correlation coefficients ranging from $r=-.08$ to $r=-.12$, all $p_s>.05$).

The regression models that were developed to predict S5 pupils' attainment in English, maths and science with the relevant demographic and cognitive measures as predictors are presented below in Table 4.10.

Table 4.10. Regression models predicting fifth-year pupils' educational attainment; information on the individual predictors and overall variance explained for attainment in a) English, b) maths and c) science.

		B	SE(B)	β	p	R^2
a) English	Gender	-0.667	0.185	-0.333	<.001	0.422
	SIMD	0.203	0.047	0.421	<.001	
	Inhibition	0.083	0.033	0.222	<.05	
	Short-term memory	0.010	0.008	0.099	.237	
b) Maths	SIMD	0.077	0.079	0.152	.329	0.424
	Inhibition	0.235	0.079	0.612	<.01	
	Colour naming speed	-0.088	0.092	-0.240	.342	
	Shifting	0.090	0.061	0.181	.141	
	Short-term memory	0.011	0.014	0.111	.430	
c) Science	Inhibition	0.297	0.118	0.592	<.05	0.317
	Colour naming speed	-0.017	0.103	-0.039	.867	

Overall, 42% of the variance in English and maths attainment and 32% of the variance in science attainment was explained by the predictors included in the respective models. The inhibition component was a significant predictor in all three models. In fact, inhibition was the only significant predictor in the maths and science models, with relatively much larger standardized regression coefficients (β=.612, $p<.01$ and β=.592, $p<.05$ respectively) than the other variables included in the models. In the case of the English attainment model, pupils' gender and SIMD were also significant predictors (β=-.333 and β=.421 respectively, both $p_s<.001$). Tests of multicollinearity for these models were satisfactory with all VIFs being less than 3.00 (VIF range was 1.01-1.13 for English; 1.15-2.59 for maths and all VIFs=2.43 for science).

4.3.3 Discussion

This section of the chapter (section 4.3) covered the relationship between EFs and educational attainment for the older pupils of the overall sample i.e. the fourth- and fifth-year pupils. For these pupils, the level of qualifications they achieved by the end of their fourth or fifth year respectively served as indication of their educational attainment. The three EF components of inhibition, shifting and working memory were examined in relation to attainment in six different curriculum areas among the S4 pupils (English, maths, science, social studies, modern languages and arts) and three curriculum areas in the case of the S5 pupils (English, maths and science). For the S5 pupils, attainment in social studies, modern languages and arts was not examined, as the number of pupils within the sample with qualifications in these curriculum areas was prohibitively small. Furthermore, for some of the curriculum areas that were considered, i.e., maths and science in S5 and modern languages and arts in S4, the number of pupils with qualifications was relatively small considering the type of analyses carried out, therefore, caution should be applied when examining and interpreting the results of the analyses corresponding to attainment in these areas.

When the relevant EF components, non-EF processes and demographic variables were considered together as predictors of attainment in the regression analyses, SIMD was once again found to be a significant predictor of attainment in the majority of models it was included in; especially among the S4 pupils. Furthermore, pupils' gender had a significant independent effect on both S4 and S5 pupils' English attainment, with girls outperforming boys in all cases. Lastly, the binary variable accounting for differences between pupils with or without conditions was found to independently predict science attainment among the S4 pupils but had no effect on S5 pupils' attainment.

The differences between the S4 and S5 pupils were more prominent as far as the effects of the EF components on attainment are concerned. Among the S4 pupils, shifting and working memory were both significant independent predictors of attainment in all curriculum areas apart from social studies and arts. Among the two, working memory had the strongest effect on attainment in English, science and modern languages, whereas shifting was the stronger predictor of maths attainment and the only significant EF predictor of attainment in social studies. The picture was very different as far as attainment in arts was concerned, which was found to be most strongly influenced by inhibition and secondarily working memory, although neither of the effects reached significance, possibly due to the small sample size.

From the above, we can conclude that, in accordance to previous studies (e.g., Latzman et al., 2010; St Clair-Thompson & Gathercole, 2006), the current results indicate towards slightly differential contributions of the three EF components to attainment in various subject areas within the current sample of S4 year pupils. However, the patterns of associations observed in this study do not correspond entirely to those of previous studies. For example, whereas inhibition has previously been consistently found to be a significant predictor of adolescents' attainment in various subjects and particularly maths and science (Cragg et al., 2017; Latzman et al., 2010; St Clair-Thompson & Gathercole, 2006), in the current study, its effect is negligible in all subjects apart from art. Furthermore, the only other study that has investigated the role of the three EFs in social studies found that working memory, not shifting, was the only significant EF predictor of attainment in this curriculum area (Latzman et al., 2010).

Among the S5 pupils, inhibition was the only EF component with a significant independent effect on attainment and this finding was consistent across all the curriculum areas examined (English, maths and science). Unfortunately, there are not many other studies that have examined the relative contribution of inhibition, shifting and working memory to attainment during the later stages of adolescence (beyond 15-16 years of age) and consequently direct comparisons to previous findings cannot be made. Compared to the results of studies focusing on younger age groups, the current results correspond to those of some, but not all studies. For example, Latzman et al. (2010) and St Clair-Thompson and Gathercole (2006) have also found independent associations between inhibition and attainment in maths and science and Berninger et al. (2017) found that inhibition uniquely contributed to reading and oral language in adolescents up to 15 years old. Furthermore, the strong relationship between inhibition and maths attainment has also been highlighted by two studies (Cragg et al., 2017; Gilmore et al., 2015) that found a significant effect of inhibition on different aspects of mathematics in a sample of adolescents up to 14 years of age as well as a sample of young adults, that is the years leading up to and straight after the age group examined in the current study.

On the other hand, in a sample of 12-13 year old pupils from Scottish secondary schools, working memory and not inhibition was found to independently predict performance on an assessment of conceptual understanding in biology (Rhodes et al., 2014) and chemistry (Rhodes et al., 2016). These findings appear slightly counterintuitive, considering that they referred to a sample which, similarly to my sample, comprised of pupils from Scottish schools. Apart from the different age group examined, the contradicting results of Rhodes et al. (2014, 2016) may be due to the different attainment outcomes they focused on, i.e., performance on novel assessments developed to measure factual knowledge and conceptual understanding in regard to a particular topic of biology or chemistry. They did also examine the grades pupils achieved on a more general assessment conducted as part of the normal science curriculum and although they found significant correlations with the EF component of working memory, this effect was no longer significant after controlling for age and vocabulary ability.

4.4. General discussion

This study set out to investigate the potential relationship between three different EF components and attainment in a variety of subjects among adolescents aged 14-18 years. Analyses were carried out separately for adolescents in the third, fourth and fifth year of secondary school, allowing the investigation of age-related differences in the relationship between EFs and attainment during the later stages of adolescence, which have been the focus of relatively few studies in the past. Furthermore, these ages were of particular interest because they provided the opportunity to track any disparities in the relations of EFs with attainment across the transition from the broad general education to the senior phase of education within the Scottish curriculum. Finally, another important aspect of the study was that it investigated the role of the EF components in predicting attainment over many different subject areas - including the less studied areas of science, social studies, modern languages and arts- whilst also controlling for the effects of relevant lower-order non-EF processes and demographic variables.

Overall, the results indicated that EFs have a significant influence on adolescents' attainment as the regression models showed that, within each of the three age groups, at least one of the three EF components independently affected attainment beyond the effects of the non-EF processes and demographic variables considered. Furthermore, this was the case for attainment in all the curriculum areas examined in the study. Thus, in addition to confirming the well documented effect of EFs on adolescents' English-language and maths attainment (Aran-Filippetti & Richaud, 2015; Berninger et al., 2010; Best et al., 2011; Gathercole et al., 2004; Latzman et al., 2010; Lehto, 1995), this study provided further evidence of a significant role of EF components in science, social studies, modern languages and arts attainment, although the sample sizes in the analyses for some of these curriculum areas, (particularly modern languages and arts) were relatively small for definitive conclusions to be drawn. For those cases where the sample sizes may have been an issue, additional analyses of covariance were carried out, which did not always produce the same results as the main regression analyses i.e., in the case of modern languages in third year (see footnote on page 105) and modern languages as well as arts in fourth year (see footnote on page 119). Therefore, particularly the findings concerning EFs in relation to attainment in modern languages and arts appear to have been influenced by the particular analyses undertaken in this thesis.

Interestingly, the EF component with the strongest effect on attainment was shown to change not as a function of curriculum area, but of the age group under examination. More specifically, within the sample of third-year pupils, shifting was the only significant EF predictor of attainment, then, within the sample of fourth-year pupils, both shifting and working memory were found to have significant effects and, finally, among the fifth-year pupils, it was inhibition, alone, that had a significant effect on attainment. With few exceptions, these trends were consistent across the curriculum areas examined within each age group. The results are therefore indicative of age-related differences in the relative contributions of inhibition, shifting and working memory to attainment during the latter stages of adolescence.

Among the three EF components, shifting appears to have a strong consistent effect on adolescents' attainment, as it independently predicted attainment in the two younger samples of the study, but after the age of 16, the results show a shift to inhibition as the single strongest EF predictor of attainment. Potentially, the replacement of shifting by inhibition as the most important determinant of adolescents' attainment may result from the fact that following the end of third year, which marks the end of the broad general education phase, pupils begin to gradually specialise in particular disciplines. More specifically, in the third year of secondary school pupils are still taught and assessed on a more or less fixed set of subjects, which vary substantially, i.e., apart from the main subjects of English and Mathematics adolescents are taught subjects relating to science, arts, religious/moral education, physical education etc. Under these circumstances, pupils' ability to shift from one subject to another may be crucial for them to handle the different bodies of information and skills that are relevant to each subject, which would explain the fact that shifting was found to be the most significant EF determinant of attainment in these ages.

On the other hand, throughout the fourth and fifth years of secondary school, pupils gradually specialise in the particular disciplines that interest them and subsequently the qualifications they are assessed on cluster around particular curriculum areas i.e., science or social studies. As a result, pupils have to handle fewer and less dissimilar bodies of information, therefore, the pivotal role of shifting in determining pupils' attainment may gradually waver. Finally, the significance of inhibition as the sole EF predictor of pupils' attainment in their fifth year may be understood when considering the numerous concerns pupils have in their final years of secondary school, when they are burdened with the stress of having to make important decisions regarding their future and working towards qualifications that may impact their future prospects. Pupils' ability to inhibit their stress and concerns may therefore, be of critical importance when completing their qualifications, which could explain why inhibition was the only EF component with a significant effect on pupils' performance on these qualifications. However, further research is needed in order to confirm these claims, which are fairly plausible but remain to a large extent speculative. Ideally, future studies would have a longitudinal design, which would allow tracking changes in the relative contributions the three EF components make to adolescents' educational attainment and should include measures of pupils' subject specialisation and/or their anxiety levels in order to test the propositions mentioned above.

Beyond the effect of the EF components, the results indicated that SIMD, which served as an index of SES, had a significant effect on pupils' attainment. Pupils from families with higher SES achieved higher levels of educational attainment than their less affluent counterparts and this finding was relatively consistent across the curriculum areas and the three different age groups examined. These results complement findings from the Scottish Survey of Literacy and Numeracy (SSLN)- an annual sample survey which monitored national performance in literacy and numeracy (in alternate years) for pupils in the fourth and seventh years of primary school (P4 and P7) and the second year of secondary school (S2). More specifically, the results of the latest series of the SSLN, based on data from 2015 for numeracy (Scottish Government, 2016) and 2016 for literacy[12] (Scottish Government, 2017), showed that pupils from the least deprived areas within Scotland consistently outperformed the pupils from the most deprived areas in both literacy and numeracy at all stages (P4, P7 and S2). Therefore, according to the results of the SSLN, a socioeconomic performance gap in literacy and numeracy is present among children as young as 7-8 years old (P4) and this gap continues to exist up to the age of 12-13 years old (S2). The results of the present study further complete this picture by confirming that SIMD (as an indicator of SES) continues to be an important determinant of pupils' attainment during the second half of secondary school and that this effect permeates attainment in a variety of subject areas.

However, it should be noted, that in the current study there were occasions in which SIMD was not found to independently predict attainment i.e., in the curriculum areas of modern languages and science and also in maths among the fifth-year pupils. The insignificance of SIMD as an independent predictor of attainment in modern languages and science may stem from the fact that there was less SIMD variability in the samples used for the relevant analyses, since the pupils from the school

[12] The SSLN has since been discontinued by the Scottish Government.

representing children from the lowest socioeconomic background did not study for or complete qualifications in any modern languages or science subjects. Consequently, the range of SIMD examined in the case of these subject areas was more restricted and did not include pupils coming from the most deprived backgrounds, which may have resulted in less pronounced difference in attainment as a function of SIMD. This highlights the importance of examining a wide range of SES in studies investigating EFs and educational attainment. In fact, in their review on SES and the developing brain, Hackman and Farah (2008) comment on this subject, by saying that the restricted range of SES that most research laboratories have easy access to has constituted a hindrance to revealing the vital role SES plays on brain development and function.

Apart from modern languages and science, all other analyses were carried out on samples with an appropriately wide socioeconomic range. Overall, the objective was to recruit participants from schools that served children from varying socioeconomic backgrounds and this was a particular strength of the study along with the variety of subjects/curriculum areas examined and the extra non-EF factors that were controlled for. However, this does not mean that this study was without limitations. In general, the differences among the samples used for analyses of attainment in the various curriculum areas, especially as far as sample size is concerned, were not ideal. In addition, as discussed above, this study was not longitudinal, hence the current results only postulate age-related changes in the relations between EFs and attainment during late adolescence. Thirdly, only non-EF processes implicated in the inhibition and working memory but not the shifting task were controlled for, which may have partially caused the stronger associations of shifting with attainment; however, the fact that inhibition and working memory were found in certain models to significantly affect attainment beyond the effect of shifting even though the relative non-EF processes were also included as predictors, contradicts any belief that not including a control for shifting had a serious effect on our results. Finally, the current study considered attainment across more general curriculum areas rather than in each specific subject, which may have masked more discrete associations between each EF component and attainment in particular subjects.

It is worth noting that some of the aforementioned limitations of this study were unavoidable since their occurrence could not have been prevented. For example, examining attainment in general curriculum areas instead of specific subjects was a result of the small number of pupils within the sample that had attended/earned qualifications in certain subjects, which prohibited analyses being carried out on attainment in each subject alone. Overall, to my knowledge, this is the only study that attempted to examine all three EF components – inhibition, shifting and working memory - in relation to older adolescents' attainment across so many subject (curriculum) areas, while also controlling for relative demographic variables and non-EF processes. Although, there are limitations to the current study, the results confirm the important role of EFs as predictors of attainment among adolescents belonging to three different age groups, while also showing that the significant link between EFs and attainment is evident across many different curriculum areas, even in the case of subjects that have not been previously examined.

Chapter 5: Exploring the potential links between adolescents' EFs and prospects in meeting the academic requirements for entry into University.

5.1. Introduction

The previous chapter focused on the relationship between EFs and educational attainment during the period of adolescence, with a particular focus on the latter stages of adolescence when individuals are faced with increasing academic demands at school. However, another reason for which late adolescence constitutes a critical period in individuals' lives and a particularly interesting period to research is that typically, during this time, individuals are called to make important choices regarding their future. For many, late adolescence is earmarked by working towards the long-term goal of getting accepted into post-secondary/higher education. Naturally, attaining such a major goal may draw upon individuals' EF abilities, since EFs are commonly accepted to be essential for the anticipation and achievement of long-term goals (Dawson & Guare, 2018; Gioia & Isquith, 2004; Luria, 1966; Welsh & Pennington, 1988). However, the possibility of a connection between individuals' EFs and their prospects for entering higher education has been largely overlooked in the existing literature.

In most educational systems, access to higher education is dependent on pupils' performance on exams/assessments they complete in their senior years of secondary school. More specifically, the academic requirements for entry into a higher education course/programme typically involve achieving a minimum overall grade or amount of points (most often in a combination of subjects relevant to the programme) on school-leaving exams or assessments. In the UK, for example, the UCAS (Universities and Colleges Admissions Service) Tariff is a framework for allocating points to post-16 (school-leaving age) qualifications and these points constitute the basis on which many universities, colleges and conservatoires make decisions about entry to particular courses/programmes. The UCAS Tariff was developed to provide a broad metric for many types of qualifications taken across the UK that count towards entry into higher education, such as the A level and AS qualifications, the Higher and Advanced Higher qualifications and many others. Typically, these types of qualifications are awarded on the basis of completing standardised, curriculum-based assessments designed to measure academic achievement in subjects attended during the final years of mandatory schooling. The number of points awarded to pupils is dependent on the particular level as well as the grade they achieve on the relevant assessments, with different conversion rates applying for the different qualification types on the UCAS Tariff. Therefore, within the UK, acquiring the necessary points to meet the academic requirements for entry into a higher education course/programme is dependent on adolescents' performance on the standardised, curriculum-based, school-leaving assessments they complete.

Certain studies exploring the relationship between EFs and attainment in secondary school have focused on adolescents' performance on standardised, curriculum-based assessments; for example, St Clair-Thompson and Gathercole (2006) showed that the EF components of working memory and inhibition were differentially associated with 11-12 year olds' performance on standardised summative tests of English, mathematics and science used within English schools. Latzman et al. (2010) also demonstrated differential relations between 11-16 year olds' inhibition, shifting and working memory and their performance on standardised tests used across the United States to assess academic achievement in a wide range of subject areas. Furthermore, the previous study conducted as part of this PhD project (see Chapter 4 of this thesis) provided further evidence of an association between EFs and performance on standardised school assessments within a sample of older adolescents in their senior phase of secondary school in Scotland.

From all the above, it is indicated that adolescents' EFs are associated with their performance on the type of assessments that lead to obtaining the qualifications required for entry into higher education. Nevertheless, the relationship between EFs and performance on such assessments has not yet been researched within the context of meeting the academic requirements for entry into higher education. This omission seems particularly counterintuitive in the light of further evidence from different studies indicating that EFs are also significantly related with students' academic performance within higher education settings i.e., University or College (Gropper & Tannock, 2009; Knouse, Feldman, & Blevins, 2014; Kirby, Winston, & Santiesteban, 2005). Therefore, although EFs have been associated with individuals' educational attainment up to the point before entry into higher education and appear to continue to predict individuals' academic achievement once in higher education, they have not yet been explored in relation to individuals' prospects (in terms of achieving the necessary grades) of being accepted into higher education courses/programmes.

In an attempt to shed light on the role EFs may play in meeting the academic requirements for entry into higher education, this study investigated whether adolescents' EFs predict their performance on qualifications that count towards points for entry into University. For pupils in Scottish schools, the main qualifications recognised by Universities for entry into undergraduate courses are Higher and Advanced Higher National Qualifications. Pupils can start working towards Higher qualifications in the fifth year of secondary school (S5) with the potential of moving into University at the end of the same year, if they manage to achieve all the qualifications necessary for entry into the programme of their choice. Alternatively, they can progress into sixth year (S6) and continue working towards further Highers as well as Advanced Highers in order to achieve the grades they are aiming for. In any case, examining pupils' grades on Higher qualifications they sat during S5 can provide an initial insight into their prospects (in terms of obtaining the necessary grades) of getting accepted into higher education courses/programmes. Therefore, as the overall dataset of this PhD project included data from S5 but not S6 pupils, performance on Highers achieved in S5 was considered as a proxy of pupils' potential to meet the academic requirements for entry into University. More specifically, the UCAS Tariff framework discussed above was used to transform pupils' performance on the Higher qualifications they completed in S5 into a numerical value/number of points, which was then examined in relation to their performance on tasks measuring three EF components - inhibition, shifting and working memory.

To my knowledge, this was the first study to research whether EFs can predict individuals' success in achieving the necessary grades for getting accepted into University; as mentioned above, previous literature has only ever investigated the relationship between EFs and attainment in school or at University. Since the measure used to assess pupils' potential in obtaining the grades necessary for entry into University derived from pupils' performance on standardised, school exams/assessments, which has previously been found to be associated with EFs (Gathercole, Brown, & Pickering, 2003; St Clair-Thompson & Gathercole, 2006), it is reasonable to assume that adolescents' EFs may be related to their prospects in meeting the academic requirements for entry into University. However, no further specific expectations can be drawn since there is no previous literature on this matter, to use as a template.

5.2. Methods

5.2.1. Participants

Similarly to the previous studies discussed in this thesis, the sample was derived from the total of 347 adolescents that were recruited for the project overall. Because this particular study concerned performance on qualifications necessary for entry into University, only the oldest adolescents, who were in their fifth year of secondary school, could be considered. As mentioned in the previous chapter (section 4.3.1), the overall sample included 99 fifth year pupils with available attainment data, but 13 of these pupils had not studied towards Higher qualifications and thus had no data that could be used for the purposes of this study. Consequently, the sample considered for this study consisted of the remaining 86 pupils (M_{age}=17.10, SD=0.33 years; 42 girls) that sat at least one Higher exam during their fifth year. At the time that the pupils were tested on the EF tasks, their ages ranged from 16.50 to 17.83 years and the mean time lag between the assessment of their EFs and their fifth year exams was approximately 3.7 months (the exact mean time lag cannot be precisely calculated due to the fact that the dates and number of exams taken differ for each pupil). The majority of pupils were British (78) and most were right handed (72), but ethnicity and handedness data were not available for two pupils.

5.2.2. Cognitive measures

Inhibition - Pupils' normative scores on the third condition of the Colour Word Interference (CWI) task from the D-KEFS were utilised as measures of their inhibition. In order to control for lower-order, non-executive processes implicated in performing this task, the normative scores from the first condition of the CWI were also utilised. The normative scores corresponding to the time needed for completing each condition were used in the analyses (see pages 60-61 for more information on the D-KEFS CWI task).

Shifting - The Free Sorting condition of the Sorting test from the D-KEFS battery was used to measure pupils' shifting ability. More specifically, two different scores from this task were considered in the analysis: the normative scores representing the number of correct sorts generated and the normative scores calculated from pupils' descriptions of the sorts (see pages 61-63 for more information on the D-KEFS Sorting test).

Working memory - The Recall of Digits Backward task from the BAS II battery was used to measure working memory. In addition, the Recall of Digits Forward task from the BAS II battery was used as a control condition to assess pupils' baseline levels of short-term memory (see pages 63-64 for more information on the BAS II Recall of Digits tasks).

5.2.3. Performance on Highers exams

Pupils' grades on qualifications they achieved during their fifth year were provided by their schools. In the fifth year of secondary school, there is no predetermined set of subjects or a collective level at which pupils study. Instead, each pupil works towards the National Qualification (NQ) that is most appropriate for them in each of the subjects they have chosen to study. Therefore, the dataset consisted of pupils' grades on 29 different subjects and at many different levels of qualifications ranging from National 3 to Higher NQs. In this particular study, only the grades for Highers were considered as these constitute the criteria on which individuals are offered places for undergraduate studies. All the grades corresponding to qualifications at lower levels were, therefore, disregarded. As a result, the final dataset included data on the following 23 subjects: English, Maths, French, Biology, Chemistry, Physics, History, Geography, Modern Studies, Music, Art & Design, Drama, Psychology, Sociology, Computing Science, Business, Design & Manufacture, Media, Graphics, Religious, Moral and Philosophical studies, Health and Food Technology and Physical Education.

Qualifications at Higher level are graded A, B, C, D or 'No Award' based on pupils' performance on the final assessment, which consists of a question paper (exam) and/or coursework (assignments, portfolios, practical activities etc.). For entry into University, pupils are expected to have achieved a specific number of Highers or Advanced Highers at the appropriate level (most frequently A and B) on a variety of subjects relevant to the programme of study, but the specific requirements can vary slightly among different Universities. Many Universities apply the UCAS Tariff when making offers to applicants. As previously mentioned, the UCAS Tariff provides a national framework for allocating points to post-16 qualifications used across the UK, making it simpler for institutions to compare applicants from all over the UK and offer them places in undergraduate courses on the basis of the total UCAS points acquired.

In order for the results of this study to be easier to interpret across the whole of the UK, pupils' Higher grades were converted into UCAS points according to the new Tariff set in May 2017 (for students starting their degrees in September 2017). The conversion rates for Higher qualifications according to the May 2017 Tariff are shown in Table 5.1. In the next step, the UCAS points pupils had earned across the different subjects on which they achieved Highers were summed. This yielded an individual 'UCAS score' for each pupil, which reflected both the number of Highers achieved by the pupil as well as the corresponding grades received on those qualifications. It is important to note that no UCAS points were awarded in cases where pupils did not achieve their Higher qualifications i.e., received a 'No Award' grade. Therefore, it is possible for pupils to have an overall UCAS score of 0 if they failed all of the Higher qualifications they set out to complete.

Table 5.1. Conversion rates of Scottish Higher grades to UCAS points for applications to courses starting in September 2017.

Qualification and grade	UCAS Tariff (May 2017)
Scottish Higher grade A	33 points
Scottish Higher grade B	27 points
Scottish Higher grade C	21 points
Scottish Higher grade D	15 points

5.2.4. Covariates

Three covariates were included in the analyses. As far as demographic variables are concerned, pupils' gender and their families' SES were controlled for. As with previous studies, SES was indicated by SIMD, which ranged from 116 to 6807 (M=4452.05, SD=1977.8) in the sample of this study. The binary variable that represented pupils' condition status was also included in the analyses in an attempt to partially control for any effects certain conditions may have on the results. Among the 86 pupils who comprised the sample for this study, 13 pupils were reported as having a condition that may affect their performance on the EF tasks.

5.2.5. Statistical analyses

The first step was to examine the zero-order correlations between pupils' computed UCAS score and their normative scores on each of the EF measures. Zero-order correlations between pupils' computed UCAS score and their gender, SIMD and condition status were also calculated. After examining the zero-order correlations, the relevant EF scores and covariates were inserted in a multiple regression model predicting pupils' UCAS score.

All analyses were carried out in R studio, using the lavaan package for Latent Variable Analysis and the Full Information Maximum Likelihood (FIML) method in order to deal with missing data. The FIML method has been previously discussed in detail in Chapter 3 (see pages 78-79).

5.3. Results

The main variables of interest for this study were the normative scores from the CWI, Sorting test and Digit recall tasks, which were used as measures of pupils' EF abilities, and the computed UCAS score variable, which acted as a proxy of pupils' prospects in achieving the academic requirements for entry into University. The number of Higher qualifications achieved by the S5 pupils in the sample ranged from 0 to 6 and as a result the computed UCAS score, which corresponded to the sum of UCAS points earned on all Highers each pupil achieved, ranged from 0 to 198 points. The remaining descriptive statistics of the variables of interest are shown in Table 5.2. For all variables, higher values indicate better performance.

Table 5.2. Descriptive statistics for the main variables of interest in this study.

	N	M	SD	Range	Skewness	Kurtosis
Inhibition, CWI INH	86	11.48	2.38	4-17	-0.4	0.18
Colour naming speed, CWI CN	85	10.05	2.3	2-13	-0.8	0.74
Shifting, ST correct sorts	85	8.12	2.01	4-13	0.2	-0.17
Shifting, ST description	85	7.42	2.22	3-13	0.06	-0.54
Working memory, RDB	84	50.23	9.63	27-72	-0.12	-0.51
Short-term memory, RDF	86	52.47	9.93	34-77	0.54	-0.34
UCAS score	86	87.87	54.46	0-198	-0.04	-1.25

Note.
CWI INH: Colour Word Interference Inhibition condition, CWI CN: Colour Word Interference Colour Naming condition, ST: Sorting test, RDB: Recall of Digits Backward, RDF: Recall of Digits Forwards

Zero-order correlations between the cognitive measures, UCAS score and SIMD are presented in Table 5.3. Among the cognitive measures, the three EF components were weakly associated with each other (correlation coefficients ranging from .23 to .31, all p_S<.05), while the two non-EF processes were moderately to strongly correlated to the relative EF components (r=.72, p<.001 between colour naming speed and inhibition and r=.53, p<.001 between short-term and working memory). No significant correlations were found amongst SIMD and any of the cognitive measures (correlation coefficients ranging from .03 to .18, all p_s>.05), but there was a significant correlation between SIMD and pupils' UCAS score (r=.39, p<.001). Finally, pupils' UCAS score was weakly but significantly correlated to their inhibition and colour naming ability (r= 30, p<.01 and r=22, p<.05 respectively) but its correlation to shifting and working memory was negligible (correlations coefficients ranging from .09 to .17, all p_s>.05).

Table 5.3: Zero-order correlations between variables representing pupils' cognitive performance, SES and UCAS score.

	1.	2.	3.	4.	5.	6.	7.
1. Inhibition	-						
2. Colour naming speed	.72***	-					
3. Shifting, correct sorts	.29*	.30**	-				
4. Shifting, description	.31**	.32**	.93***	-			
5. Working memory	.29*	.25*	.23*	.24*	-		
6. Short-term memory	.17	.12	.16	.16	.53***	-	
7. SIMD	.12	.03	.15	.18	.12	.08	-
8. UCAS score	.30**	.22*	.09	.09	.17	.16	.39***

*p<.05; **p<.01; ***p<.001

Because there was virtually no correlation between either measure of pupils' shifting ability and their UCAS score (r=.09, p>.05 for both correct sorts and description scores), shifting was not included in the regression model as a predictor of pupils' UCAS score. Furthermore, pupils' gender and their condition status were also excluded from the regression model, since the point biserial correlations between each of these variables and pupils' UCAS score were very low and non-significant (r_{pb}=-.11, p>.05 for gender and r_{pb}=-.05, p>.05 for condition status).

In the final regression model, the UCAS score was regressed on the EF components of inhibition and working memory, the respective non-EF processes (colour naming speed and short-term memory) and SIMD. The full model is presented in Table 5.4. The whole model explained approximately 23% of the variance in pupils' UCAS score. However, the individual beta coefficient estimates and corresponding p values show that pupils' SIMD was the only significant predictor (β=.354, p<.001) of their UCAS score amongst the five variables included in the model.

Table 5.4. Regression coefficients and explained variance for the multiple regression model predicting pupils' UCAS score.

		B	SE(B)	β	p	R^2
UCAS score	Inhibition	4.937	3.029	0.215	>.05	0.227
	Colour naming speed	0.995	3.057	0.042	>.05	
	Working memory	-0.003	0.637	-0.001	>.05	
	Short-term memory	0.532	0.614	0.097	>.05	
	SIMD	0.975	0.214	0.354	<.001	

*p<.05; **p<.01; ***p<.001

It should be noted that an additional regression model that only included SIMD, inhibition and colour-naming speed as predictors of pupils' UCAS score was also tested, in order to examine whether taking the working and short-term memory components out of the model would affect the results. The results were very similar to the first model: the total amount of variance explained decreased minimally to 22% and once again SIMD was the only significant predictor (β=.359, p<.001), while the effects of inhibition and colour naming speed were not statistically significant (β=.230 and β=.043 respectively, both p_s>.05).

5.4. Discussion

The purpose of this study was to explore the potential link between adolescents' EFs and their prospects in achieving the academic requirements for entry into University; a topic that has been largely overlooked in EF research. In this study, UCAS points earned by pupils on the Higher qualifications they achieved at the end of their fifth year constituted a proxy of pupils' success in getting accepted into University. A UCAS score was devised for each pupil by converting their Higher qualification grades into UCAS points, in accordance to the new 2017 UCAS Tariff, and summing these points together. The resulting UCAS score variable was then correlated to and subsequently regressed on pupils' normative scores on cognitive tasks used to assess three components of EF- inhibition, shifting and working memory- and two relevant non-EF processes – colour naming speed and short-term memory capacity.

The highest correlations were found between pupils' UCAS score and their performance on a speeded Stroop-like measure of inhibition and a measure assessing individuals' baseline speed in naming colours. The rest of the correlations between the UCAS score and performance on the other cognitive measures were smaller and non-significant, especially in the case of scores from the shifting measure. As far as the associations with demographic variables are concerned, pupils from families with higher SES, indicated in this study by SIMD, were found to have higher UCAS scores, but no significant differences were observed between male and female pupils, or between typically developing pupils and those with a type of condition that can influence cognitive performance. Follow-up multiple regression analysis showed that, once pupils' SES was controlled for, performance on the cognitive tasks did not significantly predict pupils' UCAS scores, indicating that the EF components measured in this study did not contribute to the prediction of pupils' UCAS score above and beyond SES.

The finding that SES was the strongest predictor of the UCAS score in the regression analyses corroborates the existence of a social gradient in pupils' performance on Highers in S5. More specifically, pupils from less affluent backgrounds were indicated to be further behind in regard to the number and grades of Higher qualifications they achieved in S5, which might place them in a disadvantage as far as their prospects of getting accepted into University are concerned. UCAS statistics have indeed shown that entry rates into University differ significantly between individuals from the most and least disadvantaged areas in all four countries of the UK, with the gap being most prominent at the most selective Universities (UCAS, 2016; 2017). In addition, the latest series of statistics published by the Scottish Government on school leavers' attainment and destinations (Scottish Government, 2018) demonstrated that the percentage of 2016/17 school-leavers achieving certain levels of qualifications and going on to positive follow-up destinations increased as a function of SES (percentage increased as SIMD increased). Furthermore, it was reported that leavers' attainment level was positively associated with their likelihood of going on to positive destinations (Scottish Government, 2018). Considering all the above, the results of the present study may therefore, constitute evidence that (in the case of Scotland) the socioeconomic inequality at the level of University entry might to a certain extent be attributable to the existence of a social gradient in pupils' performance on the qualifications that are necessary for entry into University. Indeed, the existence of such a social gradient has been reported in the past (Sosu & Ellis, 2014), when data corresponding to the years 2007/8 through to 2011/12 indicated that pupils from the most deprived backgrounds earned an average of 300 fewer tariff points on their school leaving qualifications compared to their least derpived counterparts. However, more research boasting longitudinal designs that will follow pupils across their final years in secondary school and into University should be carried out with the aim to pinpoint the current status of this social gradient and track its development in the future.

In regard to the scores on the cognitive measures as predictors of the UCAS score, the regression analysis provides little evidence in support of the initial hypothesis that EFs would at least partially predict pupils' potential to enter University, indicated here by the Higher qualification grades achieved in S5. The hypothesis that pupils' EF abilities would be associated with their performance on Higher qualifications in S5, was partly based on the assumption that EF attributes, such as good planning skills and self-regulatory ability, are essential for pupils' progression throughout S5 when pupils must plan their programme of study and work towards the necessary qualifications in preparation of entering University. It is important to note, however, that planning and self-regulation are often conceptualised as more complex and/or higher level constructs that arise from a combination of multiple EFs and other basic functions (Blair, 2016; Diamond, 2013; Miyake et al., 2000). In comparison to planning and self-regulation, the three EF components measured in this study are rudimentary and circumscribed (Miyake et al., 2000), which might explain why performance on the relevant tasks used in this study was not that strongly correlated with pupils' UCAS score.

In a study by Knouse, Feldman and Blevins (2014) that aimed to examine the relationship between students' attainment in higher education and EF deficits, it was found that difficulties in composite functions, such as planning/time management and organisation/problem solving were consistently more strongly related to students' grade point average (GPA) than deficits in self-restraint, a construct that resembles the more basic inhibition component (Knouse et al., 2014). Although the aforementioned study differs from the present one in that it does not specifically examine EFs in relation to individuals' potential to enter University, it does indicate towards a potential connection between complex, higher-level EFs and educational attainment relevant to University. It may be the case that reaching a major goal such as getting accepted into University, which demands great planning and effort over long periods of time, is not markedly influenced by any one EF acting in isolation, but rather depends on the coordination of a multitude of EFs, which in turn exert control over the relevant lower-order neuropsychological functions. Therefore, performance on more complex tasks tapping into composite EF structures, such as planning and problem-solving, may constitute a better predictor of individuals' capacity to receive the necessary qualifications for getting accepted into University.

Furthermore, it is important to note that, in this study, the UCAS score, which was devised to reflect pupils' achievement on Higher exams they sat in S5, was used to represent individuals' potential to meet the academic requirements for entry into University on the basis that S5 is the earliest point at which pupils can start working towards Higher qualifications and if successful in achieving the required qualifications can leave school at the end of S5 and enter University. However, not all pupils choose to leave for University after the end of S5. Pupils have the option to continue onto S6, where they can study towards additional Highers and/or Advanced Highers. For pupils who intend on moving onto S6, Higher qualifications achieved in S5 only constitute the basal level of qualifications for entry into University, on which they can expand during their sixth year, and thus, the UCAS score (as conceptualised in this study) can only be considered an early indicator of pupils' competence to get accepted into University. The data available for this study, which included exam results of pupils up to S5, dictated that the UCAS score could only be created based on Highers achieved in S5. However, a measure that reflects pupils' performance on Higher and Advanced Higher qualifications achieved up to the end of S6 may constitute a rather more concrete index of pupils' competence to enter University.

Despite its limitations, this study provided some much-needed insight into the role EFs may play in determining individuals' competence for entering University. By calculating the sum of UCAS points earned by each pupil on the Higher qualifications they achieved in S5, a (UCAS) score was created, which was considered to gauge pupils' prospects of being offered a place in University. Significant correlations were found between pupils' UCAS score and at least one of the three EF components examined, namely inhibition. However, this relationship ceased to be significant once individual differences among pupils from different socioeconomic backgrounds were accounted for. The size of this study's sample, which was limited to 86 S5 pupils with data on Higher qualifications, might to a certain extent account for the small effect sizes found and the fact that inhibition did not reach significance as a predictor of UCAS score in the regression model. Therefore, no definitive conclusions can be drawn from the results of this study before they have been replicated in larger samples.

All in all, more research is required in order to establish the existence of a potential relationship between individuals' EFs and their competence to enter University. Yet, the results of this study, which is the first to investigate this matter, provide some useful pointers to guide future research. That is, in addition to using larger sample sizes, future studies may benefit from including measures of more composite and complex EF structures and examining pupils' achievements in S6, where all or at least the majority of pupils will be studying towards Higher and Advanced Higher qualifications, thus providing a more concrete measure of meeting the academic requirements for entry into University.

Chapter 6: Examining non-verbal reasoning and numeracy skills as mediators of the relationship between executive functions and science attainment in a sample of adolescents.

6.1. Introduction

This chapter addresses the final research question of this thesis, which concerned the influence of transferable skills on the relationship between EFs and educational attainment. For this study, the focus was placed on educational attainment in the field of science, since skills important for science have been researched much less than the skills implicated in reading/English and mathematics success (Tolmie et al., 2016). This chapter concerns the study of two transferable skills thought to be essential for science, namely non-verbal reasoning and numeracy, in relation to the three EF components studied throughout this thesis (Miyake et al., 2000) and science attainment.

In terms of reasoning, different types e.g., verbal or non-verbal inductive, deductive, analogical and scientific reasoning have been examined in relation to different EF components. For instance, there exists a number of studies investigating the association between working memory and reasoning, especially inductive reasoning, in children of varying ages. The results of these studies provide evidence of working memory constituting a significant predictor of children's reasoning both concurrently (Fry & Hale, 1996; Kail, 2007; Krumm et al., 2008; Nettelbeck & Burns, 2010) and longitudinally (Kail, 2007). A separate school of study has focused more on inhibition, with a multitude of behavioural but also brain imaging studies, demonstrating that children's and adolescents' performance on deductive reasoning measures in which individuals must resolve some type of conflict (i.e., between prior beliefs/biases and logical considerations) is influenced by their inhibition ability (De Neys & Van Gelder, 2008; Houde & Borst, 2014; Moutier, 2000; Steegen & De Neys, 2012). Other studies have also linked inhibition to the development of different aspects of reasoning, i.e. analogical and scientific reasoning, in children and adolescents (Kwon & Lawson, 2000; Richland & Burchinal, 2013, although see Mayer, Sodian, Koerber, & Schwippert, 2014 where inhibition did not explain unique variance in scientific reasoning). Finally, the shifting component of the tripartite EF model has also been examined in relation to reasoning, albeit in fewer studies compared to working memory and inhibition. Nevertheless, the results of these studies demonstrate that shifting is also strongly associated with reasoning in children (van der Sluis et al., 2007). Taken together, the findings of the above studies indicate that the EF components of inhibition, shifting and working memory are all associated with reasoning skills.

Similar to the research on EFs and reasoning, there is a large literature investigating the link among EFs and skills related to understanding and using numbers in a range of different contexts, otherwise collectively referred to as numeracy. In some studies, EFs are examined in relation to a single type of numeracy skill, for example in studies of pre-schoolers, the focus is usually placed on numerical magnitude skills (Kolkman et al., 2013) or counting skills (Kroesbergen et al., 2009), whereas in studies of primary school aged children, the focus shifts to more complex skills, such as quantitative reasoning and problem solving (Agostino et al., 2010; Lee et al., 2009; Passolunghi & Pazzaglia, 2005). Regardless of the age group and the type of skill examined, however, the results of most of these studies confirm that EFs are significant contributors to numeracy skills, with working memory more often than not being found to have the largest effect when multiple EF components are tested together (Kolkman et al., 2013; Kroesbergen et al., 2009; Lee et al., 2009). Moreover, similar results have been obtained from studies examining the relation between EFs and a general numeracy component, in which working memory or in some cases inhibition was shown to be the strongest predictor of childrens' overall numeracy (Blair & Razza, 2007; Bull et al., 2008; Bull & Scerif, 2001; Lee et al., 2012). The results of the aforementioned studies unanimously demonstrate that EFs influence numeracy, with working memory (and secondarily inhibition) potentially driving this effect.

The studies described above provide considerable evidence of EFs being related to the science-associated skills of reasoning and numeracy. Furthermore, as discussed in the previous chapters of this thesis (see sections 4.1.and 5.1), the existing literature indicates that EFs are important predictors of science attainment (e.g. Latzman et al., 2010; Rhodes et al., 2014, 2016; St Clair-Thompson & Gathercole, 2006). Yet, there has been no systematic attempt to combine the findings of these two lines of research and, consequently, there are very few studies that have examined the intercorrelations of EFs with skills and educational attainment, especially as far as science is concerned.

Despite not directly focusing on science attainment *per se*, one recent study by Stevenson, Bergwerff, Heiser, and Resing (2014), examined working memory and analogical reasoning in relation to children's math and reading achievement. The results of this study confirmed that working memory and dynamic measures of analogical reasoning both uniquely predicted children's concurrent and subsequent (6 months later) achievement in reading and math. Furthermore, the results indicated that, of the two working memory components measured in the study, it was the verbal and not the visual-spatial component that uniquely contributed to children's reading and math achievement. In an earlier study by Krumm et al. (2008), working memory and reasoning were investigated in relation to adolescents' school grades in the areas of languages and science. In this study, when school grades were regressed on working memory and reasoning simultaneously, reasoning was shown to be the most powerful predictor of school grades. More importantly, however, in the next steps of the study the authors went on to test additional regression models in which a hierarchical relationship among the predictors was assumed, i.e. working memory predicted reasoning, which in turn predicted school grades. The models overall had good fit, thus indicating that reasoning might play a mediating role in the relationship of working memory with school grades in language and science subjects. The studies by Stevenson et al. (2014) and Krumm et al. (2008) provide some preliminary evidence on the role transferable skills may play in the relationship between EFs and attainment, however, their scope is relatively limited as they only examine one EF component in relation to one transferable skill at a time. Furthermore, there are generally very few of these types of studies and more evidence is needed in order to reach firm conclusions regarding the mediating role of tranferable skills in the relationsip between EF and attainment.

In this study, I set out to further investigate the potential influence of non-verbal reasoning and numeracy on the relationship between EFs and attainment in science. Motivated by the results of the Krumm et al. study (2008) and seeing as, in the existing literature, EFs are portayed as more domain-general constructs that consequently influence transferable skills (instead of the other way around), this study hypothesized that EFs contribute to non-verbal reasoning and numeracy skills, which in turn contribute to pupils' attainment in science. Thus, the two transferable skills were considered as mediators in the relationship between EFs and science attainment.

As opposed to the majority of the previous literature that examined EFs and transferable skills among young children in preschool and/or primary school, this study focused on adolescents. This is because transferable skills, such as reasoning and numeracy, might be more essential during adolescence, when individuals encounter their most complex learning at school and are challenged with making important life-course decisions (Richland & Burchinal, 2013). Moreover, many of the studies investigating EFs and transferable skills, particularly the ones focusing on reasoning skills, have only examined one EF component at a time without controlling for the contribution of other EF components. In the current study, the three EF components of inhibition, shifting and working memory, were considered together in order to determine their relative effects on non-verbal reasoning, numeracy and science attainment.

One influential study that has examined all three of the tripartite EF model's components in relation to reasoning and attainment in maths and reading was carried out by van der Sluis and her colleagues in 2007. An important aspect of this study was that it controlled for the potential influence of lower-order processes implicated in performing the EF tasks and found that, by doing this, inhibition ceased to be a distinguishable factor that could independently contribute to the variance in reasoning or attainment. Other studies have also aimed to control for the confounding effect of non-EF processes in the relationship between EFs and numeracy or reasoning skills, with the most characteristic example being short-term memory capacity, which is frequently controlled for in studies that involve working memory (Agostino et al., 2010; Bull et al., 2008; Richland & Burchinal, 2013). In accordance with this previous research, in the current study, I attempted to distinguish the role of higher-level EF processes from that of lower-order processes, by controlling for the non-EF processes that are unavoidably measured along with the EF components under study. In addition to the non-EF processes, other demographic variables that may act as covariates were also controlled for, thus, increasing the likelihood that any observed effects are driven by the EFs and not by confounding associations.

In summary, the purpose of this study was to test the hypothesis that non-verbal reasoning and numeracy skills mediate the relationship between adolescents' EFs (inhibition, shifting and working memory) and their attainment in science. All three EF components were considered together as were the two transferable skills, so that the individual effects of each of these factors on science attainment could be examined. Furthermore, the effects of relevant non-EF processes and demographic factors were controlled for in order to obtain purer estimates of the EFs' and skills' effects.

6.2. Methods

6.2.1. Participants

The sample for this study consisted of a subset of the secondary school pupils who were tested as part of the overall PhD project. More specifically, due to the focus on science attainment, only pupils who had studied science related subjects could be considered. However, third-year pupils had to be disregarded since the majority of them did not have suitable grades in science subjects (for more information on this see page 93). Furthermore, among the fifth-year pupils there were only 42 who had studied science, which was not a large enough sample size for the type of analysis I aimed to carry out. Therefore, only the fourth-year pupils were considered for this study.

A total of 93 pupils (49 females, 44 males), who achieved qualifications in science related subjects at the end of their fourth year, constituted the sample for this study. The mean age of the pupils at the time of testing was 15.88 years (SD=0.33, range 15.08-17.08) and the majority of them were British (80) and right handed (78, handedness data were missing for 3 individuals). The pupils came from two of the schools that participated in this thesis project. At the time of testing (2016), the free meal entitlement rates of these two schools were 5% and 13%, while the national rate was 14%.

6.2.2. Cognitive measures

Participants were tested for the three EF components – inhibition, shifting and updating - as well as non-verbal reasoning and numeracy skills using tasks from the D-KEFS and BAS II batteries. Different tasks were administered for measuring each of the constructs under study, therefore, three tasks were used for the measurement of the three EF components and two tasks for the measurement of the two skills. These tasks have previously been described in detail in Chapter 2 (sections 2.2.2 and 2.2.3), therefore, are only briefly presented here.

EF components

Inhibition - Pupils' normative scores on the third condition of the CWI test from the D-KEFS were used as proxies of their inhibition ability.Furtherore, pupils' normative scores on the first condition of the CWI were also included in the analysis as a proxy of the non-EF process of colour naming speed (see page 60-61 for more information on the D-KEFS CWI task).

Shifting - The Free Sorting condition of the Sorting test from the D-KEFS battery was used to assess shifting. More specifically, two different scores from this task were considered in the analysis: the normative score representing the number of correct sorts generated and the normative score calculated from pupils' descriptions of the sorts (see pages 61-63 for more information on the D-KEFS Sorting test).

Working memory - Working memory was measured using the Recall of Digits Backward task from the BAS II battery; pupils' normative scores on this task were used in the analysis. In addition, in order to control for pupils' baseline levels of short-term memory, their normative scores on the Recall of Digits Forward task from the BAS II battery were also included in the analysis (see pages 63-64 for more information on the BAS II Recall of Digits tasks).

Transferable skills

Non-verbal reasoning skills were measured using the Matrices subtest from the BAS II battery, which tests individuals' ability to identify rules governing relationships among abstract figures and applying these rules to solve puzzle-like items (see pages 64-65 for more info on the BAS II Matrices subtest). Pupils' raw scores on the

Matrices subtest were standardised for age (in accordance to the BAS II standardisation sample) and the resulting normative scores were used in the analyses.

Numeracy skills were measured using the Number skills subtest from the BAS II battery, which assesses individuals' mathematical skills in various domains, e.g. printed number recognition, elementary arithmetic, fractions etc. (see page 65 for more information on the BAS II Number skills subtest). Pupils' raw scores on the Numbers skills subtest were converted to normative scores (standardised for age) which were subsequently used in the analyses.

6.2.3. Science attainment

Science attainment scores were based on pupils' performance on National Qualifications (NQs) they obtained in science subjects at the end of their fourth year. There were three science related subjects, namely Biology, Chemistry and Physics, on which the pupils had completed NQs in their fourth year. Only seven pupils had completed NQs on all three science subjects; and of the remaining pupils, half had completed NQs on two of the subjects and the other half had only completed NQs on one science subject. Furthermore, pupils worked towards NQs in the science subjects at one of two different levels: National 4 or National 5. National 4 qualifications are awarded on a pass or fail basis, whereas at National 5 level, further distinctions are made with qualifications being graded A to D or 'No Award' according to pupils' performance on their final exams and/or coursework. Receiving a 'No Award' grade is equivalent to failing the qualification, so 'No Award' grades in National 5 qualifications were disregarded. There were also no pupils within our sample who had received a D grade on their National 5 qualifications in any of the three science subjects. Thus, a distinction was only made between A, B and C grades in National 5 qualifications. Overall, fourth year pupils' attainment on Science subjects was treated as an ordinal variable with 4 levels of achievement: National 4 qualification, National 5 qualification Grade C, National 5 qualification Grade B and National 5 qualification grade A. For pupils who had achieved NQs on more than one of the science subjects but their level of attainment in each of the subjects differed, their highest level of attainment was regarded as their overall attainment in science.

6.2.4. Covariates

Pupils' gender, SES and condition status were included in this study as covariates. Similar to the studies described in the previous chapters, SES was indicated by SIMD and pupils' condition status was summarised by a binary variable denoting whether or not an individual had a condition that could affect their performance on the cognitive tasks. In this study's sample, SIMD ranged from 913 to 6792 (M_{SIMD}=5016, SD=1583) and 14 pupils were recorded as having a condition.

6.2.5. Procedure

Tasks were administered to pupils in two sessions: one for the assessment of EFs and another for the assessment of transferable skills (see section 2.4, pages 67-68 for a detailed description of the testing procedure). The EF assessment always preceded the skills assessment and for the sample of pupils considered in this study, the mean time lag between the two sessions was 20.6 days.

6.2.6. Statistical analyses

The first step was to explore the relationships among the three EF components, the two transferable skills and science attainment by inspecting the zero-order correlations between pupils' scores on the EF and skills tasks and their science attainment scores. This was done in order to verify that the relationships necessary to support the hypothesis actually existed, that is the independent variables are correlated with the dependent variables as well as the mediators, while simultaneously the mediators are correlated with the outcome. The zero-order correlations between all these variables and pupils' gender, SIMD and condition status[13] were also examined in order to determine whether the latter should be controlled for in the subsequent analyses.

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[13] Please note that the software used to estimate the correlation coefficients in this study automatically adjusts to the type of variables considered, making it possible to estimate correlations between categorical and binary variables, as in the case of the correlations between educational attainment and gender or condition status in this study. The estimation in this case is done using

In the next step, path analysis was implemented to test the hypothesis that pupils' non-verbal reasoning and numeracy skills mediate the relationship between their EFs and attainment in science. Path analysis is an extension of multiple regression with a more complex conceptualisation of the independent variables as predictors of the dependent variables (Howitt & Cramer, 2011). For example, in path analysis, causal relations among a set of variables can be drawn and tested, thus making it the most suitable method for testing a mediation model, which entails causal relationships among multiple variables. Moreover, path analysis constitutes a special case of structural equation modelling (SEM), where each construct (variable) can be represented by a single indicator (measure) (Senn, Espy, Paul, & Kaufmann, 2004), rendering it an appropriate methodology for our study in which each of the EF and skill constructs were measured by performance on only one specific task.

In the first step of path analysis, SEM can be used to develop a regression model (a priori) that includes specific relations among the variables of interest. Subsequently, the model is fitted to the available data and estimates of the magnitude and significance of the hypothesized connections among the variables are calculated. To test the mediation hypothesis, a multiple regression model was developed that consisted of the EFs and skills as predictors of science attainment scores, as well as the EFs as predictors of the skills, thus establishing both direct paths from the EFs to science attainment and indirect paths via the skills constructs. This model was then fitted to the data and the path coefficients between variables as well as the significance of the direct and indirect effects of EFs on science attainment were examined to determine the plausibility of the hypothesis.

A path diagram of the full model is shown in Figure 6.1. The mediators (numeracy and non-verbal reasoning skills) were allowed to correlate with each other but not causally (indicated in Figure 6.1 by a double headed instead of a single headed arrow), rendering this a parallel-mediation model, meaning that the indirect effects of the EFs on science attainment through the two skills were considered in parallel, thus allowing for the relative effects of each skill on science attainment to be calculated. The three EFs were also allowed to correlate with one another, in order to gauge their unique contribution to each of the two transferable skills and science

polychoric/tetrachoric correlations, but for reasons of coherence, all types of correlation referred to throughout this chapter are simply reported using the general symbol r.

attainment. In addition to the EFs, transferable skills and science attainment, the model included non-EF processes and demographic characteristics with potential confounding effects as control variables. The inclusion of these control variables in the model was guided by the zero-order correlations calculated in the previous step, i.e. only variables that were significantly correlated with science attainment and at least one of the EFs or transferable skills were included in the model together with the EFs as predictors of the transferable skills and science attainment.

All analyses were conducted in R studio, version 1.1.453. Missing data were multiply imputed by chained equations in the R mice package. Across the whole dataset, less than 2% data were missing, so five imputations were considered sufficient for obtaining the best results. Missingness was constrained to the EF and transferable skill measures, so only these variables needed to be imputed and imputation was carried out directly on the normative scores of these measures. All the variables that were to be included in the analyses as well as variables that were potential correlates of missingness were incorporated in the imputation model in order to address the missing at random (MAR) assumption.

After the imputations were completed, the lavaan and semTools packages in R, version 3.5.1 were used to develop and fit the necessary models to each of the five imputed datasets and pool the results together using Ruben’s rules. The pooled results are presented below.

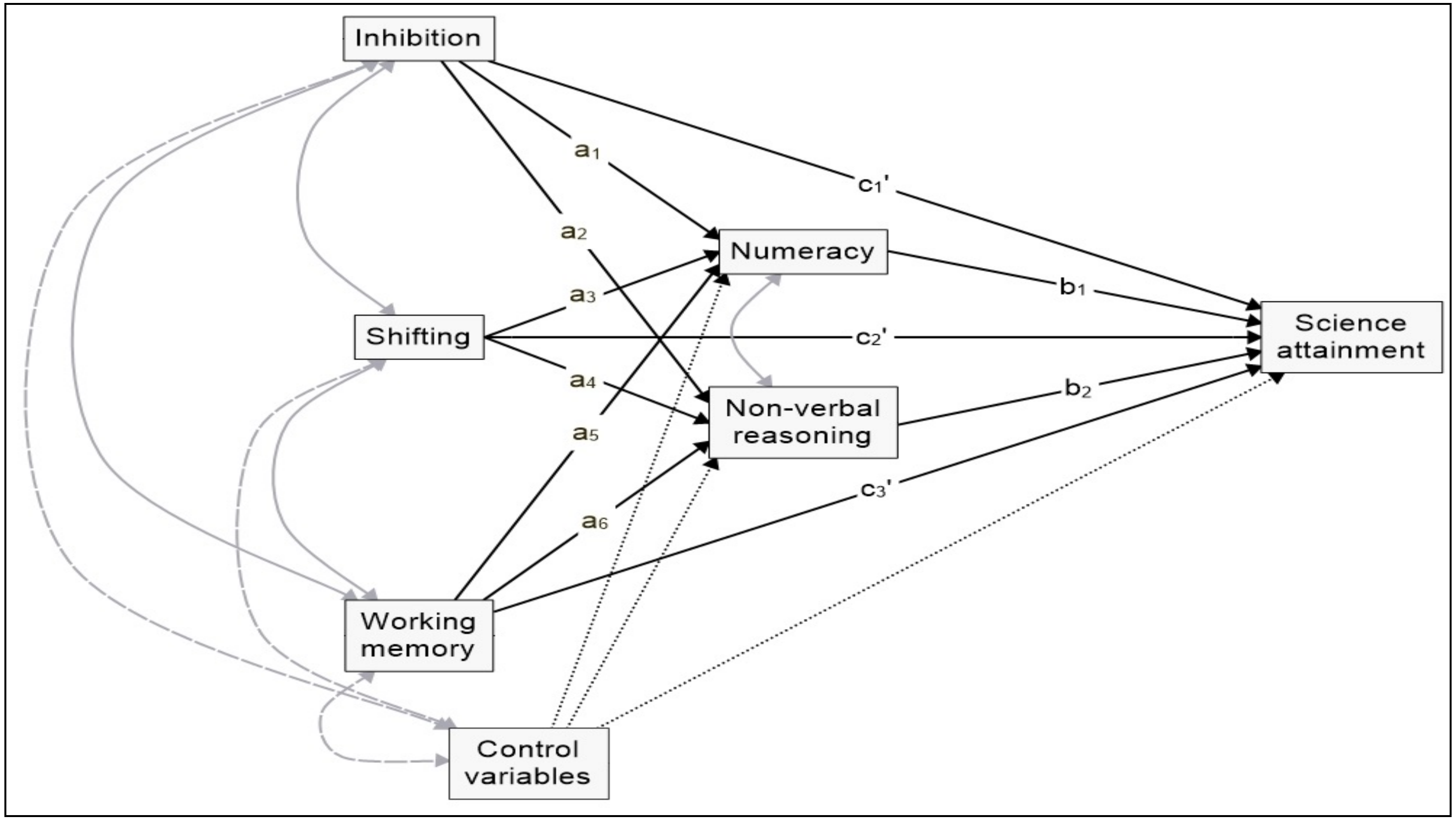

Figure 6.1. Path diagram of the model that was developed to test the mediation hypothesis. The model included each of the three EF components (inhibition, shifting and working memory) as predictors of both numeracy and non-verbal reasoning (paths a1-a6), which in turn were considered as predictors of science attainment (paths b1 and b2), thus establishing the indirect effects of the EF components on science attainment. The model also included direct effects from each of the three EF components on science attainment (paths c1'-c3'). Any remaining variables that needed to be controlled for were included in the model as predictors of the skills and science attainment (dotted-line paths).

6.3. Results

The descriptive statistics of pupils' normative scores on the tasks used to measure their cognitive abilities and transferable skills are shown in Table 6.1 and the distribution of pupils across the four levels of science attainment is shown in Table 6.2. Each level of science attainment was represented by a sufficient amount of pupils, therefore, no levels were collapsed and science attainment was included in the analysis as an ordinal variable with four levels.

Table 6.1. Descriptive statistics for the cognitive abilities and transferable skills measures based on the original data before imputations were carried out. The first column shows the number of pupils (N) with normative scores on each measure and the remaining columns present the mean (M), standard deviation (SD), skewness and kurtosis of the scores for those pupils.

	N	M	SD	Skewness	Kurtosis
Inhibition, CWI INH	91	11.19	2.09	-0.50	-0.49
Colour naming speed, CWI CN	90	9.90	2.80	-0.90	0.39
Shifting, ST correct sorts	92	8.47	2.53	0.21	0.34
Working memory, RDB	92	51.60	9.35	-0.54	0.44
Short-term memory, RDF	93	54.02	9.53	0.16	-0.70
Non-verbal reasoning, Matrices	86	55.63	10.53	-0.44	1.12
Numeracy, Number skills	86	109.01	15.72	-0.31	0.22

Note.
CWI INH: Colour Word Interference Inhibition condition, CWI CN: Colour Word Interference Colour Naming condition, ST: Sorting Test, RDB: Recall of Digits Backward, RDF: Recall of Digits Forward

Similar to the studies reported in the previous chapters, the two sets of normative scores that derived from the Sorting test (correct sorts and description scores) were found to be very strongly correlated ($r=.92$, $p<.001$) within this sample of fourth-year pupils. Consequently, the normative scores that corresponded to the number of correct generated sorts were considered as the sole indicator of pupils' performance on the Sorting test and, therefore, only these scores were included when imputing missing data and running the analyses reported throughout the remainder of this chapter.

Table 6.2. Number of pupils achieving each level of National Qualifications in science.

	Science attainment
National 4	25
National 5, grade C	15
National 5, grade B	24
National 5, grade A	29
Total:	93

The zero-order correlations among the measures of cognitive ability, transferable skills and science attainment are presented in Table 6.3. Each of the three EF components was significantly correlated with both non-verbal reasoning (correlation coefficients ranging from r=.34 to r=.47, all p_s<.01) and numeracy skills (correlation coefficients ranging from r=.29 to r=.37, all p_s<.05) as well as science attainment (correlation coefficients ranging from r=.22 to r=.45, all r_s<.05). In addition, both non-verbal reasoning and numeracy skills were significantly correlated with science attainment (r=.44 and r=.58 respectively, both p_s<.001). Therefore, all the correlations that are required for the mediation hypothesis to hold were evident in this sample.

The non-EF processes measured by the relevant control tasks were also significantly correlated with science attainment (r=.21, p<.05 for colour naming speed and r=.42, p<.001 for short-term memory capacity) and at least one of the transferable skills (r=.25, p<.05 and r=.14, p>.05 for colour naming speed and r=.32 and r=.26, both p_s<.01 for short-term memory capacity).These results indicate that both non-EF processes needed to be controlled for in the final model.

Table 6.3. Zero-order correlations among the cognitive abilities (three EFs and two non-EF processes), tranferable skills and science attainment.

		1.	2.	3.	4.	5.	6.	7.	8.
1.	Inhibition	-							
2.	Colour naming speed	0.66***	-						
3.	Shifting, correct sorts	0.20	0.19*	-					
4.	Working memory	0.48***	0.56***	0.11	-				
5.	Short-term memory	0.31**	0.36**	0.15	0.63***	-			
6.	Non-verbal reasoning	0.36**	0.25*	0.34***	0.47***	0.32**	-		
7.	Numeracy	0.29*	0.14	0.37**	0.34**	0.26**	0.52***	-	
8.	Science attainment	0.22*	0.21*	0.36**	0.45***	0.42***	0.44***	0.58***	-

*p<.05; **p<.01; ***p<.001

As far as the demographic variables are concerned, no significant correlations were observed among any of the variables of interest and pupils' gender (correlation coefficients ranging from $r=-.01$ to $r=.12$, all $p_s>.05$) or their SES, as indicated by SIMD (correlation coefficients ranging from $r=.01$ to $r=.15$, all $p_s>.05$). Therefore, these variables were not considered in the model. However, the binary variable representing pupils' condition status was found to be associated with the EF component of inhibition ($r= -.25$, $p<.05$) and the corresponding non-EF process of colour naming speed ($r= -.18$, $p<.05$) as well as numeracy ($r=-.24$, $p<.05$) and science attainment ($r= -.37$, $p<.001$), therefore, it was included as a control variable in the final model.

Since the correlations among the variables of interest were found to be significant, the next step was to test the hypothesis that the skill constructs mediate the effect of EFs on science attainment, by developing and testing the appropriate multiple regression model. The full model consisted of non-verbal reasoning and numeracy as mediators of the relationship between inhibition, shifting, working memory and science attainment, whilst colour naming speed, short-term memory and pupils' condition status were included as covariates. A path diagram of the full model including the standardised path coefficients and their significance is depicted in Figure 6.2. The non-EF processes and condition status variables were controlled for by being included in the model as predictors of the two transferable skills and science attainment, but the relevant paths (and path coefficients) have been omitted from Figure 6.2, since their inclusion would render the path diagram cumbersome and harder to comprehend.

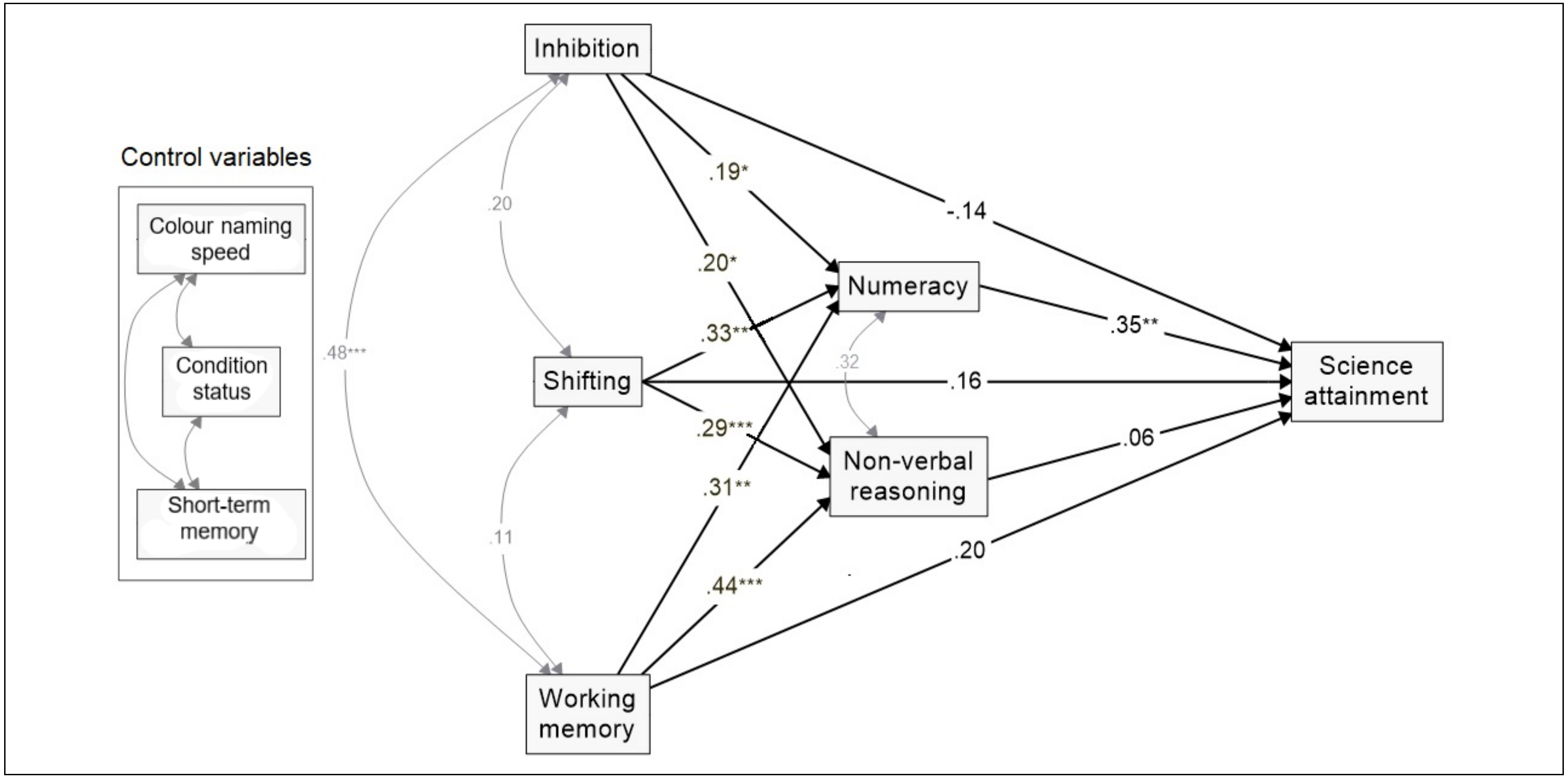

Figure 6.2. Path diagram of the full model depicting the standardised path coefficients among the variables of interest and their significance. The correlation coefficients among the EF components and between the two transferable skills are presented in grey. The control variables that were included in the model are also depicted, but without any coefficients for reasons of frugality.

*p<.05; **p<.01; ***p<.001

As can be seen in Figure 6.2, all three EF components were significant predictors of both non-verbal reasoning (coefficients ranging from b=.20 to b=.44, all p_s<.05) and numeracy skills (coefficients ranging from b=.19 to b=.33, all p_s<.05), even after controlling for the non-EF processes and condition status. Approximately 30% of the variance in numeracy and 34% of the variance in non-verbal reasoning was explained by the EFs and the control variables. The figure also shows that when both transferable skills were considered simultaneously, numeracy was a significant predictor of science attainment (b=.35, p<.01), while non-verbal reasoning was not (b=.06, p>.05). Finally, the direct effects of the EF components on science attainment were not statistically significant (coefficients ranging from b=-.14 to b=.20, all p_s>.05), meaning that none of the EF components explained unique variance in science attainment over and above the two transferable skills.

A more detailed account of the direct, indirect and total effects of each EF component on science attainment and the relevant significance values is provided in Table 6.4. From the second column of this table, which shows the EF components' indirect effects on science attainment through each mediator separately, it is apparent, that shifting and working memory had significant indirect effects on science attainment through numeracy (b=.12 and b=.11, both p_s<.05). However, none of the EF components had a significant indirect effect on science attainment through non-verbal reasoning (coefficients ranging from b=.01 to b=.03, all p_s>.05).

Table 6.4. Breakdown of the effects of the three EFs on science attainment. Coefficients and their significance are presented for: the direct effect of each EF, the indirect effect of each EF through a) numeracy and b) non-verbal reasoning and the total effect of each EF on science attainment.

	Direct effect	Indirect effect		Total effect
		a) Numeracy	b) Non-verbal reasoning	
Inhibition	**-.14,** p>.05	(.19)x(.35)=**.07,** p>.05	(.20)x(.06)=**.01,** p>.05	**-.06,** p>.05
Shifting	**.16,** p>.05	(.33)x(.35)=**.12,** p<.05	(.29)x(.06)=**.02,** p>.05	**.30,** p<.01
Working memory	**.20,** p>.05	(.31)x(.35)=**.11,** p<.05	(.44)x(.06)=**.03,** p>.05	**.34,** p<.01

Finally, as seen in the third column of Table 6.4, which contains the total effects (direct + indirect) of each EF on science attainment, shifting and working memory were significant contributors to science attainment (b=.30 and b=.34 respectively, all p_s<.01) whereas inhibition was not (b=-.06, p>. 05). Overall, the full model, containing all the paths from the EFs, transferable skills and control variables to science attainment explained 52% of the variance in pupils' science attainment.

6.4. Discussion

The main objective of this study was to investigate the possibility that transferable skills associated with success in science mediate the relationship between EFs and science attainment. More specifically, two core skills for science – non-verbal reasoning and numeracy skills – were tested as mediators of the relationships among three EF components (inhibition, shifting and working memory) and science attainment in secondary school (indicated by performance on National qualifications in science subjects). The results showed that, within a sample of 93 fourth-year pupils, there is indeed evidence of transferable skills mediating the relationship between EFs and science attainment.

Initially, the correlational analyses revealed significant zero-order correlations among all the variables of interest, i.e. all three EF components were significantly correlated with both transferable skills but also with science attainment and in turn the two skills were significantly correlated with science attainment, consistent with mediation. The next step necessary for testing the mediation hypothesis was to develop a multiple regression model that included direct and indirect effects (mediated by the two skills) of the EFs on science attainment and to calculate the magnitude and significance of these effects while simultaneously controlling for the effects of pupils' condition status and non-EF processes. The results of this analysis showed that two of the EF components examined – shifting and working memory – had significant indirect effects on science attainment though numeracy but not non-verbal reasoning; thus, at least partially confirming the hypothesis that skills thought to be necessary for learning and success in science mediate the relationship between EFs and science attainment.

This study is one of the few that has investigated all three components of the tripartite EF model (Miyake et al., 2000) in relation to transferable skills and science attainment. Among the three EF components, inhibition was found to consistently be the weakest predictor of both skills and science attainment. In fact, as opposed to shifting and working memory, inhibition did not even have a significant indirect effect on science attainment via numeracy, which in turn rendered its total effect on science attainment also non-significant. The zero-order correlations between inhibition and each of the two transferable skills were as strong as those between shifting and the two tranferable skills. Yet, in the path analysis, when all variables were considered together, inhibition's effect diminished to a larger extent than that of shifting and working memory, leading to the conclusion that part of the variance in the two skills that inhibition explains is shared with that explained by different predictors. Indeed, there were two other predictors in the model that were strongly correlated with inhibition while also being significant predictors of non-verbal reasoning and numeracy: colour naming speed and working memory. Therefore, the fact that inhibition explained relatively less unique variance in the two skills (and science attainment) compared to the other two EF components might be attributable to covariance with colour naming speed (i.e., the non-EF process implicated in performing the inhibition task) and working memory.

The finding that inhibition's effect on the skills was attenuated due to its association with the non-EF process of colour naming speed resembles the finding of a study by van der Sluis et al. (2007) in which CFA was utilised to distinguish between the varience (in EF performance) explained by EFs and that explained by non-EF processes. The CFA in that study showed that inhibition did not account for any variance beyond that explained by a general (non-EF) naming factor, so inhibition was not treated as a separate EF component and was subsequently not regarded as a predictor of reasoning and attainment. Although the van der Sluis et al. (2007) study involved younger children (aged 9 to 12), which might explain some discrepancies with the current study's results (i.e., the fact that in the current study inhibition's effect was simply attenuated and not completely cancelled out by the non-EF processes), it supports the finding that among the three EF components, inhibition may be the one most affected by controlling for non-EF processes. The large influence that non-EF processes were found to have on inhibition (both in the current study and the van der Sluis et al. study) is an indication of the importance of controlling for non-EF processes in studies where the measures used to assess EFs also heavily draw on non-EF processes.

Although the relative effects of the three EF components on non-verbal reasoning and numeracy differed in strength, they were all significant (i.e., each of the three EF components was a unique predictor of each skill), which actually contrasts the results of many previous studies. In the case of numeracy skills, for example, many studies have shown that when the three EF components are considered together, only one of them – more often than not working memory - constituted a unique contributor (Bull & Scerif, 2001; Espy et al., 2004; Lee et al., 2009, 2012). However, these studies concerned preschoolers and young children as opposed to adolescents, so it is possible that their different findings are due to age differences. More specifically, the inconsistencies in the findings may reflect the different organisation of EFs in adolescence compared to childhood. Existing literature has shown that, in young children, the components of inhibition, shifting and working memory are not fully differentiated (Brydges et al., 2014; van der Sluis et al., 2007; Van der Ven et al., 2012), which might explain why in the studies examining EFs in relation to skills in preschool and primary-school years, not all EF components uniquely contributed to the skill constructs. Moreover, the developmental literature's findings indicate that working memory is the first of the three EF components to become fully dissociable around primary school age, which once again corresponds to the findings of studies that have showed that working memory is the only component to explain unique variance in young children's tranferable skills. It is, therefore, reasonable to assume that, as the EF components differentiate with age, each of them subsequently becomes an independent predictor of transferable skills. Consequently, the fact that, in the current adolescent sample, all three components have independent effects on the tranferable skills serves as evidence that inhibition, shifting and working memory are distinct processes (albeit correlated) at the age of 15-16.

Perhaps the most striking finding from this study was that, among the two science-related skills considered, only numeracy was found to be a significant mediator of the relationship between EFs and science attainment. Despite the fact that the initial zero-order correlations between each of the two skills and science attainment were both significant, when the two skills were considered together in the path analysis model, numeracy but not non-verbal reasoning was found to be a significant predictor of science attainment. Seeing as non-verbal reasoning and numeracy were also moderately correlated with one another, it becomes apparent that the significant correlation of non-verbal reasoning with science attainment was based on variance that was shared with numeracy.

Of course, the fact that non-verbal reasoning did not individually predict science attainment is slightly counterintuitive considering the strong link between reasoning and fluid intelligence (Carroll, 1993), a construct that is considered relatively general and all-encompassing, since it is a core part of general intelligence (Cattell, 1971). As a domain-general ability, fluid intelligence permeates attainment and success in many different academic areas including science (e.g., Colom, Escorial, Shih, & Privado, 2007; Di Fabio & Palazzeschi, 2009; Downey, Lomas, Billings, Hansen, & Stough, 2013; Lynn & Mikk, 2007). Therefore, through its association with fluid intelligence, non-verbal reasoning would be expected to explain (at least some) unique variance in science attainment. My contradicting results may stem from the fact that in this study non-verbal reasoning was not examined in relation to science attainment in isolation, but alongside numeracy skills. More specifically, the explanation may lie in the fact that, numeracy was conceptualised as the amalgamation of many different math-related skills (e.g., number recognition, mathematic operations and problem solving), as assessed using the Number skills test of the BAS II. This potentially rendered the measure of numeracy a more inclusive construct than non-verbal reasoning, which might justify why numeracy explained unique variance in science attainment over and above non-verbal reasoning. This assumption appears even more credible when considering some of the more complex items of the Number Skills test used to measure numeracy (i.e., the items that require solving problems that involve maths). This type of arithmetic word problems require individuals to use their non-verbal reasoning skills, as manifested by studies' findings that non-verbal reasoning predicts performance on mathematic word problems (Fuchs et al., 2006; Swanson, Jerman, & Zheng, 2008; Taub et al., 2008). This further supports the notion of non-verbal reasoning as a more specific skill whose effect on science attainment is completely attenuated by the more all-encompassing numeracy skills.

Alternatively, the finding that numeracy but not non-verbal reasoning was an independent predictor of adolescents' science attainment might stem from the nature of the assessments used as a measure of attainment in this study.

Traditionally, standardardised, curriculum-based assessments of science, such as the National qualifications examined here, are designed to assess the simple recall of facts/theory as well as the ability to apply that theory to solve problems. The findings of a study by Rhodes et al. (2014) underlined the largely factual content of standardised science assessments and this may have been linked with the fact that, in a follow up study, (Rhodes et al., 2016) performance on such assessments was independently predicted by adolescents' vocabulary ability but not their higher-order cognitive abilities. In the case of the current study, for the year that the data analysed was collected, the Scottish National qualifications in science subjects comprised of factual-based questions and complex problem solving items in a ratio of approximately 1:1 (although this varied slightly across the different science subjects). Evidently, the former type of questions simply assessed pupils' memory of science concepts, without necessarily tapping higher-order cognitive abilities such as reasoning. Therefore, pupils' performance on almost half of the science assesement may not be dependent on their reasoning skills. Furthermore, the remaining complex problem-solving items in their majority involved performing mathematical calculations and therefore may have relied more heavily on pupils' numeracy rather than their non-verbal reasoning skills. Taken together these two points may potentialy explain why numeracy was found to be the stronger and significant predictor of adolescents' performance on the science assessments examined in this study. In the future, it may be beneficial to try to repeat this study using different types of science assessments as the outcome variable in order to clarify whether the results are specific to the nature of the assessment examined and more fully understand the skills that are drawn upon for success in different aspects of science.

All in all, the results of this study were in support of the notion that transferable skills mediate the relationship between EFs and educational attainment. Focusing on attainment in science, the current study demonstrated that the relationship among the three components of Miyake's (2000) tripartite EF model and science attainment is mediated by numeracy skills. These results were obtained using a cross sectional sample of 93 fourth-year secondary school pupils; unfortunately, it was not feasible to carry out the relevant analyses with the third- and fifth- year pupils in the overall sample and thus corroborate the results in different (adolescent) age groups. As a result, the conclusions cannot be generalized to the wider period of adolescence until further research is carried out to replicate this study in larger samples covering a wider age range of adolescents. Nevertheless, this study provided evidence of transferable skills acting as mediators between EFs and educational attainment in an age group that has been overlooked in the past. Moreover, this study went beyond other studies in that it examined three different EF components and two science-related transferable skills and as such managed to elucidate the relative effects of each EF component and skill on science attainment. To my knowledge, there is no other study that has examined both non-verbal reasoning and numeracy skills in relation to EFs and science attainment among adolescents, therefore, this study is the first to provide preliminary evidence of numeracy being the dominant mediator of the relationship between EFs and science attainment. However, since there are no previous results with which to compare these findings, firm conclusions cannot be drawn before these results are replicated in future studies. Nevertheless, this study generated some significant stand-alone results, while also laying the foundation for future studies and further research into the mediating role of tranferable skills in the relationship between EFs and educational attainment.

Chapter 7: General discussion

Overall, this project focused on the study of EFs, more specifically inhibition, shifting and working memory, during the previously overlooked period of late adolescence. This thesis described the results from a number of studies carried out using a sample of 347 adolescents aged 14-18 (third to fifth year of secondary school) who were recruited for this project. Each of the studies corresponded to one of the main research questions that were set out at the beginning of the project (see section 1.5, page 46).

The **first study** concerned the development of the three EF components during the ages of 14-18 years. The main result was that there were no significant age-related differences in adolescents' shifting ability or their working memory, however, the component of inhibition was found to differ significantly with age. Consequently, this thesis provides further evidence in support of current thinking that the development of EFs is protracted, with certain aspects of EF continuing to change and mature throughout adolescence, including the latter stages thereof (Boelema et al., 2014; Conklin et al., 2007; Gur et al., 2012; Magar et al., 2010). Furthermore, the fact that only one of the three EF components examined was found to significantly change within the period of 14-18 years of age is in line with the conclusion drawn from previous research that distinct EF components follow different developmental trajectories (Best et al., 2009) and mature at different rates (Boelema et al., 2014; Luna et al., 2004; Prencipe et al., 2011).

The finding that inhibition was the only component that continued to undergo significant change is slightly contradictory to the findings of previous studies which showed that among the three components, working memory and shifting, not inhibition, undergo the largest changes during adolescence (e.g., Boelema et al., 2014; Magar et al., 2010). Such inconsistencies are most likely a result of the different tasks used to measure the EF components across studies, seeing as in studies where inhibition was measured using Stroop-like tasks, similar to that used in the current PhD project, inhibition was found to continue improving beyond the age of 15 (Huizinga et al., 2006; Leon-Carrion et al., 2004). Evidently, the use of different EF tasks across studies is a major issue in EF research, since it can be the cause of great discrepancies among studies' results. Indeed, certain developmental studies using multiple tasks to measure each EF construct have provided strong evidence that performance on different tasks measuring the same EF component improves at different rates, reaching maturity at different ages (Conklin et al., 2007; Huizinga et al., 2006). Therefore, the results of any study should always be observed in the light of the tasks used to assess EFs. Of course, ideally, studies should not rely on a single task for the assessment of any EF component, but should rather use multiple different tasks per EF component. This was a limitation of the current PhD project, where time limitations when testing at schools did not allow for the administration of more than one task per EF component examined. In the future, studies should attempt to use multiple measures of EF components wherever possible and utilize the increasingly popular methods of latent variable modelling and CFA to extract the shared variance across the relevant tasks. This would provide a more comprehensive measure of each EF component and allow for more definite conclusions to be drawn.

The **second study** described in this thesis regarded the investigation of the relationship between the three EF components and adolescents' educational attainment. Analyses were carried out separately for the third-, fourth- and fifth-year pupils, since adolescents' educational attainment was measured by different curriculum-based assessments within each year group (i.e., school grades among the third-year and National qualification scores among the fourth- and fifth-year pupils). Furthermore, in order to obtain the fullest possible picture of EFs' relationship with achievement in different disciplines, attainment in a variety of subject areas was investigated. Overall, the results of this study revealed that, across the ages of 14-18 years, significant associations exist between adolescents' EFs and their attainment in various curriculum areas. In the final regression models, when the relevant EF components and other covariates (demographic variables and non-EF processes) were all included as predictors simultaneously, at least one EF component remained a significant predictor of attainment in the majority of subjects across all three age groups. Therefore, this thesis provides good evidence that the relationship between EFs and educational attainment -a relationship that has been well documented during preschool and primary school years- persists well into adolescence, beyond the age of 15 which currently constitutes the upper age limit examined in the bulk of research.

Direct comparisons of the way EFs are related to attainment across the three different year groups could not be made, due to the incompatibility of the curriculum-based assessments that were used as measures of educational attainment in each year. However, the results did reveal a noteworthy pattern regarding the strongest EF predictor of attainment within each year group. More specifically, shifting appeared to have a strong, consistent effect on younger adolescents' attainment, as it independently predicted attainment in the two younger year groups, but after the age of 16, the results showed a shift to inhibition as the single strongest EF predictor of attainment. Surprisingly, this major change did not coincide with pupils' transition to the senior phase of their curriculum in the fourth year of secondary school, but instead occurred one year later in fifth year. One possible explanation for this unexpected result revolving around the fact that pupils gradually specialise in particular disciplines as they progress from the third to the fifth year of secondary school, has already been presented in the general discussion section of the relevant chapter (see pages 124-129).

Here, I focus on another explanation for this puzzling result, which becomes apparent when the result is considered in conjunction to the findings of the previous study concerning the developmental differences in the three EF components. The fact that shifting was not found to differ with age among the sample of 14-18 year olds may imply that shifting had reached relatively mature levels by the age of 14 compared to working memory and inhibition.This could also explain the powerful effect it was found to have on attainment among the third and fourth year pupils, who might rely on shifting more since they have not yet reached their full potential as far as working memory and inhibition are concerned. In the mean time, inhibition was shown to continue to change throughout the ages of 14-18, thus by the age of 16-18 (corresponding to the fifth year pupils), inhibition would be more mature and adolescents may therefore rely on it more, explaining the finding that inhibition took over as the EF component with the greatest effect on attainment among the fifth-year pupils. Of course, this is only one possible interpretation of the results that cannot be securely verified since my conclusions on the development of EFs are based on results from a cross sectional study. The fact that this whole project was based on cross-sectional rather than longitudinal data constitutes one of its major limitations, however following a cohort of pupils through the ages of 14-18 and testing them at one-year intervals would not have been possible for this PhD thesis.

It would, however, be interesting to see whether future studies examining the relation between EFs and attainment longitudinally across the ages 14-18 reach similar results.

As far as the various subject areas in which attainment was examined in relation to EFs are concerned, this thesis does not only confirm the well-established effect EFs have on English, maths and science attainment, but also provides evidence of associations between EFs and attainment in the previously overlooked areas of foreign languages, social studies and arts. However, in some cases (mainly regarding attainment in foreign languages and arts) the results of this thesis can only be considered as preliminary considering the small sample sizes available for the corresponding analyses. Therefore, particularly in the case of foreign languages and arts, further studies looking into EFs in relation to attainment should be carried out to confirm the effects found in this thesis.

In the **next study** of this thesis, the three EF components were examined in relation to the oldest (fifth-year) adolescents' performance on school-leaving qualifications, in an attempt to determine whether EFs are associated with adolescents' success in meeting the academic requirements necessary for entry into higher education. To my knowledge, this is the first study that attempted to examine this matter and, therefore, this thesis provides unique insight into the potential role of EFs in shaping pupils' opportunities to enter higher education. The results showed that none of the three EF components had a significant effect on adolescents' overall performance on their qualifications, once other covariates were controlled for.

The finding that adolescents' EFs are not important predictors of them acquiring the necessary qualifications for entry into University seems slightly contrasting when considering the results of the previous study, which indicated that EFs influence adolescents' performance on qualifications in a variety of subjects. However, due to the lack of other research investigating EFs as determinants of adolescents' prospects for entering University, it it is not appropriate to speculate on the reasons that may have brought about this study's counterintuitive results. Furthermore, it is important to note that in this study pupils' prospects for meeting the academic requirements to enter University were estimated based on the points earned on qualifications they completed in their fifth year, but in some cases this may not correspond to the final amount of points pupils hold for entry into University since some pupils may move on to an additional year of secondary school where they can study towards further qualifications. Potentially, then, the results regarding EFs as predictors of pupils' prospects for University entry may have been different if the sample had consisted solely of pupils in their sixth year of high school. Therefore, future studies should aim to acquire more information on the topic of EFs in relation to meeting the academic requirements for entry into University but should do so using samples consisting solely of pupils in their final year of secondary school.

The **final study** of this thesis concerned the investigation of the role transferable skills may play in the relationship between EFs and educational attainment. More specifically, the study focused on attainment in science, with numeracy and non-verbal reasoning skills being hypothesized to mediate the relationship between adolescents' EFs and their science attainment. The results showed that, among the fourth-year pupils examined, numeracy but not non-verbal reasoning skills mediated the relationship between EFs and attainment in science. These results underline the importance of numeracy skills in science and build a case for the development of numeracy early in education as a foundation skill to aid later science achievement. Consequently, these findings warrant the fact that numeracy is treated as a core skill that needs to be focused on from early on in many curricula around the world, including Scotland's Curriculum for Excellence (Scottish Government, 2009).

The fact that this study only examined two science-related transferable skills is a potential limitation as there may be others that are also implicated in the relationship between EFs and science attainment. For example, literacy constitutes another skill that typically receives ample attention from early on in children's education and has also been shown to correlate with children's (Maerten-Rivera, Myers, Lee, & Penfield, 2010; Van Laere, Aesaert, & van Braak, 2014) and adolescents' (Cano, García, Berbén, & Justicia, 2014; Cromley, 2009) science attainment. Therefore, literacy, more specifically scientific literacy, could also be researched as a potential mediator between EFs and science attainment; however, in the current study it was not examined due to time limitations and challenges in finding a suitable, standardised (scientific) literacy assessment.

In addition, it would be interesting to explore whether non-verbal reasoning and numeracy skills mediate the relationship between EFs and attainment in other disciplines apart from science. This PhD project focused on science in particular because the skills underpinning science achievement have received less attention in comparison to skills needed for reading or mathematics (Tolmie, 2012; Tolmie et al., 2016). However, the two transferable skills examined in this thesis, are not exclusively related to science achievement alone; they are also important for success in other discipines, the most characteristic example being mathematics. Numeracy skills in particular, are commonly considered as indicators/predictors of math achievement (Best et al., 2011; Blankenship et al., 2015; Bull et al., 2008; De Smedt, Verschaffel, et al., 2009; Fazio et al., 2014; Latzman et al., 2010; Mazzocco et al., 2011) and since they were found to constitute significant mediators in the relationship between adolescents' EFs and their science attainment, it is expected that the same will be true in the case of maths. Non-verbal reasoning skills, have also been repeatedly found to predict attainment in maths (Gómez-Veiga et al., 2018; Hofer et al., 2012; Krumm et al., 2008; Stevenson et al., 2014; Taub et al., 2008). Furthermore, due to their close association with problem-solving abilities (Chuderski, 2014; Greiff et al., 2016, 2015), non-verbal reasoning skills may be critical for solving mathematical word problems, which typically constitute one of the components that older adolescents are assessed on in standardised maths tests. Therefore, there is certainly scope for further research into the potential mediating role of numeracy and non-verbal reasoning skills in the relationship between EFs and attainment in maths, while attainment in related disciplines, such as business and economics, should also potentially be investigated.

Nevertheless, due to this study, this thesis provides preliminary evidence of the mediating role transferable skills may play in the relationship between adolescents' EFs and science attainment**.** Obviously, in order to be able to draw more firm conclusions, these results need to be replicated. Furthermore, future studies could expand on these findings by investigating whether the finding of transferable skills mediating the relationship between EFs and science attainment holds for younger ages as well. The latter could help determine whether transferable skills begin to act as mediators of the EFs-attainment relationship at particular ages and consequently inform educational practice about the appropriate ages at which skills should be introduced into curricula.

Overall, despite having certain limitations, this thesis makes various significant contributions to the existing literature on EFs in adolescence, both by confirming and expanding on previous findings regarding the development and relation of EFs with educational attainment and by providing novel insight into two previously virtually unexplored areas of EF research - the relation between EFs and acquiring the necessary qualifications for University entry and the relation between EFs, transferable skills and attainment. Moreover, taken together, the results of the studies presented in this thesis have some important implications for research and practice.

In regard to research, some ideas and directions for future studies based on the results of each study presented in this thesis, have already been discussed above (see pages 169-174). In addition to these (study) specific sugestions, however, there are also certain trends observed across the entirety of this thesis that have important implications for research into the subject of EFs. The first general trend concerns the significant effect that SES was observed to have in most of the analyses reported in this thesis. More specifically, the proxy of individuals' SES used in this project (i.e., SIMD) was found to have a significant effect on adolescents' EFs, their attainment in most school subjects and their prospects in meeting the academic requirements for entry into University. In fact, in the study examining fifth-year pupils' school attainment in the context of their prospects for entering University, SES was the only significant predictor of adolescents' performance on qualifications that count towards University entry. Taken together, these results highlight the need for researchers to consider SES in studies examining EFs in a developmental or an educational context, since failure to do so may distort their results and impede them from gaining a clear and complete picture in regard to the intricate nature of EFs and their involvement in educational attainment.

These findings come at a time when the importance of SES is gradually being recognised more and more in the field of cognitive neuroscience and researchers are beginning to treat SES as a subject of study in its own right rather than simply a "nuisance variable" that needs to be co-varied out of studies' results (Farah, 2017). In fact, in recent years an increasing body of research has begun to study SES from a neuroscience perspective, examining whether the SES disparities in cognition and attainment have neural explanations. Evidence from studies using direct measures of brain function, such as functional MRI or event-related potential (ERP), indicates that differences among individuals' SES are linked with differences in their brain activity when performing EF tasks or academic assessments (Farah, 2017). At the same time, many studies focusing on brain structure, as revealed by MRI, have found SES disparities to be correlated to structural differences within various brain regions, more often than not the hippocampus and frontal cortex (see Farah, 2017 for an extensive review). Although, researchers are still far from making any generalisations about a brain signature of SES, this would certainly fit well with the recurring finding in this thesis of SES having a substantial effect on cognitive and academic outcomes beyond that of other factors that were simultaneously included in the regression models developed in each study.

A second recurring finding of this thesis concerns the importance of a different covariate that was controlled for in the analyses: the non-EF processes implicated in performance on the EF tasks. More specifically, the two non-EF processes of coulour naming speed and verbal short-term memory that were considered in this project were consistently found to have a significant effect on the outcomes considered in many of the studies presented in this thesis. For instance, in the study investigating the development of the EF components of interest, the non-EF processes were found to explain much of the age-related differences in pupils' inhibition and working memory scores. Furthermore, in the subsequent studies, the non-EF processes were shown to be significantly associated with pupils' attainment in many subjects as well as the number of points pupils acquired on qualifications counting towards entry into University and their transferable skills. In one case in fact, the non-EF process of short-term memory was even shown to be a significant predictor of pupils' attainment in science above and beyond the effect of the EF components. It is, therefore, apparent that controlling for the non-EF processes significantly influenced the results of the studies presented in this thesis and therefore, it was essential to control for them.

Of course, it should be noted, that the two non-EF processes that were controlled for, i.e., colour naming speed and short-term memory, corresponded to performance on the tasks used to assess inhibition and working memory respectively. However, no non-EF process was considered in the case of the shifting component due to there being no task suitable for measuring the non-EF processes involved in performing the shifting task. This is clearly an important omission and may in part be linked to this thesis's results indicating that among the three EF components examined, shifting was often the strongest predictor of pupils' attainment. All things considered, this thesis makes a case for the importance of controlling for relevant lower-order, non-EF processes when investigating EFs. Especially in studies exploring EFs in relation to educational attainment, it is crucial to always consider the non-EF processes implicated in performing each of the tasks used to assess EFs in order to get a correct picture of the effects of EFs on attainment.

Most importantly, seeing as this thesis mainly concerned the exploration of EFs in relation to educational attainment, its results may be particularly informative for educational practice. Indeed, the results of the majority of studies in this thesis examining EFs in relation to measures of educational attainment showed that EFs play an important role in adolescents' attainment during the ages of 14-18 years. The third study was the only exception, since its results demonstrated that the three EF components of interest do not influence adolescents' prospects of acquiring the necessary qualifications for entry into University. In contradiction to this, however, the results of the second study, show that EFs influence adolescents' attainment across a variety of subject areas, while the results of the fourth study additionally suggest that EFs may underpin the transferable skills that are necessary for success/attainment in these areas. In the case of the fourth study, it is also important to note that the finding that EF components affect pupils' science attainment through numeracy but not non-verbal reasoning skills, could be considered to corroborate the results of previous studies indicating that EFs predict attainment above and beyond intelligence (Blair & Razza, 2007; Aran-Filippetti & Richaud, 2015), since the measure used to assess intelligence in these studies was the same as that used to measure non-verbal reasoning in this thesis. Taken together, these findings provide evidence of EFs as domain-general abilities that underly attainment across different disciplines. This, in combination with the results of the first study, which indicated that EFs may still be developing during the period of 14-18 years of age, underlines the pertinence of EFs as an important construct for informing adolescents' education.

More specifically, the general pattern accruing throughout this thesis indicated that among the three EF components studied, shifting and to a lesser extent inhibition have the strongest effect on adolescents' attainment. This is a particularly interesting finding because these two EF components are both implicated in individuals' ability to selectively attend and focus on specific information/stimuli (Diamond, 2013). Consequently, this thesis's results indicating that shifting and inhibition are significant predictors of adolescents' attainment imply that adolescents' ability to successfully handle the ample information they receive everyday at school is an important determinant of their educational attainment. Adolescents with a limited ability to voluntarily shift their attention and selectively focus on the information they choose may, therefore, be at a disadvantage as far as their learning and academic outcomes are concenred. This can have important implications for practice as it suggests that manipulating elements of pupils' everyday school experience relating to the level of shifting or interference control they need to exert may significantly influence their learning experience and achievement. For example, within the context of the classroom, reducing the amount of distractions and irrelevant information that pupils are subject to may help those pupils with weaker inhibition abilities perfom better in class.

Of course, in the case of shifting, the significant results need to be considered with caution since, as has been previously mentioned (see page 176), they may to a certain extent be driven by the fact that non-EF processes associated with shifting performance were not controlled for. Moreover, the type of task that was used to measure shifting in this project needs to also be acknowledged when interpreting the results relating to the effect of shifting on attainment. More specifically, the Free Sorting condition of the D-KEFS ST that was used here, differs from other sorting tasks in that it requires identifying sorting rules in a relatively unrestricted manner i.e., participants are asked to create as many sorts as they can, rather than having to identify the sorting rules applied by the experimenter as is done in the Sort Recognition condition of the ST and in the WCST. Consequently, performance on the Free Sorting condition of the ST is not just dependent on individuals' set shifting ability, but also draws on their ability to intiate problem-solving behaviour and on their motivation. Especially when testing children and adolescents, their level of engagement with the task may play a crucial role in their performance. On the other hand, however, previous studies, which used factor analysis to explore the aspects of EF tapped by the various D-KEFS tasks, have shown that adolescents' scores on the Free Sorting condition of the ST loaded more strongly on a shifting-associated factor compared to scores on the more restricted Sort Recognition condition of the ST (Latzman & Markon, 2010; Li et al., 2015). This constitutes evidence that despite performance on the Free Sorting condition being potentially more sensitive to individuals' level of engagement in the task, it nevertheless, remains a strong index of shifting ability. Consequently, this thesis's results are in fact indicative of shifting being a significant predictor of adolescents' attainment, albeit motivational factors may play a part in this as well. If this is the case, implications for practice extend further than manipulating the EF demands placed on pupils to augmenting pupils' motivation and engagement in class.

All the above highlight some of the different ways in which the results of this thesis can contribute to educational practice. However, one essential prerequisite for any of these suggestions to be applied, is that teachers are aware of the concept of EFs and informed about their potential as tools to assist learning. Studies have shown that teachers' knowledge of concepts related to educational neuroscience is generally poor (Dekker, Lee, Howard-Jones, & Jolles, 2012) and that their familiarity with constructs such as EFs is limited to and governed by what they have experienced through their teaching, as more often than not they do not receive formal instruction on such matters (Gilmore & Cragg, 2014). Perhaps then, the largest contribution of this thesis to educational practice simply lies in the fact that seeing as it makes a good case for EFs underpinning various aspects of adolescents' achievement, it can constitute a helpful resource for teachers and education authorities. This thesis is particularly informative because it provides insight into the development and effect on attainment of three distinct EF components rather than a single aspect or composite construct of EF. The three EF components of inhibition, shifting and working memory were chosen to be examined on the basis that they are frequently postulated in the developmental and educational literature and are generally perceived as more basic constructs, or at least more basic compared to complex concepts like planning (Miyake et al., 2000). Therefore, although inhibition, shifting and working memory may not represent all possible aspects of EF, the results presented in this thesis may constitute important starting points and inform future studies aiming to investigate additional and/or more complex EF constructs.

Chapter 8: References

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Appendix A: Ethical Approval form

PSYCHOLOGY RESEARCH ETHICS COMMITTEE
SCHOOL of PHILOSOPHY, PSYCHOLOGY and LANGUAGE SCIENCES
The University of Edinburgh
7 George Square
Edinburgh EH8 9JZ
Telephone +44 (0) 131 651 5002
Email Lynsey.Buchanan@ed.ac.uk

5 March 2015

Ethics proposal 126-1415/2, entitled Investigating the relationship between executive functions and educational attainment among adolescents. and submitted by Thalia Theodoraki, Sarah MacPherson and Sarah McGeown has been approved by the Psychology Research Ethics Committee per the Department's ethics regulations.

The following files were uploaded with the application:

Filename: Letter to Head Teacher.docx
Date: 15 Feb 2015 02:31 PM
Purpose: Information/Consent Sheet

Filename: Letter to Parents.docx
Date: 15 Feb 2015 02:31 PM
Purpose: Information/Consent Sheet

Filename: Letter to Student.docx
Date: 15 Feb 2015 02:32 PM
Purpose: Information/Consent Sheet

Filename: debrief form.docx
Date: 15 Feb 2015 02:32 PM
Purpose: Experiment debrief

Filename: ReviewComments-126-1415_1.pdf
Date: 17 Feb 2015 10:53 AM
Purpose: (Reply to)/PREC Review
Note: Comments from reviewer in response to your submission.

Filename: OPT IN form.docx
Date: 26 Feb 2015 12:02 PM
Purpose: Information/Consent Sheet

Appendix B: Letter-consent form for Head Teacher

Schools A and B

Thalia Theodoraki

School of Philosophy,
Psychology
and Language Sciences

University of Edinburgh

s1460006@sms.ed.ac.uk

Dear Head Teacher

I am a PhD student at the University of Edinburgh and am writing to ask whether your school would be interested in participating in a research project focused on understanding the relationship between cognitive abilities and adolescents' educational attainment.

The cognitive abilities in question are called executive functions and are necessary for the control and planning of behaviour. They include inhibition (ability to override dominant impulses), working memory (ability to store, process and monitor information) and shifting (ability to shift attention).

At present, there is no research with adolescents aimed at understanding the relationship between these basic cognitive abilities and other skills (numeracy, reasoning) or educational attainment. Therefore, the results of this study are likely to be very informative to schools interested in the best ways to support their students and the use of training targeting executive functions.

I would like students aged 14 – 17 to participate in this project. Students would be assessed individually on executive function tasks (40 minutes), would participate in numeracy and reasoning assessments as a whole class (45 minutes) and I would also ask the school for students' educational attainment scores. Following completion of this project, I would write a full report for the school, highlighting the results of the study and the educational implications of these.

Specifically, in the executive functions tasks, several sequential stimuli, e.g. words, letters or pictures, will be presented to the students either visually or orally. According to the task, students will be asked to respond to each stimulus in a particular way, e.g. name the colour of ink the word is written in, sort the presented stimuli into categories or repeat what they saw/heard in a certain order.

The group tests will be simple pen and paper assessments. Worksheets containing a number of questions/items will be distributed and the students will have to complete them in a certain amount of time. The numeracy test consists of various number-based tasks ranging from simple mathematical operations and fractions to problems. The reasoning test contains matrices of abstract figures, which are incomplete and students have to select from among six figures the one that completes each matrix.

If you would like more information, please do not hesitate to contact me. If I don't hear from you within 2 weeks, I will follow this letter up with a phone call. If, following a further discussion, you would like your school to participate, please indicate this below and send this letter back to me via email. Head teacher and student consent is necessary for participation and parent opt out forms will be provided. The school's and students' identity will be protected by ensuring confidentiality and anonymity throughout.

This project has received ethical approval from the Psychology Research Ethics Committee, University of Edinburgh and I have a recent disclosure (PVG Scheme).

Yours sincerely,
Thalia Theodoraki

Note of consent

Name of School:

Name of Head Teacher:

Signature of Head Teacher:

School C

Thalia Theodoraki

School of Philosophy,
Psychology
and Language Sciences

University of Edinburgh

Dear Head Teacher

I am a PhD student at the University of Edinburgh and am writing to ask whether your school would be interested in participating in a research project focused on understanding the relationship between cognitive abilities and adolescents' educational attainment.

The cognitive abilities in question are called executive functions and are necessary for the control and planning of behaviour. They include inhibition (ability to override dominant impulses), working memory (ability to store, process and monitor information) and shifting (ability to shift attention).

At present, there is no research with adolescents aimed at understanding the relationship between these basic cognitive abilities and other skills (numeracy, reasoning) or educational attainment. Therefore, the results of this study are likely to be very informative to schools interested in the best ways to support their students and the use of training targeting executive functions.

I would like students aged 14 – 17 to participate in this project. Students would be assessed individually on executive function tasks (40 minutes), would participate in numeracy and reasoning assessments as a whole class (45 minutes) and I would also ask the school for students' educational attainment scores. Following completion of this project, I would write a full report for the school, highlighting the results of the study and the educational implications of these.

Specifically, in the executive functions tasks, several sequential stimuli, e.g. words, letters or pictures, will be presented to the students either visually or orally. According to the task, students will be asked to respond to each stimulus in a particular way, e.g. name the colour of ink the word is written in, sort the presented stimuli into categories or repeat what they saw/heard in a certain order.

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If you would like more information, please do not hesitate to contact me. If I don't hear from you within 2 weeks, I will follow this letter up with a phone call. If, following a further discussion, you would like your school to participate, please indicate this below and send this letter back to me via email. Head teacher, parent and student consent is necessary for participation. It is up to you whether you will require opt in or opt out forms from the students' parents. The school and students' identity will be protected by ensuring confidentiality and anonymity throughout.

This project has received ethical approval from the Psychology Research Ethics Committee, University of Edinburgh and I have a recent disclosure (PVG Scheme).

Yours sincerely,
Thalia Theodoraki

Note of consent

Name of School:

Name of Head Teacher:

Signature of Head Teacher:

Appendix C: In loco parentis consent form

In loco parentis Consent Form

School of Philosophy, Psychology and Language Sciences
University of Edinburgh

Project title: *NAME OF PROJECT TITLE*

I confirm that I give my approval for Thalia Theodoraki to carry out her research study in *NAME OF SCHOOL/NURSERY* regarding the relationship between executive functions and educational attainment among adolescents. I also confirm that the “opt-out” approach to parental consent (as outlined in the researchers’ letter to parents dated 07/05/2015) has my approval and that I am therefore giving consent *in loco parentis*.

Name:

Position:

Signature:

Date:

Appendix D: Letter to parents/carers and opt-out form

Schools A and B

Thalia Theodoraki

School of Philosophy, Psychology and Language Sciences

University of Edinburgh

S1460006@sms.ed.ac.uk

Dear Parent

I am a PhD student at the University of Edinburgh and have permission from your child's school to carry out a research project which looks at how cognitive abilities (e.g., working memory, reasoning) are related to adolescents' educational attainment. This project is aimed at providing schools with research evidence so that they can best support their students.

Please find attached an opt out form. Please complete and return this form only if you do not wish for your child to participate. Students with completed opt-out forms will not be invited to participate. Students without completed opt-out forms will be invited to participate, but do not have to (i.e., following detailed information about the project, they will have the opportunity to agree to or decline participation).

Students who participate will take part in 5 tasks. Three of these tasks (similar to puzzles) will be carried out on an individual basis and two tasks will be carried out in class. This will take place during class time and will take approximately 1 ½ hours in total, over a period of two days.

Specifically, in the individual tasks, several sequential stimuli, e.g. words, letters or pictures, will be presented to the students either visually or orally. According to the task, students will be asked to respond to each stimulus in a particular way, e.g. name the colour of ink the word is written in, sort the presented stimuli into categories or repeat what they saw/heard in a certain order.

The group tests will be simple pen and paper assessments. Work sheets containing a number of questions/items will be distributed and the students will have to complete them in a certain amount of time. The first test will evaluate students' numerical skills and will consist of various number-based tasks. The second test, which will evaluate students' reasoning abilities, will contain incomplete matrices of abstract figures and the students have to select from among six figures the one that completes each matrix.

Confidentiality and anonymity is promised to all students; their individual results will not be shared and their names will be turned into codes to protect their identity. The school will receive a report of the results of this project and the implications of these (i.e., advice on how best to support students); however only group results will be shared (rather than an individual's results).

This project has received ethical approval from the Psychology Research Committee, University of Edinburgh.

Yours sincerely,

Thalia Theodoraki

CONSENT FORM

FOR PERMISSION FOR A SCHOOL AGE CHILD TO PARTICIPATE IN A RESEARCH STUDY

To be completed by the child's parent or guardian

Please read the following notes carefully before completing the form.

This form must be attached to a covering letter (which you may detach and keep) and should only be completed and returned **IF YOU ARE UNWILLING** to have your child participate in the research study described in the attached letter.

If you **do not complete and return** the form this will be taken as implying that you
WISH your child to participate in the study.

ONLY COMPLETE AND RETURN THIS FORM IF YOU DO NOT WISH YOUR CHILD TO PARTICIPATE IN THE RESEARCH STUDY

PLEASE USE BLOCK CAPITALS

I, (Insert your Name) ____________________

BEING THE (Insert your Relationship to the child, e.g. Mother/Father/Guardian) ____________________

OF (Insert Child's Name with Class/Reg ____________________

OF (Insert Name of School) ____________________

DO NOT GIVE PERMISSION FOR MY CHILD TO PARTICIPATE IN THE RESEARCH STUDY DESCRIBED IN THE LETTER ATTACHED.

SIGNATURE: ____________________ DATE: ____________________

School C

Thalia Theodoraki

School of Philosophy,
Psychology and Language
Sciences

University of Edinburgh

S1460006@sms.ed.ac.uk

Dear Parent

I am a PhD student at the University of Edinburgh and have permission from your child's school to carry out a research project which looks at how cognitive abilities (e.g., working memory, reasoning) are related to adolescents' educational attainment. This project is aimed at providing schools with research evidence so that they can best support their students.

Please find attached an opt out form. Please complete and return this form only if you do not wish for your child to participate. Students with completed opt-out forms will not be invited to participate. Students without completed opt-out forms will be invited to participate, but do not have to (i.e., following detailed information about the project, they will have the opportunity to agree to or decline participation).

Students who participate will take part in 5 tasks. Their answers from these tasks will be compared to their school performance and/or exam results in various subjects. Three of the tasks (similar to puzzles) will be carried out on an individual basis and two tasks will be carried out in class. This will take place during class time and will take approximately 1 ½ hours in total, over a period of two days.

Specifically, in the individual tasks, several sequential stimuli, e.g. words, letters or pictures, will be presented to the students either visually or orally. According to the task, students will be asked to respond to each stimulus in a particular way, e.g. name the colour of ink the word is written in, sort the presented stimuli into categories or repeat what they saw/heard in a certain order.

The group tests will be simple pen and paper assessments. Work sheets containing a number of questions/items will be distributed and the students will have to complete them in a certain amount of time. The first test will evaluate students' numerical skills and will consist of various number-based tasks. The second test, which will evaluate students' reasoning abilities, will contain incomplete matrices of abstract figures and the students have to select from among six figures the one that completes each matrix.

Confidentiality and anonymity is promised to all students; their individual results will not be shared and their names will be turned into codes to protect their identity. The school will receive a report of the results of this project and the implications of these (i.e., advice on how best to support students); however only group results will be shared (rather than an individual's results).

This project has received ethical approval from the Psychology Research Committee, University of Edinburgh.

Yours sincerely,

Thalia Theodoraki

CONSENT FORM

FOR PERMISSION FOR A SCHOOL AGE CHILD TO PARTICIPATE IN A RESEARCH STUDY

To be completed by the child's parent or guardian

Please read the following notes carefully before completing the form.

This form must be attached to a covering letter (which you may detach and keep) and should only be completed and returned **IF YOU ARE UNWILLING** to have your child participate in the research study described in the attached letter.

If you **do not complete and return** the form this will be taken as implying that you
WISH your child to participate in the study.

ONLY COMPLETE AND RETURN THIS FORM IF YOU DO NOT WISH YOUR CHILD TO PARTICIPATE IN THE RESEARCH STUDY

PLEASE USE BLOCK CAPITALS

I, (INSERT YOUR NAME) ____________________

BEING THE (INSERT YOUR RELATIONSHIP TO THE CHILD, E.G. MOTHER/FATHER/GUARDIAN) ____________________

OF (INSERT CHILD'S NAME WITH CLASS/REG ____________________

OF (INSERT NAME OF SCHOOL) ____________________

DO NOT GIVE PERMISSION FOR MY CHILD TO PARTICIPATE IN THE RESEARCH STUDY DESCRIBED IN THE LETTER ATTACHED.

SIGNATURE: ____________________ DATE: ____________________

Appendix E: Letter/Assent form for pupils

School A

Thalia Theodoraki

School of Philosophy, Psychology and Language Sciences

University of Edinburgh

Dear Student

I am a PhD student at the University of Edinburgh and am interested in understanding how skills related to memory and attention affect educational attainment. The skills I am interested in are often called executive functions (they help people focus and control their actions, in order to achieve their goals). I hope that my research project will benefit schools so that they know how best to support their students. I am writing to ask whether you would be interested in taking part in my project.

It is completely up to you whether to take part or not. If you take part, you will be asked to complete three tasks (like puzzles) individually; this will take no longer than 40 minutes. You will also be asked to complete two tasks with the rest of your class; this will take no longer than 45 minutes. It is not possible to fail these tasks and your score on them will not be related to your school performance or grades in any way. You will be asked to give your name for these tasks. In addition, your teachers may be informed about your performance on them; this is so they know how to best support you at school.

If you choose to take part, you can also withdraw at any time if you do not feel comfortable for any reason.

If you choose not to take part, that is completely fine. Your teacher will give you something to do within the classroom while other students complete the tasks.

Please reply below:

I understand all of the information above and have been given additional support to understand this information (if necessary). Please tick as appropriate:

I would like to take part in this project ☐

I would not like to take part in this project ☐

Student name:

____

Schools B and C

Thalia Theodoraki

School of Philosophy,
Psychology and Language
Sciences

University of Edinburgh

Dear Student

I am a PhD student at the University of Edinburgh and am interested in understanding how skills related to memory and attention affect educational attainment. The skills I am interested in are often called executive functions (they help people focus and control their actions, in order to achieve their goals). I hope that my research project will benefit schools so that they know how best to support their students. I am writing to ask whether you would be interested in taking part in my project.

It is completely up to you whether to take part or not. If you take part, you will be asked to complete three tasks (like puzzles) individually; this will take no longer than 40 minutes. You will also be asked to complete two tasks with the rest of your class; this will take no longer than 45 minutes.

There will be no pass or fail score in these tasks and they will not affect your performance or grades at school in any way. You will be asked to give your name, but all the answers you give will remain completely confidential and only I will be able to see your answers (your teachers will not have access to these). Your answers, from these tasks, will be compared to your school performance and/or exam results in various subjects e.g. Maths, Science and English.

In addition, after the project is completed, I will turn your name into a code, therefore you will not be able to be identified. The identity of your school will also be anonymous. If you choose to take part, you can also withdraw at any time if you do not feel comfortable for any reason.

If you choose not to take part, that is completely fine. Your teacher will give you something to do within the classroom while other students complete the tasks.

Please reply below:

I understand all of the information above and have been given additional support to understand this information (if necessary). Please tick as appropriate:

I would like to take part in this project ☐

I would not like to take part in this project ☐

Student name:

____

Appendix F: Debrief form for pupils

Thalia Theodoraki

School of Philosophy, Psychology

and Language Sciences

University of Edinburgh

Dear Student

Thank you very much for taking part in this project, which looked at the relationship between skills requiring attention and memory, and educational outcomes. Your participation was much appreciated as it will contribute to the completion of my PhD. If you have any further questions about this project please feel free to contact me via email at s1460006@sms.ed.ac.uk .

Yours sincerely,

Thalia Theodoraki

Appendix G: Further information on the characteristics of the overall sample

Table G.1. Presentation of the overall sample of the project broken down by school, year group, gender and condition status[14]. The values correspond to number of pupils.

		School A			School B			School C		
		S3	S4	S5	S3	S4	S5	S3	S4	S5
Female	No condition	8	3	7	43	37	25	5	10	10
Female	Condition	1	-	-	4	7	5	4	2	1
Male	No condition	6	3	4	41	31	23	7	12	15
Male	Condition	-	-	-	11	6	6	4	1	4
	Total	15	6	11	99	81	59	20	25	30

[14] Refers to the categorisation of pupils into two groups (Condtition, No Condition) denoting whether or not they had a developmental, learning and/or physical difficutly that could affect their performance on the cognitive tasks. A list of all the conditions that were considered to influence cognitive performance is provided in Appendix I.

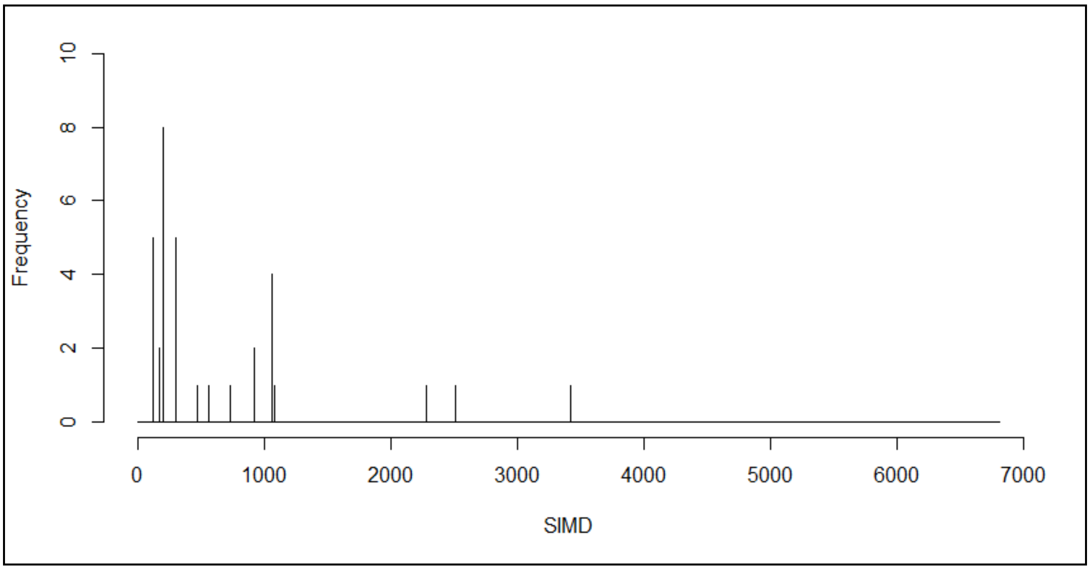

Figure G.1. Histogram depicting the distribution of SIMD among the pupils recruited from School A.

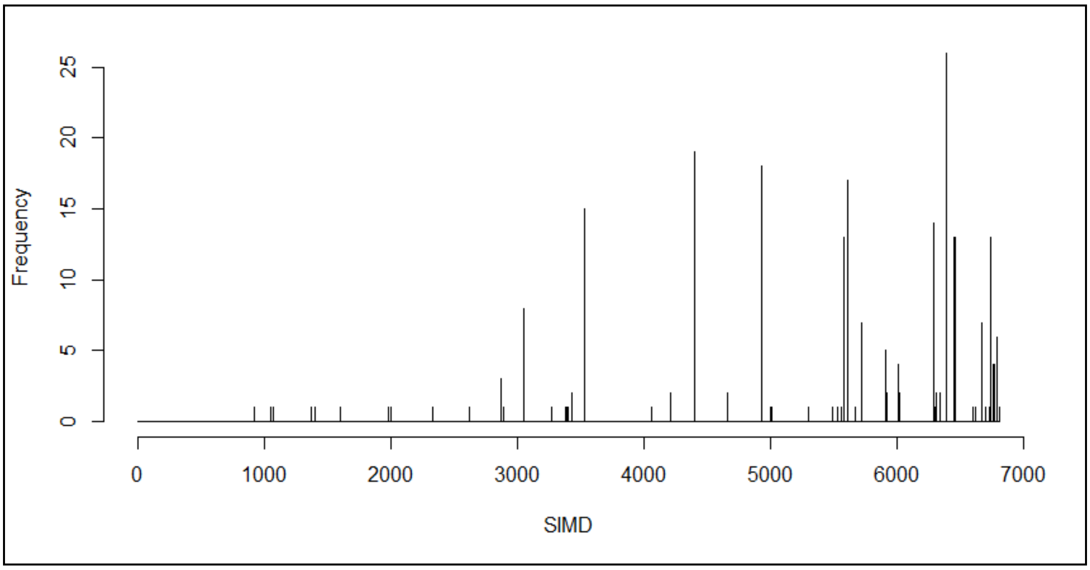

Figure G.2. Histogram depicting the distribution of SIMD among the pupils recruited from School B.

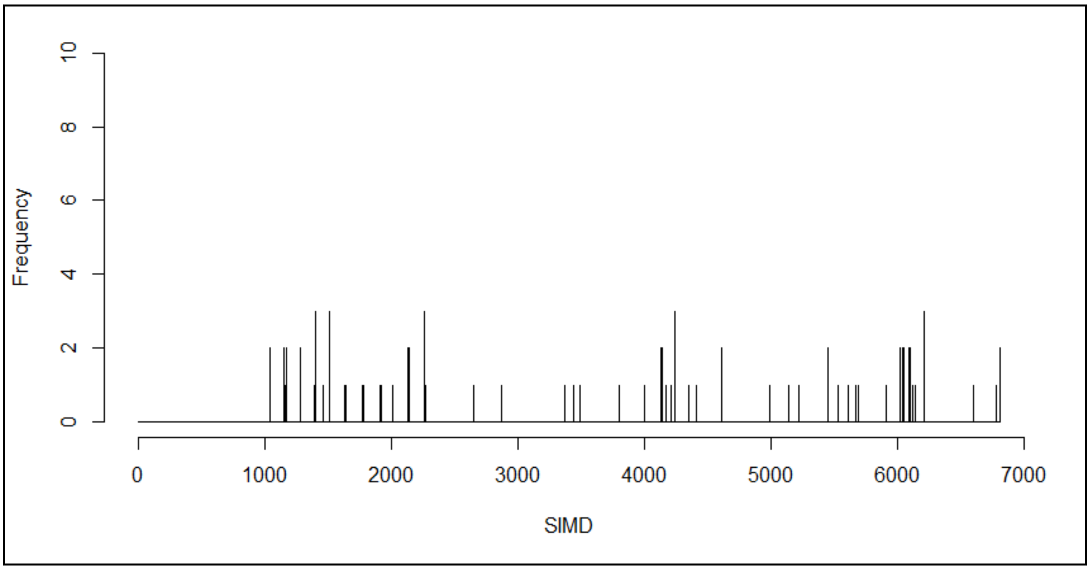

Figure G.3. Histogram depicting the distribution of SIMD among the pupils recruited from School C.

Appendix H: Pupil demographic characteristics form

Information Form

Name:

Gender:

Date of Birth:

School Year currently in:

Ethnicity:

Handedness: I write with my right ☐ left ☐ or both ☐ hand/s

Postcode:

Appendix I: Form containing the list of developmental conditions, learning and/or physical difficulties that all pupils were checked against

Pupil's Information Form

Name:

Please state whether the student suffers from any of the disorders/disabilities listed below. The remark may just be a yes/no statement, which indicates that the child either does/does not suffer from one or more of these conditions. Naming or description of the precise disorder/disability is not necessary.

- Learning disability
- Autism spectrum disorder
- Past Head Injury requiring hospitalisation /Traumatic Brain Injury
- Reading, Written Expression or Mathematics disorder
- Hearing, Speech or Vision problems (incl. colour-blindness)
- Motor impairment

Remark:

Appendix J: Information on the D-KEFS and BAS II batteries

Delis Kaplan Executive Function System

The Delis-Kaplan Executive Function System (D-KEFS) is a battery of tests used to assess executive functions in both children and adults (from ages 8 to 89 years). It consists of nine tests* each of which can act as a stand-alone instrument to be used individually, or in combination with other tests from the battery. The D-KEFS tests have been standardised using a large representative sample of over 1,700 children and adults in the U.S. Therefore, researchers can yield both raw scores and their corresponding standardised scores from each of the D-KEFS nine tests. Moreover, the standardised scores of the different tests can be directly compared since all the tests were standardised on the same reference sample.

One further strength of the D-KEFS battery is that, unlike most of the existing assessment instruments of higher-order cognitive functions, it does not make use of a single achievement score for each test. Because executive-function tests tap a variety of higher-order and more fundamental cognitive functions, each of the D-KEFS tests generates a number of raw (and their equivalent standardised) scores that reflect different aspects of one's performance. More specifically, in addition to the primary scores for each test, a number of optional measures are also provided that allow for a more detailed inspection of various aspects (i.e., verbal and non-verbal) of individuals' performance on the task. The primary scores on the different conditions of a test can also be combined to produce compound or contrast measures that allow to isolate and quantify the contribution of different fundamental and higher-order cognitive functions to overall performance.

British Ability Scales Second Edition

The British Ability Scales Second Edition (BAS II) is a battery of tests used to assess both cognitive abilities and educational achievement in children and adolescents from age two years, six months to seventeen years, eleven months. The battery consists of the Cognitive scales, which measure specific cognitive abilities, and the Achievement scales, which measure educational achievement.

The Cognitive scales are available in two versions: a) the Early Years battery for use with children aged from two years, six months to five years, eleven months and b) the School Age battery for children aged from six years to seventeen years, eleven months. Within each of these groups, the Cognitive scales can be further distinguished into Core scales, which can be used to generate one's General Conceptual Ability Score, and Diagnostic scales, which provide additional information on more discrete abilities. The composition of tests in each of the aforementioned categories is slightly different for the different age groups.

The three Achievement scales of the BAS II are designed to assess three different aspects of educational achievement: Word reading, Spelling and Number skills. All three scales are intended for use with school-age children (aged from six to seventeen years, eleven months).