The Contribution of the Magnocellular Visual Pathway to the Process of Visual Word Recognition

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MPhil

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2007

Acknowledgements

I would like to thank Dr Louise Kelly for supervision, Professor Martin Pickering for reading through rough drafts and offering advice, Dr Richard Shillcock and Dr Scott McDonald for general advice about theories and experiments, Dr Sarah Haywood and Dr Janet McLean for advice on thesis layout, Dr Jamie Pearson for help with formatting, and Callie, Sam and T.J. Comrie.

Abstract

Previous research on visual word recognition has uncovered a variety of factors which influence how easily this process is achieved. Some factors are intrinsic to the word itself (e.g., length, frequency, regularity) and some are environmental factors (e.g., stimuli contrast or visual field position). Any proposed account of visual word recognition must consider not only the properties of the word itself, but also the properties of the visual system that processes the words. This thesis tested the hypothesis that the magnocellular visual pathway contributes to the processing of words and that this contribution is most evident when words are presented in parafoveal vision.

Experiments 1 and 2 investigated the effect on the recognition of isolated words of limiting input to the visual system by occluding one eye. We looked at the effect of visual field presentation position and word length. Previous research using binocular viewing had shown a large length effect in the left visual field. We found that occluding the right eye reduced the left visual field length effect.

Experiments 3, 4 and 5 looked at the impact of varying presentation position on competent readers and dyslexics. Numerous studies in sentence processing have shown that phonological information can be extracted during parafoveal preview. We asked whether dyslexics' well attested phonological impairment will hinder their ability to extract phonological information in parafoveal vision. Experiments 3 and 4 demonstrated that only the dyslexic group showed an effect of word regularity. Experiment 5 used a rhyme-matching task to show that only dyslexic readers have a problem in extracting phonological information from word pairs presented to the right visual field. We relate this to magnocellular functioning.

Experiments 6, 7 and 8 used isoluminant stimuli to directly test the consequences of inhibiting the magnocellular visual pathway on the recognition of words presented both foveally and parafoveally. The results of these experiments show that blocking

the magnocellular pathway affects parafoveal areas of the visual field more than the foveal area and that words are affected by this whereas non-words are not.

In conclusion, we demonstrated that the magnocellular pathway does contribute significantly to the recognition of words and that the parafoveal area of the retina is more heavily dependent on the magnocellular pathway compared to the foveal area of the retina. We go on to propose plans for future research looking at the role of the magnocellular pathway in parafoveal preview in sentence reading.

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Chapter 1

Introduction

1.0 Chapter Overview

The main issue that the thesis addresses is: To what extent do the factors that are not intrinsic to the word itself influence how easily a word is recognised? The thesis concentrates on the properties of the visual system (such as retinal eccentricity and visual field presentation position) that have a bearing on how easily word recognition is achieved. We discuss the differences between foveal and parafoveal perception of stimuli and relate this to the functioning of the parvocellular and magnocellular visual pathways. We describe how the magnocellular and parvocellular pathways input to two left-hemisphere cortical processing streams: The dorsal and ventral streams and we relate this to the word recognition abilities of both skilled and poor readers. Section 1.1 provides an overview of the thesis questions. I will give an account of the “external” factors (properties of the visual system) that may influence word recognition, including dorsal and ventral stream processing. Section 1.2 provides an overview of the thesis chapters.

1.1 Issues Central to the Thesis

This thesis focuses on exploring the aspects of the visual system that influence how easily a word is recognised. Specifically, I will be examining the influence of presentation position of the stimuli (foveal and parafoveal) and the possible contribution of the magnocellular visual pathway to the process of word recognition in both skilled and poor readers. The literature on the recognition of individually presented words shows that not all words are recognised with the same ease. There are many factors that have been shown to influence how easily an individual word is recognised. Some of these factors are related to the word itself. These include word frequency (e.g., Monsell, 1991), with high frequency words being recognised faster than low frequency words. Word length also plays a role with shorter words being recognised faster than long words (e.g., Ellis, 2004). The regularity of grapheme-to-phoneme correspondence also influences how quickly the word is recognised. Regularly spelled words that are pronounced in the same way that they are spelled are more easily recognised than exception words that have a pronunciation that is not related to the way they are spelled (e.g., Stanovich & Bauer, 1978).

The area of the visual field in which the word is viewed can affect word recognition. Words are more easily recognised when they are viewed in foveal vision compared to when they are viewed in parafoveal vision. It has been proposed that this is due to the decrease in visual acuity as retinal eccentricity increases (Henderson, Dixon, Petersen, Twilley, & Ferreira, 1995). We propose an account that considers not only visual acuity but also visual attention and the relative contributions of the dorsal and ventral processing streams. In addition, environmental factors can influence the recognition of words. The level of contrast between text and background can affect how easily word recognition is achieved with the highest contrast level (black and white) being the easiest to distinguish (e.g., Bruce & Green, 1990; Williams, 2000). In the thesis we relate this to magnocellular-parvocellular functioning and to the functioning of the dorsal and ventral processing streams. These findings imply that any proposed account of visual word recognition must take into account not only the differences between types of words but also the environment that the words are viewed in and the properties of the visual system that must process the words. The main goal of this thesis is to explore the brain mechanisms that allow visual word recognition to occur and to examine how these mechanisms are affected by environmental factors (such as visual field presentation position) and by the properties of the words themselves (such as word frequency, regularity of spelling etc.).

As well as investigating the effects of different presentation positions on the recognition of words, the thesis will also explore the contribution of the magnocellular and parvocellular visual pathways to word recognition. We describe the two left hemisphere cortical processing systems and provide evidence for the segregation of the magnocellular and parvocellular streams in these systems. It is believed that the ventral processing system receives both magnocellular and parvocellular input (Ferrera, Nealey, & Maunsell, 1994; Nealey & Maunsell, 1994) but that the dorsal stream receives almost exclusively magnocellular input (Maunsell, Nealey, & De Priest, 1990). We describe the neurological models that attribute lexical and sub-lexical reading processes to these two routes (e.g., Sandak et al., 2004) with sub-lexical processing being attributed to the dorsal route and lexical processing being attributed to the ventral route. We discuss the evidence that indicates that the ventral processing route develops later and can be related to the skill level of the reader (e.g., Zoccolotti et al., 2005). We also examine the claim that there is an impairment in the ventral processing stream in readers who have dyslexia (Zoccolotti et al., 2005).

1.2 Thesis Summary

In order to put the thesis research into context, chapter 2 gives an overview of the neurological background to the research. I will cover details of the structure and function of the human eye and provide details of the cells types in the retina and I describe the two main types of visual pathway (the magnocellular and the parvocellular) that arise from the retina and project to the brain. I will then give a description of the sub-cortical brain structures that are important in visual perception such as the lateral geniculate nucleus and the superior colliculus. I describe how these structures connect to, and interact with higher cortical areas such as the visual cortex and posterior parietal cortex and how the magnocellular-parvocellular distinction is maintained in these structures. In this section I will give an account of how the two types of visual pathway project to the previously mentioned cortical areas and to what extent they remain segregated in the higher visual areas of the brain.

Chapter 3 provides a more detailed account of how the visual field is projected to the brain. I will look at properties of the visual field such as the differences between the left and right visual fields and the differences between processing by the foveal area of the retina and the parafoveal area of the retina. In this section I will provide evidence of the segregation of magnocellular and parvocellular visual input to the dorsal and ventral processing streams and will also give a brief introduction to the relative importance of both of these streams in visual word recognition and reading ability in general. I will then go on to look at the evidence for a parafoveal preview and to examine the types of lexical information that are available in parafoveal preview. I will describe how this relates to visual word recognition by the magnocellular and parvocellular visual pathways.

Chapter 4 contains experiments 1 and 2. These experiments used a lexical decision paradigm to investigate the effect that limiting input to the visual system - by occluding one eye – had on the recognition of isolated words. We present evidence that suggests that occluding one eye causes a change in the distribution of visual attention throughout the visual field (Roth et al., 2002). Experiment 1 tests the effect of monocular occlusion on words presented in different areas of the visual field: left visual field, central, and right visual field. Experiment 2 investigates the effect of monocular occlusion on word length effects in the left visual field. Previous research using binocular viewing had shown a larger effect of word length in the left visual field compared to in the right visual field. We test the impact of manipulating visual attention on these word length effects.

Numerous studies in sentence processing have shown that phonological information can be extracted during parafoveal preview. In Chapter 5 we describe a further set of experiments which explores the impact of varying the presentation positions of stimuli on both competent readers and those with developmental dyslexia. We hypothesise that if dyslexic readers do have a dorsal stream impairment then this will hinder their ability to extract phonological information from words that are viewed in parafoveal vision. We go on to propose that a disruption in the magnocellular visual pathway (and therefore a dorsal stream deficit) will exacerbate existing phonological difficulties and that they will be most evident when processing words that are viewed parafoveally. Using a lexical decision paradigm, in Experiment 3 we centrally present regular and exception words to gauge the ability of dyslexic and control readers to extract phonological information in foveal presentation. Experiment 4 replicates this method but also presents the stimuli parafoveally in left or right visual fields. We extend the manipulation of visual field presentation in Experiment 5.

Using an eye tracking paradigm, dyslexic and control readers are required to extract phonological information to successfully complete a rhyme matching task. We examine the differences between the abilities of the non-impaired group and the dyslexic group on making rhyme judgements in both foveal and parafoveal presentations. We relate the findings to the functioning of the ventral and dorsal processing streams.

In Chapter 6, we present experiments 6, 7 and 8. We directly test the contribution of the magnocellular pathway and the dorsal processing stream to visual word recognition. It is well established that using a red background inhibits the activity of the magnocellular pathway. If dorsal route input is almost exclusively magnocellular then dorsal stream processing should be impaired by inhibiting the magnocellular pathway. We exploited this technique to test the relative contributions of the dorsal and ventral processing streams to word recognition. In Experiment 6 this was achieved using a Word Superiority Task. In Experiment 7 we looked at the effect of presenting words against a red background on word and non-word recognition using a lexical decision task. A further lexical decision task in Experiment 8 looked at the effect of magnocellular/ dorsal stream inhibition on the recognition of regular versus exception words in the fovea and in the parafovea.

In chapter 7, we bring together the evidence from the literature and the current thesis experiments to demonstrate that both the magnocellular and the parvocellular pathways are essential for the accurate recognition of words and that the parafoveal area of the retina is more heavily dependent on the magnocellular pathway compared to the foveal area of the retina. We relate the functioning of the magnocellular and parvocellular pathway to the dorsal and ventral processing streams and we present a theory that attempts to account for the distribution of the ventral and dorsal processing streams throughout the visual field. We outline plans for future research that further tests the contributions of the dorsal and ventral processing streams in relation to visual attention and in the context of sentence reading.

Chapter 2

Neurological Background

2.0 Chapter Overview

In order to provide a background for the thesis hypotheses and experiments, it is necessary to explain how the eye transmits the visual signal to the brain and also what happens to visual input once it has reached the brain. This chapter provides an overview of the structure of the eye and of the brain areas that are important for visual perception. In section 2.1 I describe the structure of the eye and the different types of cell that are present in the human retina. I will examine how these cells form neuronal pathways from the eye to the brain and how these visual pathways operate. Section 2.2 covers the sub-cortical brain structures that play an important role in visual perception and also describes the projection of the two main visual pathways to the sub-cortical structures that are essential to the processing of visual stimuli. In section 2.3 I will describe what happens to the input when it reaches primary visual cortex and how area V1 projects on to the higher visual areas such as V2, V4 and MT. Section 2.4 provides a more detailed account of the higher cortical visual areas with reference to the projections of, and the segregation of, the magnocellular and parvocellular visual pathways.

2.1 Overview of the Structure and Function of the Eye

In this section I will describe the structure of the eye and the types of cells that are found in the retina. I will explain how these cells transform the light that falls on the retina into an electrical signal that is then transmitted to the brain. I will demonstrate how the retinal input begins to split and how different types of input are processed by different sub-types of cells. This is the point at which the magnocellular–parvocellular segregation begins.

2.1.1 Cell Types in the Retina

The human eye does not directly detect the properties of objects in the visual field. Instead, cells in the retina detect variations in the levels of light that are reflected from different objects in the visual field. The image that is projected onto the retina is an inversion of the visual field. The inner half of the retina that is closest to the nose (the nasal hemiretina) receives ipsilateral visual input and the outer half of the retina that is closest to the temple (temporal hemiretina) receives contralateral visual input.

Much of the processing of visual information occurs before the visual signal reaches the brain (Kuffler, 1953). Between the photoreceptors (the cells that receive the light that enters the eye) and the retinal ganglion cells (the cells that transmit the visual signal from the eye to the brain) the image is refined and information about diffuse illumination is suppressed through lateral inhibition, a neural mechanism where strongly activated neurons inhibit their less strongly activated neighbouring cells. This refined information is then transmitted to the brain for further processing. Two types of cell in the human retina are of particular importance in the processing of the visual signal before it reaches the brain: photoreceptors and retinal ganglion cells. I will give a brief description of their functions.

Photoreceptors: Photoreceptors are the first cells in the retina to receive the visual signal when it enters the eye. Even at this early stage of visual perception we can see how the input begins to diverge. There are two types of photoreceptor: rods and cones. Rods are more sensitive to low levels of light and so are specialised for perceiving visual stimuli in conditions of low luminance. Cone cells on the other hand, function optimally in conditions of high luminance. Only cone cells are involved in colour vision, rods are colour-blind. Cones are densely packed in the fovea (the area of the retina that perceives the central visual field) and there are a greater number of rods than cones in the peripheral retina (the area of the retina that perceives the peripheral regions of the visual field). Photoreceptors map onto retinal ganglion cells (the cells that transmit the visual signal from the eye to the brain) through bipolar cells. Rod photoreceptors converge onto a large number of bipolar and ganglion cells making the rod system highly sensitive to low levels of light (because they sum the inputs from a larger area of the visual field). Cone photoreceptors converge onto only a few bipolar and ganglion cells making them highly sensitive to spatial resolution but less sensitive to low levels of light. Because of this, under conditions of high luminance the human eye has good spatial resolution whereas under conditions of low luminance, we can only see hazy outlines. This also explains why stimuli that appear in the area of the visual field that is sampled by the fovea are seen in more detail compared to stimuli that appear in the area of the visual field that is sampled by the parafoveal and peripheral areas of the retina. The different response properties of the two types of photoreceptor allows us to see, even at this early stage of processing, that different types of visual input (e.g., colour, contrast, luminance) are processed by different sub-types of cell. This segregation of the input continues to exist as far as visual cortex and possibly beyond to higher cortical areas. As different aspects of the visual input are split between two cell types it suggests that both cell types are required in order to fully process the visual image.

Retinal ganglion cells: The retinal image is processed by approximately one million retinal ganglion cells. Retinal ganglion cells receive information from photoreceptors through bipolar cells and they, in turn, generate action potentials to transmit visual information from the eye to the brain. The size of the receptive field of retinal ganglion cells varies depending on which part of the retina they arise from. The receptive fields of ganglion cells get larger as they move away from the foveal towards the peripheral region of the retina. Ganglion cells in extra-foveal regions of the retina receive input from a greater number of photoreceptors compared to the ganglion cells in the foveal regions of the retina. This makes the peripheral regions of the retina more sensitive to low levels of light and stimulus motion whereas the fovea is more sensitive to high spatial frequencies. Visual stimuli that appear in the foveal area of the retina are seen in more detail compared to stimuli that appear in the parafoveal area of the retina. This can be related to the finding that word recognition is easier when the words are viewed by the fovea compared to when they are viewed by the parafovea (Henderson et al., 1995).

Ganglion cells have a centre-surround organisation. The strongest cellular response to light falling on the receptive fields of these cells is generated when only the centre or only the surround of the cells is stimulated. When both centre and surround are stimulated, the cells only generate a weak response to light. Fifty per cent of retinal ganglion cells have an excitatory centre and an inhibitory surround and fifty per cent have an inhibitory centre and an excitatory surround (Dowling, 1987). This centre-surround organisation is the mechanism that allows us to selectively inhibit the magnocellular visual pathway in the experiments in chapter six. It has been shown that a percentage of magnocellular retinal ganglion cells have an inhibitory surround that is maximally responsive to lights of longer wavelengths (e.g., Lee, 1996) and that a uniform field of red light can suppress the activity of these neurons (Wiesel & Hubel, 1966). We make use of this in chapter six to test the effect of magnocellular inhibition on word recognition.

This centre-surround organisation of the cells creates a retinotopic map that is then projected to the brain. This is a map of the variance of points of light in the visual field. Objects in the visual field reflect different amounts of light and it is this that allows objects to be perceived as separate from other objects and from the background. A retinotopic map is a direct copy of the visual field. There is a one-to-one correspondence between the visual field and the map on the retina. The map is preserved in the LGN, the superior colliculus and some areas of cortex, including area V1. The preservation of the retinotopic map indicates that the neural representations of the foveal and parafoveal areas of the visual field remain separate in the brain.

P and M ganglion cells: There are three main types of retinal ganglion cell: M cells (magnocellular), P cells (parvocellular) and non-M, non-P type cells (or “K cells” which are koniocellular). P cells are the most numerous type of cell in the retina with approximately 80% of retinal ganglion cells being classified as P-type cells. Ten per cent of retinal ganglion cells are M cells (Perry et al., 1984a) and the remaining ten per cent are K cells. The K cells are not as extensively researched as M and P cells. It is thought that instead of playing a direct role in visual perception they might play a role in the modulation of visual cortex. Most of the output (90%)

from these K cells transmits to the LGN. K cells also have projections to the superior colliculus (10% of K input). The K ganglion cells transmit to the koniocellular layers of the LGN and are not central to this discussion (see Reid, 1999, for a review).

The distinction between M and P cells is central to the topic of this thesis. As we intend to test the contribution of the magnocellular visual pathway to word recognition it is important to make clear the differences in processing capabilities between M and P cells and to highlight the differences in the cortical projections of both cell types in order to show how our experimental manipulations affect each visual pathway. The differences between M and P cells arise as early in visual processing as the connections between photoreceptors and bipolar cells (Shapley, 1995). The spatial resolution of a retinal ganglion cell depends on the number of photoreceptors that converge their output onto the ganglion cell. If a ganglion cell receives input from many photoreceptors, spatial resolution will be poor (the input photoreceptors sample a larger area of the visual field so it is not possible to accurately pinpoint a precise spatial location for the origin of the stimulus). P retinal ganglion cells have relatively few photoreceptors mapping onto them. As a consequence of this, P retinal ganglion cells have good spatial resolution but poor temporal resolution. P cells are particularly well adapted to the processing of small targets and fine detail.

In contrast to P cells, M cells receive input from a large number of photoreceptors, and have receptive fields that are two to three times larger than the receptive fields of P cells. These characteristics make M cells ideally suited to detect stimulus motion in the visual environment. The large receptive fields make M cells ideal for detecting the sudden onset of a visual stimulus, which enables them to redirect spatial attention to the new stimulus. However, because an individual M cell samples a larger area of the visual field, (due to their large receptive fields), M cells do not have the same degree of spatial resolution as P cells and are only suitable for the perception of coarse-grain, global visual input. M cells have a transient response. P cells have a sustained response.

In addition to the above mentioned differences, M and P cells also differ with respect to the areas of the visual field that they sample. P cells are the most common type of cell to arise from the foveal area of the retina (Dacey, 1994; Perry et al., 1984a; Polyak, 1941). P cells are found mostly in the foveal area of the retina but are also found, to a lesser extent, in the parafoveal and peripheral areas. The fovea is a small, but highly sensitive area of the retina that receives the centre of the visual field extending approximately 2° around the point of fixation. The centre of the visual field gives rise to a much more detailed retinal image because the P cells that sample this area respond optimally to fine-grain detail and colour stimuli.

M retinal ganglion cells are the most common type of ganglion cell in the extra-foveal regions of the retina (Dacey, 1994). There are relatively few M cells compared to the number of P cells in the retina. The axons of M cells (the part of the cell that conducts the nerve impulse) are thicker and have more myelination compared to P cells giving M cells a faster conductance rate by approximately 20ms (Lamme & Roelfsema, 2000; Schmolesky et al., 1998). The faster conductance rate of M cells means that these cells are specialised for detecting stimuli of high temporal frequencies. Because M cells do not detect high spatial frequencies, the image outside of the central visual field is less clearly defined, as M cells are the most common types of cell outside of the fovea. M cells are also colour-blind. Only P cells (and K cells) are able to detect colour in a stimulus.

The differences in the response properties of the two main types of retinal ganglion cell enables us to understand why words are recognised faster when they are presented in foveal vision compared to when they are presented in parafoveal vision. As the most common type of retinal ganglion cell to sample the foveal area of the retina is the parvocellular retinal ganglion cell then we can see why foveal word perception is easier. Parvocellular retinal ganglion cells are more specialised for detecting fine-grain detail (such as printed words). On the other hand, magnocellular retinal ganglion cells are more common in the parafoveal and peripheral areas of the retina. These cells are specialised for detecting more coarse-grained visual input. This makes recognition of parafoveally viewed words more difficult than foveal recognition of words.

2.1.2 Projections of the Visual Pathways from Eye to Brain

We have seen in the previous section that M and P cells detect different properties of the stimulus and that each cell type contributes in varying degrees to stimulus perception in different areas of the visual field. In this section, I will show how the differences between these two cell types are preserved in the projections from the eye to the brain.

On leaving the eye, the axons of the P, M and K retinal ganglion cells converge together to form the optic nerve. The visual signal is transmitted along the optic nerve from the eye to the brain. The two optic nerves (one from each eye) meet at the optic chiasm and become the two optic tracts. The optic tract connects the optic chiasm to the lateral geniculate nucleus (LGN). The LGN is an area of the thalamus that relays visual input through the optic radiation to primary visual cortex (area V1). This is the geniculostriate pathway, and is the main projection of the optic nerve. The optic nerve also has a lesser projection called the collicular pathway which sends axons to the superior colliculus (SC). The superior colliculus retains the retinotopic map and is responsible for tracking eye-movements and for spatial orientation. The majority of the input to the superior colliculus is transmitted by M retinal ganglion cell axons suggesting a major role of this projection of the magnocellular pathway is to direct the eyes towards potentially relevant stimuli in the visual field. Input to the LGN is from both P and M axons.

The magnocellular pathway is responsible for fast transmission of coarse-grain visual information from the retina to the superior colliculus and the LGN. M retinal ganglion cells map onto the magnocellular layers of the LGN. The parvocellular pathway is responsible for the transmission of fine-grain, colour visual information from the central regions of the retina to the LGN. P retinal ganglion cells map onto the parvocellular layers of the LGN. This partitioning of the input means that the foveal region is more strongly represented in the parvocellular layers of the lateral geniculate nucleus and the extra-foveal (parafoveal and peripheral) regions of the retina are more strongly represented in the magnocellular layers of the LGN (P cells are more common in the fovea, M cells are more common in the peripheral retina). The magnocellular and parvocellular pathways remain mostly segregated in the lateral geniculate nucleus meaning that information about stimulus motion and stimulus colour are also segregated at this stage of visual processing.

In summary, retinal ganglion cells receive input from photoreceptors and transmit the visual signal from the eye to the brain. Parvocellular retinal ganglion cells are the most common type of ganglion cell to arise from the foveal region of the retina. They have good spatial and poor temporal resolution and are responsible for the processing of colour and fine detail. Magnocellular retinal ganglion cells are the most common type of ganglion cell to arise from the extra-foveal regions of the retina. They have poor spatial and good temporal resolution. They have a faster conductance rate and are specialised for detecting motion and global spatial information in the visual field. M and P retinal ganglion cells transmit visual information from the eye to the brain along the optic nerve. The main projection from the eye to the brain is the geniculostriate pathway which projects to the LGN. This pathway is a combination of M, P and K axons. A lesser pathway (the collicular pathway) projects to the superior colliculus. This pathway is mainly magnocellular demonstrating that the magnocellular pathway is responsible for planning of saccades and the location of stimuli in the visual field.

2.2 Sub-cortical Brain Regions Involved in Processing Visual Stimuli

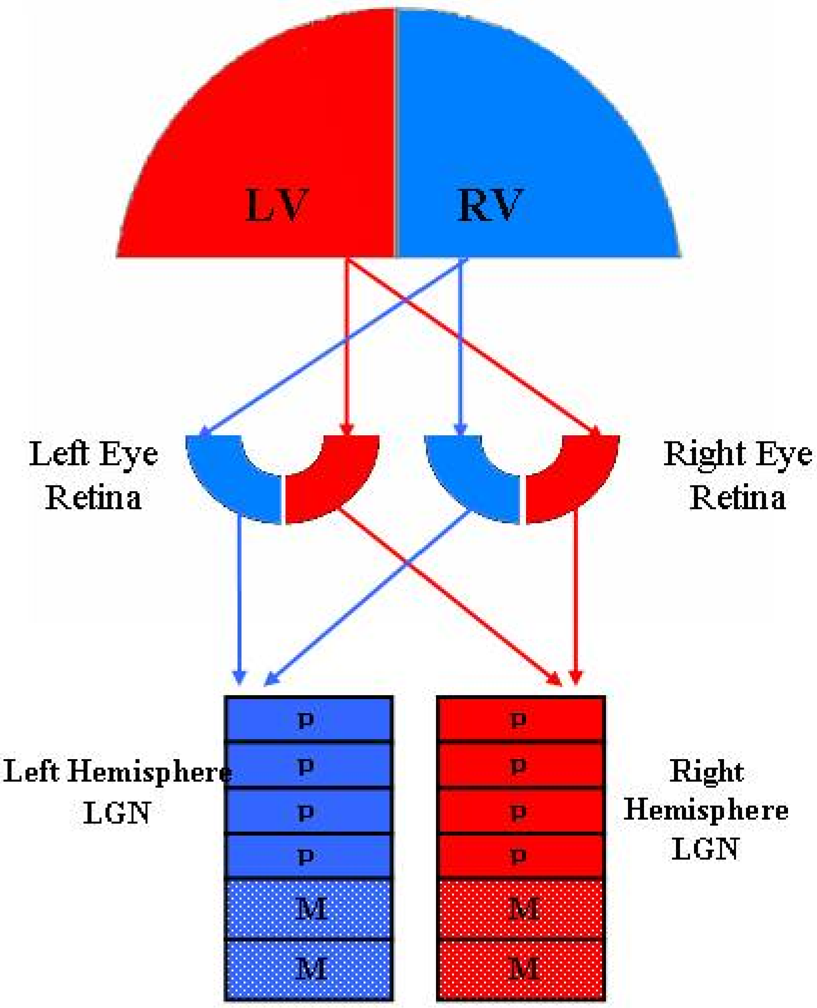
In the previous sections we have looked at the processing differences between the two main visual pathways and have briefly looked at the differences in the cerebral projections of these two pathways. In this section, the segregation of the two types of visual pathway will be examined in more detail. I will also look at why the continued segregation of the input is necessary in visual perception.

2.2.1 The LGN

The lateral geniculate nucleus (LGN) is part of the thalamus, a sub-cortical brain structure that acts as a “relay station” for visual and auditory information. There is one LGN in each cerebral hemisphere. Each LGN has six distinct layers and receives input from both eyes. The nasal hemiretinae (the halves of the retina that are closest to the nose) project contralaterally to the LGN so the left hemisphere

LGN receives nasal hemifield input from the right eye and the right hemisphere LGN receives nasal hemifield input from the left eye. The temporal hemiretinae (the halves of the retina that are closest to the temples) project ipsilaterally to the LGN so the left hemisphere LGN receives temporal hemifield input from the left eye and the right hemisphere LGN receives temporal input from the right eye. Since the temporal hemiretinae receive contralateral input from the visual field and the nasal hemiretinae receives ipsilateral input from the visual field, the entire LVF is projected to the right hemisphere LGN and the entire RVF is projected to the left hemisphere LGN (see Figure 1 for a schematic diagram of the projections to the LGN).

Figure 1:Projections of the left visual field (LV) and the right visual field (RV) to the LGN. The LGN shows magnocellular (M) layers and parvocellular (P) layers



The LGN is segregated in a series of six layers. Layers 1 and 2 are magnocellular, and layers 3, 4, 5 and 6 are parvocellular. The cell bodies of the neurons in layers 3 to 6 are much smaller than the cell bodies of the neurons in layers 1 and 2. P retinal ganglion cells project to the parvocellular layers of the LGN and M retinal ganglion cells project to the magnocellular layers of the LGN. K ganglion cells project to koniocellular layers that lie between the six main layers (not shown). The cells in the LGN appear to have very similar properties to their corresponding cells in the retina (Bullier & Norton, 1979). In the LGN, input remains segregated. The magnocellular/ parvocellular distinction is maintained. The two visual fields (left and right) are kept separate, as is information about which eye a particular signal originated from.

The LGN receives input from the reticular activating system which modulates the activity of the LGN. This area of the brain controls levels of alertness and attentiveness. Therefore, the level of activation of LGN neurons depends on how much attention the observer is paying. There is also a massive amount of recurrent connections from area V1 to the LGN. At least 80% of the total input to the LGN is feedback connections from V1. The feedback connections are magnocellular (the fastest type of visual pathway). The presence of these recurrent projections shows a mechanism that allows for the influence of top-down processing on visual processing.

The representation of the fovea in the parvocellular layers of the LGN takes up a large amount of the LGN (Connolly & Van Essen, 1984; Le Gros Clark, 1941; Malpeli & Baker, 1975; Walls, 1953). There is a dense population of photoreceptors in the fovea compared to the peripheral visual field. It is this that enables the perception of very fine detail in the visual field. As a consequence of this, the fovea occupies a large part of the retinotopic map. The representation of the fovea is magnified compared to peripheral regions of the retina. The fovea takes up 0.005mm circumference in the retina and is magnified 10,000 times to take up 0.5mm in the cortex. The magnocellular / parvocellular segregation appears to be maintained as far as V1, and possibly, to some extent, as far as V4 and V5. The LGN has projections to visual cortex (specifically, area V1). This image is a precise retinotopic map.

2.2.2 The Superior Colliculus

About 10% of the output from M retinal ganglion cells projects to a sub-cortical structure known as the superior colliculus. The superior colliculus (SC) is involved in the planning and execution of saccadic and pursuit eye movements. This area of the brain identifies where an object is in the environment and orients the head and eyes towards the visual targets. The superior colliculus also co-ordinates sensory information such as vision, hearing and touch and detects movement in the visual field. Output from the superior colliculus goes to the frontal eye fields (to control saccadic eyemovements, the tectospinal tract (to control movements of the head) and the pulvinar of the thalamus (to help maintain a stable vision of the world, even when the head moves). After leaving the pulvinar, the signal is projected back to visual cortex (area MT) for further processing. There are also connections to the tectopontine tract that provides input to the cerebellum. All of these functions mentioned above are dependent on magnocellular input.

In summary, the main projection from the eye to the cerebrum is through the optic nerve to the lateral geniculate nucleus. The LGN has six layers: two magnocellular and four parvocellular. The right visual field projects to the LGN in the left hemisphere and the left visual field projects to the LGN in the right hemisphere. The LGN also receives input from the reticular activating system meaning that the activity of LGN neurons depends on the attentional levels of the viewer. Eighty per cent of the total input to the LGN is from recurrent projections from higher visual areas (suggesting an influence of top-down processing on visual perception). These recurrent projections are magnocellular. The magnocellular – parvocellular distinction is maintained in the projections to area V1 in visual cortex, as is ocularity. The retinotopic map is maintained with the fovea being magnified in the representation. Both the magnocellular and parvocellular pathways project from the eye, through the LGN, and then to visual cortex. Only the magnocellular pathway projects to the superior colliculus (involved in eye movement control and spatial orientation) (see Farah, 2000, for details).

2.3 Visual Cortex

In this section I will consider the evidence for the continued segregation of the magnocellular and parvocellular pathways in the higher cortical brain areas. I will compare the functions of both pathways in order to show how each pathway contributes to visual processing.

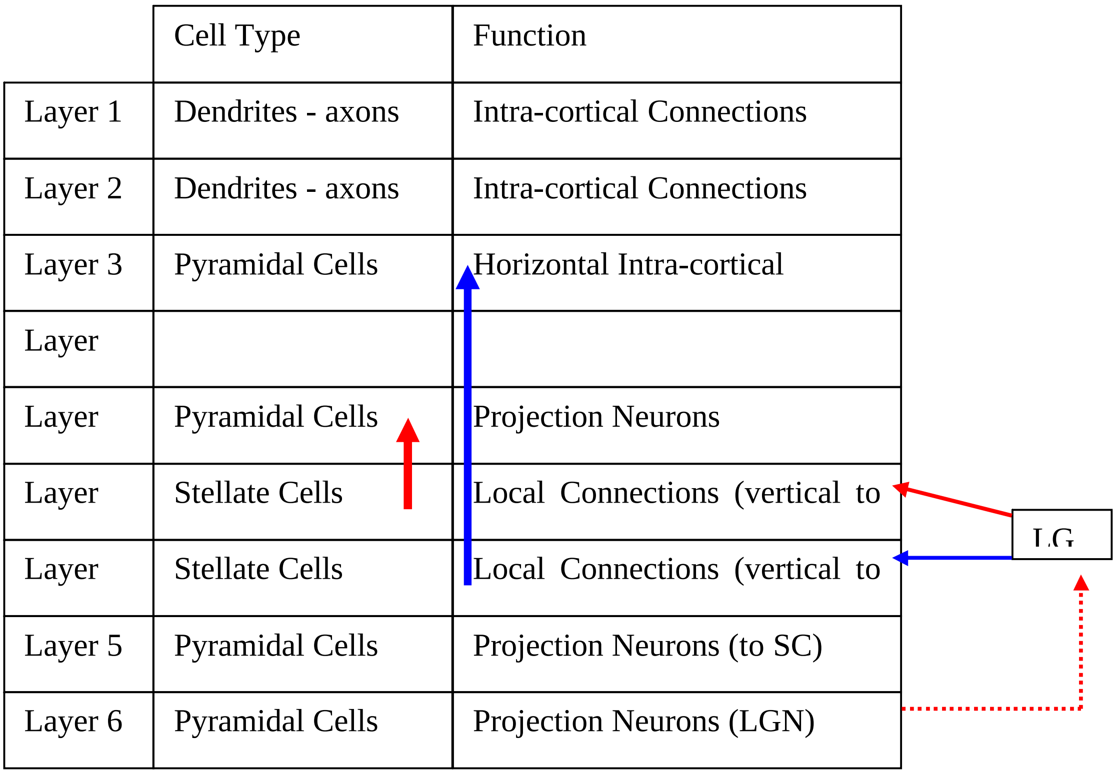
2.3.1 Visual Area V1

The main projection of LGN is to area V1 (primary visual cortex). V1 receives projections from, and sends output to, the LGN, area V2, area V3, area V4, and area V5 (MT). The LGN projects a precise, retinotopic map to area V1. The fovea takes up a large proportion of this map (and consequently, a large amount of brain processing power) because it is the most detailed area of the retina. This leads to "cortical magnification" of the fovea (e.g. Tootell et al 1982).

The main difference between the LGN and visual area V1 is the difference in the types of receptive fields of the cells. There are still some cells in area V1 that have the centre-surround organisation of the retinal ganglion cells but there are also "Simple cells" and "Complex cells" (Hubel & Weisel 1962). Simple cells respond to bars of light or dark at a particular orientation and location. Complex cells only respond to the orientation of a bar (ignoring the location). This is where the process of feature abstraction begins.

There are nine layers in area V1 (layer 1, layer 2, layer 3, layer 4a, layer 4b, layer 4ca, layer 4cß, layer 5 and layer 6). Layers 1 and 2 are mostly acellular; they contain only axons and dendrites that project to other areas of the cortex. Layer 3 contains pyramidal cells which are projection neurons: they carry output from area V1 to other brain areas, including area V4. Layer 4b also contains pyramidal cells. Layer 4ca and 4cß contains stellate cells (these are local projections. They project to other layers within area V1. For example, layer 4ca projects to layer 4b and 4cß projects to layer 3). Layers 5 and 6 contain pyramidal cells. Layer 5 pyramidal cells have large receptive fields and project to the superior colliculus (showing a possible mechanism for the influence of top-down processing on eyemovement control) and layer 6 projects back to the LGN. The projection back to the LGN is largely magnocellular (see Figure 2 for a schematic diagram of area V1 projections).

Figure 2: The layers of area V1 showing the cell types in each layer and the functions of each type of cell. Magnocellular projections are shown in red. Parvocellular projections are shown in blue



	Cell Type	Function
Layer 1	Dendrites - axons	Intra-cortical Connections
Layer 2	Dendrites - axons	Intra-cortical Connections
Layer 3	Pyramidal Cells	Horizontal Intra-cortical
Layer		
Layer	Pyramidal Cells	Projection Neurons
Layer	Stellate Cells	Local Connections (vertical to
Layer	Stellate Cells	Local Connections (vertical to
Layer 5	Pyramidal Cells	Projection Neurons (to SC)
Layer 6	Pyramidal Cells	Projection Neurons (LGN)

Most of the neuronal projections from the LGN synapse onto layer 4c of area V1. The magnocellular pathway inputs to layer 4ca, the parvocellular pathway inputs to layer 4cß, and the koniocellular pathway inputs to the cortical blobs in layer 3. Therefore, the separation of the magnocellular and parvocellular streams is still maintained in primary visual cortex. The projections from area V1 to higher cortical areas also maintain the magnocellular – parvocellular distinction to some extent.

Layer 4 of area V1, where the LGN projections terminate, contains ocular dominance columns. If the input to cortex from one eye is chemically labelled, stripes about 0.5mm wide appear in layer 4 of area V1. These stripes are ocular dominance columns. These columns are groups of neurons that share the same type of input (e.g. from the left eye or from the right eye). Each ocular dominance column responds to one eye only. The ocular dominance column for the inputs from the left eye for a particular point in space are directly adjacent to the ocular dominance column for inputs from the right eye for that same point in space.

2.3.2 Magnocellular and Parvocellular Projections to Area V1

Cells from the magnocellular layers of the LGN project to layer 4Ca of area V1 which, in turn, projects to layer 4B of area V1. The cells in layer 4B have orientation selectivity, binocular sensitivity, and are sensitive to the direction of stimulus motion. These cells are not sensitive to colour making the magnocellular pathway specialised for analysing the motion of an object but insensitive to the colour of the object.

Cells from the parvocellular layers of the LGN project to layer 4cß of area V1 which projects to layers 2 and 3 of V1. The cells in layers 2 and 3 have small receptive fields and are highly sensitive to stimuli orientation. They are also sensitive to binocularity. Information from the two eyes begins to merge in layers 4B and 3 but the magnocellular and parvocellular signals remain segregated. In layer 3, the parvocellular pathway projects to two different areas: blobs and interblobs. Blob cells contain single eye information and interblobs contain mixed information from both eyes.

These two functional subdivisions of area V1, blobs and interblobs (Livingstone & Hubel, 1988) become highlighted under cytochrome oxidase staining. When this staining is applied to area V1, spots appear in layers 2 and 3 (Hubel & Livingstone, 1987; Wong-Riley, 1979). These are known as cortical blobs. I will give a brief description of blob and interblob functional specialisations and their projections to other cortical areas.

Blobs receive parvocellular input from layer 4cß in area V1 and also koniocellular input directly from the LGN. Blobs are located within ocular dominance columns and only respond to input from one eye. Blobs are sensitive to colour and respond best to low spatial frequencies. These cells are not sensitive to stimulus orientation and respond equally to all orientations of a stimulus. Blobs project to the thin stripes of area V2.

Interblobs are found between the blob regions. Both the magnocellular and parvocellular interblob streams are orientation selective with each containing cells that respond only to a particular orientation of a stimulus. Small receptive fields make the cells ideally suited to processing stimuli of high spatial frequency. These cells are binocular (they begin to integrate information from both eyes) and are relatively insensitive to colour. Interblobs project to the pale stripes of area V2.

2.4.1 Visual Area V2 - Thick, thin and pale stripes

Area V1 has output connections to other brain areas such as the superior colliculus and the LGN but the main projections from area V1 are to area V2. Area V2 also has strong recurrent projections back to area V1. The retinotopic map is preserved between area V1 and area V2 although the map becomes inverted in area V2. Anatomically, area V2 is split into four sections: a dorsal and a ventral part in each cerebral hemisphere. Each of these parts contains a representation of a quarter section of the visual field. The four parts together form a complete representation of the whole of the visual field. Together, the cells in V2 are responsive to the properties of orientation, colour and spatial frequency. They are also tuned to the orientation of illusory contours (the ability to recognise that a shape is a whole shape when the shape is partially obscured by another object). Area V2 contains neurons that respond to an edge depending on whether the edge belongs to the object or the background (Hegde & Van Essen, 2004). When area V2 is stained with cytochrome oxidase, patterns containing three different alternating types of stripes appear. These are thick, thin and pale stripes (Baizer, Robinson, & Dow 1977: Moutoussis & Zeki, 2002). These areas receive different types of input information suggesting three functional subdivisions of area V2.

Thick stripes are collections of neurons that are sensitive to bars that move in a particular direction at a particular speed. Some of these cells are involved in depth perception. The thick stripes receive magnocellular input from layer 4B in area V1.

Thin stripes are collections of neurons that are sensitive to specific wavelengths and so are specialised at detecting colour. Thin stripes receive input from the blob system (parvocellular and koniocellular) in layer 3 of area V1.

Pale stripes are collections of neurons that are sensitive to the orientation of a bar or edge. Pale stripes receive input from the interblob system of layer 3 in area V1. Interblobs can be either magnocellular or parvocellular.

2.4.2 Magnocellular and parvocellular segregation in visual cortex: the dorsal and ventral Streams

In the previous section we have discussed the degree to which magnocellular and parvocellular input remains segregated throughout visual cortex. In the present section we will examine the evidence for magnocellular-parvocellular segregation in the two higher cortical processing streams: The ventral and dorsal streams. Most researchers believe that the processing of a visual stimulus depends on two separate, but related processes. Traditionally, Trevarthen (1968) and Schneider (1969) both distinguished between a "focal" system for recognising objects and an "ambient" system for guiding visual behaviour. Ungerleider and Mishkin (1982) further developed this idea through lesioning studies carried out on monkeys. They found that lesions to inferior temporal cortex led to impairments in object recognition and that lesions to parietal cortex led to problems in locating stimuli. They proposed the existence of a "What" and a "Where" visual pathway. The "What" system being the route from visual cortex to inferotemporal cortex (concerned with the identity of an object) and the "Where" system being the route from visual cortex through area MT to posterior parietal cortex (concerned with where an object is in the environment).

These findings led to the development of the idea of two left hemisphere visual processing streams: the ventral stream (occipital-temporal to inferior temporal) that specialises in determining "what" an objects identity is, and the dorsal stream (occipital-parietal to parietal cortex) which specialises in locating an object in the environment. Using fMRI, Haxby et al (1991) showed that these visual pathways also exist in humans. This has led to the development of neurophysiological models of visual word recognition. Pugh et al (2000) suggested that visual word recognition relies on two processing streams in the left hemisphere: They propose that when learning to read, readers rely on the dorsal processing stream. The dorsal stream is associated with the mapping of sub-lexical orthographic units onto individual phonemes and the integration of spelling and sound representations. It is only when reading skill develops that the ventral processing stream begins to contribute to word recognition. This processing stream is faster and allows words to be recognised as whole units once they have been established in lexical memory. Indeed, Joubert et al (2004) demonstrated using fMRI, that lexical and sub-lexical processing of words activates different brain regions. They compared very high frequency regular words (which would be well established in lexical memory and so would rely on ventral stream processing), very low frequency regular words (to which the reader has had less exposure and so can be considered to be unfamiliar and therefore still reliant on dorsal stream processing), and non-words (of which there can be no representation in lexical memory as they have never been encountered before and so must rely on dorsal stream processing). They found that tasks that involved lexical processing activated the area between the left angular and supramarginal gyri and they suggested that this region may be involved in mapping whole word orthographic representations to whole word phonological representations. On the other hand, tasks that involved sub-lexical processing activated the left inferior prefrontal gyrus. This area is thought to be involved in grapheme-to-phoneme conversion and verbal memory. Further support comes from Borowsky et al (2006) who conducted a similar fMRI study but compared exception words and pseudohomophones. Exception words cannot be processed sub-lexically as they do not have regular grapheme-to-phoneme correspondence. Therefore, they must be processed by the ventral route. Pseudohomophones must be read by mapping spelling onto sounds and therefore must be read using the dorsal route. Borowsky et al's results support the distinction between lexical-ventral word processing and sub-lexical-dorsal processing. Next we will examine how the magnocellular and parvocellular pathways contribute to dorsal and ventral processing.

The dorsal stream arises from area V1 and initially projects to area MT (which is responsible for analysing the direction of stimulus motion) and area MST (which is responsible for the perception of stimulus motion and for directing eyemovements). There is columnar organisation in area MT and cells in this region have much larger receptive fields than those in area V1. Area MT receives direct input from layer 4b of V1 and indirect input from V1 via V2 (blobs and interblobs). Around 90% of the cells in MT show sensitivity to the direction of movement of a stimulus. The dorsal pathway terminates in the posterior parietal lobe which controls movements that are guided by visual input (such as reaching for an object in the environment, or eyemovements during reading). The dorsal stream is important for object localisation and visual attention. The ventral stream arises from area V1 and projects to area V4 (responsible for the processing of colour stimuli (Zeki, 1971, 1973). Later work showed that area V4 is also sensitive to stimuli orientation, length and width (Desimone & Schein, 1987; Zeki, 1978a). Area V4 provides major input to IT (inferotemporal cortex) which is specialised for processing spatial arrangements. The ventral pathway is responsible for processing stimuli shape and colour (Mishkin et al., 1983; Ungerleider & Mishkin, 1982; Van Essen, 1985; Van Essen & Maunsell, 1983).

The Magnocellular – Parvocellular distinction in the Dorsal and ventral streams

It was traditionally believed that the dorsal and ventral streams were composed of magnocellular and parvocellular input respectively with there being a clear separation between the two streams. Supporting this, there is both anatomical and functional separation between the ventral and dorsal streams and the neurons in each have different response properties (Merigan & Maunsell, 1993). Many researchers initially believed that this dissociation might reflect a magnocellular - parvocellular division (Desimone & Ungerleider, 1989; De Yoe & Van Essen, 1988; Felleman & Van Essen, 1991; Kaas & Garraghty, 1991; Livingstone & Hubel, 1987a, 1988; Martin, 1988; Maunsell, 1987; Maunsell & Newsome, 1987).

However, Nealey and Maunsell (1994) have argued against the idea that the magnocellular and parvocellular pathways remain completely segregated in visual cortex. They argue that the differences in the magnocellular and parvocellular signals cannot completely account for the differences in the functions of the dorsal and ventral streams. They recorded responses from area V1 while blocking either the magnocellular or the parvocellular layers of the LGN. Inactivation of either the M or P divisions of the LGN reduced neuronal responses in V1. They also found neurons that appeared to receive both magnocellular and parvocellular input and found no evidence that the magnocellular pathway inputs were restricted to either blobs or interblobs. The magnocellular pathway contributed responses throughout area V1. They concluded that the regions of V1 that give rise to the ventral processing stream (bobs and interblobs) appear to contain both parvocellular and magnocellular signals and so the ventral stream depends on both magnocellular and parvocellular signals.

Maunsell, Nealey and De Priest (1990) repeated the procedure of blocking the magnocellular and parvocellular signals at the level of the LGN while measuring the responses of area MT (a major projection of the dorsal processing stream). They found that blocking the magnocellular layer of the LGN led to decreased responses in area MT whereas blocking the parvocellular layer of the LGN had little effect. They therefore concluded that most of the input to area MT (and therefore the dorsal stream) is magnocellular. Repeating the procedure for area V4, they found that this part of visual cortex received a mixture of magnocellular and parvocellular input (Ferrera, Nealey, & Maunsell, 1994). It would appear that there is not a one-to-one mapping between the M and P systems and the dorsal and ventral streams. Instead, it appears that the ventral stream depends on both magnocellular and parvocellular input but that the dorsal stream is magnocellular dependent. There is also some evidence for a small amount of involvement of the parvocellular stream in the motion detection areas of the brain (Maunsell et al., 1990). The movement of red and green stimuli is more difficult to detect (parvocellular cells are red-green centre-surround) than black and white motion (Dobkins & Albright, 1998). When viewing red-green stimuli the ability to detect motion is impaired but motion can still be perceived. This suggests that there is some parvocellular input. However, an alternative account is that the magnocellular pathway is able to signal the presence of borders defined by red - green contrast, despite their inability to signal information about the colours themselves (e.g. Lee et al., 1988).

2.4.3 The contribution of the magnocellular pathway to reading

The magnocellular theory of dyslexia (Chase 1996; Cornelissen et al 1998; Stein & Walsh 1997) proposes that, for a proportion of dyslexics, a deficit in the magnocellular pathway may contribute to the reading problems of this group. Post-mortem evidence has shown disruption of the magnocellular neurons in the visual pathways in some dyslexics (Galaburda, Menard & Rosen, 1994). If a deficit in the magnocellular pathway is a factor in the reading problems of dyslexics then it can be assumed that this pathway contributes significantly to the recognition of words in non-impaired readers. There is some evidence that the magnocellular pathway can aid word recognition (Chase 1996). Chase (1996) proposes that the magnocellular pathway initially processes global aspects of the word and that the magnocellular representation is then clarified by detailed parvocellular processing of the stimuli. The faster conductance rate and larger receptive fields of the magnocellular neurons makes them ideally suited to rapid, global processing.

However, there have been claims that the magnocellular pathway does not significantly contribute to lexical processing. Skottun (e.g., Skottun et al., 1999, 2000) argues that words are only processed by the parvocellular pathway. In this account, the magnocellular pathway only contributes indirectly to the process by suppressing parvocellular responses during saccades to avoid an overlap of foveal representations. One of the questions that this thesis investigates is the hypothesis that the magnocellular visual pathway contributes directly to the recognition of words, rather than simply modulating the parvocellular pathway. We also investigate the idea that if the magnocellular pathway does make a contribution to word recognition that this contribution will be most obvious in parafoveal vision as the most common cell type to arise from the parafoveal area of the retina is the magnocellular retinal ganglion cell. In the next chapter I will examine in more detail the properties of the visual system that influence word recognition and the role that the magnocellular and parvocellular pathways play in this process.

Chapter 3

Visual Processing in Reading

3.0 Chapter Overview

This chapter provides more a more detailed analysis of the structure of the visual field including the processing differences between the foveal and parafoveal areas of the retina and how this impacts on visual word recognition. I will relate these processing differences to the magnocellular and parvocellular pathways. Section 3.1 examines the structure of the visual field and the projection of the visual field to the brain in more detail. In section 3.2 I describe the processing differences between the foveal and the parafoveal area of the retina and relate this to magnocellular – parvocellular functioning. Section 3.3 introduces the idea of a parafoveal preview and looks at the types of information that can be extracted from text by the parafoveal area of the retina and why it is important for reading. I will then explore the relationship between the magnocellular and parvocellular pathways and parafoveal and foveal vision.

3.1 Structure of the Visual Field and Visual Field projections

Each eye receives input from both the left and the right visual fields. The retina of each eye is split vertically. The half of the retina that is closest to the nose is referred to as the nasal hemiretina and the half of the retina that is nearest to the temples is referred to as the temporal hemiretina. The nasal hemiretina receives input from the ipsilateral visual field (the left eye's nasal hemiretina receives input from the left visual field and the right eye's nasal hemiretina receives input from the right visual) (see Figure 1 in Chapter 3). The temporal hemiretina receives input from the contralateral visual field (the temporal hemiretina of the left eye receives information about RVF stimuli and the temporal hemiretina of the right eye receives information about LVF stimuli. Under normal binocular viewing conditions, each cerebral hemisphere receives two representations of the contralateral visual field (one from each eye). The left cerebral hemisphere receives right visual field input from the left eye temporal hemiretina and the right eye nasal hemiretina. The right cerebral hemisphere receives left visual field input from the left eye nasal hemiretina and the right eye temporal hemiretina.

The connections from the nasal hemiretinae cross over to the contralateral cerebral hemisphere at the optic chiasm and the connections from the temporal hemiretinae project to the ipsilateral hemisphere (they do not cross over at the optic chiasm). Information from the contralateral nasal hemiretinae go to layers 1, 4 and 6 of the lateral geniculate nucleus and information from the ipsilateral temporal hemiretinae go to layers 2, 3 and 5 of the lateral geniculate nucleus. Input from the two eyes is kept separate (ocularity is preserved) in the six layers of the LGN before being transmitted on to visual cortex (V1). These six layers combine to form a complete representation of the contralateral visual field. The left hemisphere receives the whole of the right visual field and the right hemisphere receives the whole of the left visual field. It is not yet fully understood why this segregation into separate layers is necessary in the LGN. The six layers preserve ocularity suggesting that it is important to retain information about which eye the input signal originated from and also maintain the magnocellular – parvocellular distinction suggesting that it is important to segregate the different types of input at this stage of processing. There are two magnocellular layers in each LGN, one receives input from the left eye and the other receives input from the right eye. However, there are four parvocellular layers in each LGN; two receive the input from the left eye and two receive the input from the right eye. It is not fully understood why the visual field input from each eye is represented twice in the parvocellular layers.

The connections between the nasal hemiretinae and the LGN are more numerous and are more heavily myelinated compared to the connections from the temporal hemiretina (Hubel & Wiesel, 1962). A greater amount of myelination gives the nasal hemiretinal connections a faster conductance rate than the connections between the temporal hemiretinae and the LGN (Perry et al., 1984). Consequently, as the LGN is the first area of the brain to receive the visual signal, the information that falls on the nasal hemiretinae reaches the brain, and therefore the next stage of visual processing before the information from the temporal hemiretinae.

The language dominant left hemisphere receives input from the nasal hemiretina of the right eye. The nasal hemiretina of the right eye transmits information from the RVF central, parafoveal and peripheral regions. In addition, each hemiretina has a magnocellular component and a parvocellular component. The information that is transmitted by the magnocellular pathway is the most common form of output from the parafoveal and peripheral regions of the retina. The information transmitted by the parvocellular pathway arises mostly from the foveal regions of the retina. The magnocellular pathway has a faster transmission rate than the parvocellular pathway. This suggests that parafoveal and peripheral input from the visual field reaches the brain before the parvocellular (foveal) representation because of the faster transmission rates of the magnocellular pathway. While this segregation of nasal and temporal hemifields has been shown to exist, it may not be absolute. Some crossover may occur.

Because the RVF parafoveal and peripheral regions (carried by the faster magnocellular pathway) are transmitted via the more quickly transmitted nasal hemiretina to the language dominant left hemisphere, we propose that this may selectively facilitate the extraction of visual information from the area of the visual field that is viewed by the parafovea. We further propose that this enables parafoveal preview to occur in sentence reading. The following sections develop this idea more fully.

3.2 Processing Differences between the Fovea and the Parafovea

The fovea is a small concentration of cone cells in the retina. This area is capable of transmitting a very detailed, colour image of the central two degrees of the visual field (Rayner & Bertera, 1979). Parvocellular retinal ganglion cells are the most common type of cell found in the foveal region of the retina. These cells transmit colour information (to the parvocellular blob system) and high spatial frequency information (to the parvocellular interblob system) in the visual cortex. The parafovea region of the retina lies outside of the fovea (outside of the central 2° of visual angle). The parafovea encompasses 5 – 10° of visual angle (Rayner & Bertera, 1979). Magnocellular retinal ganglion cells are the most common type of cell sampling this region of the retina. These cells transmit information about stimulus motion (to the superior colliculus) and coarse-grain, low spatial frequency information (to the LGN and V1). The remainder of the visual field is classified as peripheral vision (10° to the edge of vision). This part of the retina only detects information of very low spatial frequency. The extreme edges of the visual field are colour blind because there are no parvocellular retinal ganglion cells there. The peripheral retina (the area that extends from outside of the parafoveal region to the edge of the perceivable visual field) cannot detect rapid changes in the colour of a stimulus but can detect rapid changes in the luminance levels of a stimulus (Theeuwes, 1995) suggesting that most of the output from this region of the retina is transmitted only by magnocellular retinal ganglion cells.

The central and peripheral regions of the retina have been found to project to different brain areas. Ungerleider and Desimone, (1986) investigated the transmission of visual information from area V1, through area MT, on to the parietal lobe in Macaque monkeys. Their results indicate that the representations of the central visual field in both areas V1 and V2 project into the heavily myelinated zone in area MT whereas the far peripheral representations of both V1 and V2 project on the upper area of area MT. The difference in the amount of myelination in the areas that the central visual field and the peripheral visual field project to in area MT implies that there might be a difference in the processing between central and peripheral visual fields.

3.3 Parafoveal Preview

In this section I will give a brief description of what parafoveal preview is and why it is important in reading. I will examine the types of information that can be extracted from parafoveal preview during the processing of text and I will relate this to the perceptual abilities of the parafoveal area of the retina. I will then go on to explore the relationship between the functioning of the magnocellular and parvocellular pathways and foveal and parafoveal processing of text.

When reading a paragraph of text, the eye makes horizontal movements along the lines of text from left to right (for languages that read left to right). These eye movements are called saccades. Saccades are punctuated by fixations, which are short pauses in the movement of the eye, typically about 200 – 250 ms long (Liversedge & Findlay, 2000; Rayner, 1998; Starr & Rayner, 2001). The eye only takes in visual input during a fixation (Ishida & Ikeda, 1989; Wolverton & Zola, 1983). Using the contingent change technique, Wolverton and Zola (1983) replaced an entire line of text with either another line of text, a line of random letters, or a row of symbols for a period of 20ms, during either a saccade or during a fixation. Reading was only disrupted when the change took place during a fixation, but not when it took place during a saccade. This demonstrates that the eye does not take in any information that is relevant to reading when it is moving. The mechanism of saccadic suppression reduces input to the eye when the eye is moving to avoid a blurring of the image on the retina (Bridgeman et al., 1975; Burr, 2004; Burr et al., 1996; Matin, 1974).

The fovea is essential for the efficient processing of text as it is the area of greatest acuity in the retina (Rayner & Bertera, 1979; Rayner et al., 1981). Reading without using foveal vision (the central 2° around the fixation point, (Rayner, 1998)) is very difficult. Without this area of high acuity, word recognition becomes almost impossible. The nature of text requires very fine-grain spatial discrimination and there is a steep drop in acuity from the centre of fixation (sampled by the fovea) to the peripheral regions of the retina (sampled by the parafoveal and peripheral regions). Therefore, it becomes more difficult to recognise a word the further into the periphery the stimulus is presented (Henderson et al., 1995). However, the parafovea is also essential for the efficient processing of written words (e.g., McConkie & Rayner, 1975; Rayner et al., 1982). These studies used the “Moving Window” paradigm (McConkie & Rayner, 1975) to investigate the impact of losing the input from the parafovea. The Moving Window paradigm is an experimental technique that limits the amount of text that is available to the reader at any one time.

A portion of the text around fixation is clearly visible; however, outside of the "window" the text is replaced by meaningless symbols (e.g., XXXXX). When the reader moves their eye, the window moves too, obscuring different sections of the text. These experiments have demonstrated that both foveal and parafoveal vision are essential for efficient sentence reading as when either the foveal area or the parafoveal area is obscured, reading rate is slowed. As previously mentioned, foveal processing is largely the responsibility of the parvocellular visual pathway and parafoveal and peripheral processing is largely dependent on the magnocellular visual pathway indicating that both of these visual pathways play an important role in word recognition in sentence reading.

3.3.1 Eye-movements

The centre of the visual field is where acuity is greatest so eye-movements are needed to bring new sections of the sentence into the central visual field for processing to be completed. The reader needs to move the eye along the line of text in order to get a clear fixation on a word. The regions of the retina outside of the fovea guide the eye to the regions that need to be processed. It is thought to be the magnocellular pathway that controls the movement of the eyes to a new point in the text (Breitmeyer, 1993). Breitmeyer (1993) proposed that the magnocellular pathway directs the eye towards the position of interest in the visual field and then the parvocellular pathway extracts the detailed representation of that part of the visual field once it is directly fixated by the fovea. In the present thesis, we take this one step further, by proposing that not only does the magnocellular pathway help to direct fixations but it also plays an important role in the actual processing of the word.

This notion that the magnocellular pathway simply guides the eye to the relevant area of interest may, however, be underestimating the role of the magnocellular system in lexical processing. Work by (Chase et al., 2003) leads to a prediction that the magnocellular system might play an important role in the actual processing of words themselves. If it can be shown that the magnocellular pathway can influence the recognition of words even when the process of directing the eye is removed – such as in single word presentation where fixation position is already established – then a more detailed picture of the role of the magnocellular system can emerge. The present thesis seeks to do precisely this.

There is evidence that some lexical processing does occur before the fovea fixates the word. For example, not all of the words in the sentence are fixated. Approximately one third of words in a sentence are skipped. Around 80% of single-letter words are skipped (Vitu et al., 1995). This skipping rate falls off as word length increases but even words of seven letters are skipped 10% of the time (Vitu et al., 1995). Words that are skipped do not receive a direct fixation. This implies that a sufficient level of processing of the word has already been achieved and further (foveal) fixations are not necessary. An alternative explanation is that enough of the word has fallen within foveal vision for that word to be processed as the fovea extends approximately 3 – 4 characters to the right of fixation. However, there is a great deal of evidence to suggest that some processing of words occurs in parafoveal preview. Readers show facilitation effects of having viewed words in parafoveal preview so we can infer that words in the right visual field are processed before fixation actually occurs (Rayner, 1998). As magnocellular retinal ganglion cells are most common in the parafoveal area of the retina, we propose that it is the magnocellular pathway that is responsible for these facilitatory effects.

The perceptual span (the area of the visual field from which useful information can be extracted) is asymmetrical: it extends approximately 14-15 characters to the right of fixation and approximately 3-4 characters to the left of fixation (McConkie & Rayner, 1975). This asymmetry is due to the fact that English is read from left to right so unless a regression is planned, attention is directed to the right after sufficient encoding of the fixated word has been achieved (Binder et al., 1999; Henderson & Ferreira, 1990). Rayner and others (Ishida & Ikeda, 1989; Liversedge et al., 2004; Rayner et al., 2003; Rayner et al., 1989) have shown that a stimulus presentation of only 50-60 ms is sufficient for a fixated word to be encoded. Rayner et al., (1989) showed that sentence reading was only disrupted when the fixated word was masked before 50 ms. As fixations last 200-250 ms (e.g., Liversedge & Findlay, 2000), and it takes around 150 ms to initiate a saccade (Rayner et al., 1983), this suggests that after 60 ms attention moves to the word that is directly to the right of the fixated word. Indeed, disappearance or masking of the word to the right of fixation has also been found to disrupt reading (Rayner et al., 2006) even when masking occurs after 60 ms. This finding suggests that in the initial 60 ms of fixation, information is extracted from the fixated word. After the initial 60 ms of exposure, attention shifts to the word to the right of fixation.

3.3.2 Types of Information extracted from the parafoveal preview

If information about non-fixated words can be extracted from parafoveal vision then the question of interest is: What are the types of information that can be extracted from parafoveal preview? When a word is presented to parafoveal vision before foveal fixation occurs, it is processed more quickly when it is eventually fixated compared to if it had not been previously viewed in the parafovea (e.g., Jacobs, 1986, 1987a; Rayner & Morrison, 1981). Interestingly, if the word is presented to the parafovea in larger letters than those which are normally used in printed text then the entire processing of the word can be achieved in the parafoveal preview, without needing a saccade to bring the word into the range of the fovea (Pollatsek, Rayner & Collins, 1984). This is consistent with the fact that magnocellular retinal ganglion cells have large receptive fields; larger stimuli are more easily recognised than small. The fact that larger letters are processed more easily in parafoveal vision than small letters suggests that it is the magnocellular pathway that is extracting information from these words.

There are two main ways that parafoveal information can be used in sentence reading. A parafoveal preview can help to determine where to fixate next in the sentence and it can also be used to facilitate the recognition of words that are due to be fixated. It is generally accepted in the literature that the magnocellular pathway is responsible for locating a stimulus in the visual field (see Lennie, 1993 for a review but see Graves, 1996, and Milner & Goodale, 1995, for an alternative account). However, in this thesis we investigate the claim that the magnocellular pathway also facilitates the recognition of words (e.g., Chase, 1996).

One technique for investigating the contribution of parafoveal preview in sentence reading is the boundary paradigm (Rayner, 1975). In this paradigm, participants are required to read sentences. An invisible boundary is marked in the text just before the designated preview word. As the reader’s eye crosses the boundary to fixate on the target word, the preview word can either remain the same or alter into a new word. The preview word can differ from the target word either orthographically, phonologically or semantically. Preview benefit can be measured by the reduction in processing time on the word when it is eventually fixated. It is generally agreed that some orthographic (e.g., Binder, Pollatsek, & Rayner, 1999) and some phonological (e.g., Miellet & Sparrow, 2004) information may be extracted in the parafoveal preview. However, semantic or morphological similarity between the prime word and the target word does not appear to produce a parafoveal preview benefit (Kambe, 2004; Lima, 1987; Lima & Inhoff, 1985; Rayner & Morris, 1992). We will now examine the evidence for the extraction of orthographic and phonological information from parafoveal preview.

3.3.3 Processing of words in parafoveal preview

Pollatsek et al. (1992) using the boundary paradigm (Rayner, 1975), demonstrated that phonological information can be extracted from a word that is viewed in the parafovea and that this can facilitate subsequent recognition of that word. They showed that preview words that were homophones of the target word facilitated recognition of the target word more than orthographically similar preview words. They also demonstrated that there was a preview benefit for homophones that were not orthographically similar to the target word. Henderson et al. (1995) showed that when the prime word and the target word share the same initial letters but the initial letters are pronounced differently (e.g. “mint” and mine”) the preview benefit is reduced. These findings suggest that phonological information is extracted from the parafoveal preview and that the influence of phonological pre-processing may be greater than that of orthographic pre-processing.

These findings were replicated by Miellet and Sparrow (2004) who found that both orthographic and phonological information are extracted from parafoveal preview. They found a greater amount of preview facilitation for pseudohomophones than for orthographically similar non-words. Also, fixation durations were shorter for orthographically similar words when they were pseudohomophones than when they were not pseudohomophones. They conclude that both orthographic and phonological information are extracted from parafoveal preview and maximum facilitation is achieved when both types of information are available. Less facilitation occurs if the preview is a homophone but is not orthographically similar (phonological representations are maximally activated, orthographic representations are less activated) or if the preview is visually similar but not a homophone (orthographic representations are maximally activated, phonological representations are less activated).

In another boundary paradigm experiment, Chace, Rayner, and Well (2005) looked at the differences between the abilities of skilled and less-skilled readers to extract information from parafoveal preview. They presented preview words that were either identical to the target word, were homophones of the target word, were orthographically similar to the target word, or else were unrelated strings of consonants. They found that skilled readers got more benefit from homophone previews compared to orthographically similar previews but that the less skilled readers did not show this effect. They concluded that less skilled readers were less able to use phonological information to facilitate subsequent recognition of the target word and did not appear to get the whole preview benefits.

Related to the previous study, Unsworth and Pexman (2003) used a lexical decision task to investigate the abilities of poor and skilled readers to extract phonological information from words. They used two lexical decision tasks: A normal lexical decision task (decide whether a letter string is a word or a non-word), and a phonological lexical decision task (decide whether the letter string sounds like a word). They found that the poorer readers showed effects of word regularity whereas the skilled readers did not and they concluded that the skilled readers were more able to extract phonological information than the poor readers.

The ability to extract phonological information from words in general (including from parafoveal preview) is related to reading skill (Chace, Rayner, and Well, 2005). It appears that even poorer readers are able to extract orthographic information from parafoveal preview but that they are less able to extract phonological information. The ability to extract phonological information gives a greater preview benefit than orthographic information alone and therefore leads to more efficient reading. This can be related to how efficiently the ventral (or lexical) reading route has developed and this is a question that we will explore in depth throughout the thesis. When learning to read, there is heavy reliance on the sub-lexical or dorsal route which incrementally assembles the identity of a word through mapping sub-lexical units onto individual phonemes. As words become more familiar and reading skill improves, there is a greater reliance on the lexical or ventral processing stream. It is thought that dyslexic readers fail to adopt this faster lexical route and remain reliant on the slower sub-lexical route. Martens and De Jong (2006) used a lexical decision task to investigate the differences between ten year old dyslexics and reading- and age-matched control participants. When tested on words and pseudo-words of 3-6 letters, they found that the length effects were much stronger in the dyslexic children and the reading-age matched control group children than in the chronological age-matched group. They concluded that the dyslexic children were continuing to rely on the sub-lexical (dorsal stream processing) procedures that the younger group of children were using and that the older children were beginning to rely on the faster lexical (ventral stream processing) procedures. We will explore this issue in greater depth throughout the thesis and we will relate the functioning of the dorsal (magnocellular) and ventral (magnocellular and parvocellular) streams to reading ability and the ability to extract useful information from words that are presented in parafoveal vision.

3.4 Summary of the Relationship between the Visual Pathways and Parafoveal and Foveal processing

In summary, we have looked in more detail at the structure of the visual field and have examined the differences in the processing capabilities between the foveal and parafoveal areas of the retina and have looked at how this impacts on visual word recognition. We have shown how the processing differences between the fovea and the parafovea relate to the processing differences of the magnocellular and parvocellular pathways. We have also explored the idea of a parafoveal preview in sentence reading and have examined the evidence for the extraction of both orthographic and phonological information before a word is fixated on. This thesis proposes that the information that is extracted from parafoveal preview may be largely dependent on reading ability and also on magnocellular functioning as this is the most common type of pathway to arise from the parafoveal area of the retina.

The experiments in the rest of this thesis test the processing capabilities of both the foveal and parafoveal areas of the retina and also examine the factors that influence processing in these areas of the visual field. We interpret the findings in light of what is known about the projection, and the processing capabilities, of the magnocellular and parvocellular pathways and attempt to link magnocellular (and ventral-dorsal stream) functioning to the phenomenon of parafoveal preview. In the next chapter we will look at the effect of losing the input of one of the eyes on the recognition of words in both foveal and parafoveal presentation positions.

Chapter 4

The Effect of Monocular Occlusion on Visual Word Recognition

4.0 Chapter Overview

In this chapter we present two experiments that investigate the influence of occluding one of the eyes on the recognition of single words. The experiment in section 4.1 looks at the effect of monocular occlusion on the recognition of words presented in the left and right visual fields, and in section 4.2 we look at the influence of occluding the right eye on the recognition of words varied by length (and with word frequency controlled for) that are presented in the left visual field. Section 4.3 addresses the issue of whether there are differences between the methods of lexical access in each of the two brain hemispheres and offers an alternative, attention-based account of the word length effect.

4.1 The Effect of Monocular Occlusion and Visual Field Presentation on Word Recognition

Recent research has found that occluding one eye while completing a cognitively demanding task can influence the attentional asymmetries of the brain. For example, Roth et al. (2002) tested the effect of occluding one eye in an attempt to manipulate hemispheric attentional asymmetries in non-impaired participants during a line bisection task. In the line bisection task, participants are required to mark the point on a line where they perceive the middle of the line to be. This has traditionally been used to investigate the effects of unilateral spatial neglect (Harvey et al., 1995; McIntosh et al., 2005; McIntosh et al., 2004; Olk & Harvey, 2002). Under binocular viewing conditions, non-impaired participants show an attentional bias towards distant space (Chewring et al., 1998; Jewell & McCourt, 2000). Roth et al found that occluding the left eye during a line-bisection task led to an increased bias towards near, low space. This is thought to be reflective of the processing style of the left hemisphere (Heilman et al., 1993a; Lux et al., 2004; Weissman & Woldorff, 2005; Weissman & Banich, 1999; Yamaguchi et al., 2000) suggesting that the activity of the right hemisphere had been suppressed and that the activity of the left hemisphere had been enhanced leading to an attentional bias for near space. Occluding the right eye showed a bias in line bisection for distant, upper space, similar to that of binocular viewing. Roth et al concluded that occluding one eye leads to a decreased level of activation for the brain hemisphere contralateral to the occluded eye and an enhanced level of activation for the brain hemisphere ipsilateral to the occluded eye which in turn creates a bias in the processing style employed in the task. They found that occluding the left eye created a bias towards near, low space when bisecting vertical lines suggesting that hemispheric dominance for the task had been altered. This leaves the unanswered question: does monocular occlusion have the same effect on the processing of words as it does on the perception of lines? Is it possible to force an apparent switch in hemispheric dominance for a linguistic task in the same way as it occurs in a visuo-spatial task?

Hemispheric Attentional Systems

Monocular viewing may produce processing biases in the line-bisection task by enhancing the activation levels of the superior colliculus and cortical attention systems in the brain hemisphere ipsilateral to the occluded eye (Roth et al., 2002). Studies of unilateral spatial neglect have provided insight into the balance of the attentional systems of the left and right hemispheres. Unilateral spatial neglect is caused by damage to one of the brain hemispheres and results in an attentional bias which causes a failure in the ability to orient to, or respond to, stimuli that appear in the visual field contralateral to the site of the lesion (Heilman, 1979a; Vallar et al., 2003). This type of neglect can result from damage to cortical areas and/or to the superior colliculus in the cerebral hemisphere contralateral to the neglected area of space with damage to both areas causing a more severe deficit (Payne et al., 1996). As the superior colliculus receives input from ipsilateral cortical areas as well as directly from the retina of the contralateral eye, a cortical lesion leads to a decreased level of activation in the superior colliculus in the ipsilateral cerebral hemisphere. The superior colliculus controls the direction of eye-movements towards potentially relevant stimuli in the contralateral visual field. Damage to the superior colliculus leads to attentional problems in the contralateral visual field leading to an increase in the severity of the attentional problems caused by the cortical damage. Importantly for this study, inhibiting the action of the superior colliculus in the opposite cerebral hemisphere has been found to reduce the effects of this damage (Lomber & Payne, 1996). Decreasing the input to the attentional systems in one cerebral hemisphere increases the activation of the attentional systems in the opposite cerebral hemisphere.

The Role of the Attentional Systems in the Line-bisection Task

Milner et al. (1992) showed that the perceptions of the dimensions of a line by non-impaired participants could be altered by influencing the focus of their attention. They found that the section of the line that received direct attention appeared to be longer than a section (of equal length) that did not receive direct attention. This would suggest that when participants marked the middle of the line as being further to the left from the actual centre than it was that they were focusing attention on the furthest part of the line making it appear to be larger than it was. This indicates a right hemisphere processing bias. The left hemisphere is thought to have a bias for near space while the right hemisphere is thought to be biased towards far space in the visual field (Heilman et al., 1995; Heilman et al., 1993a; Lux et al., 2004; Weissman & Woldorff, 2005; Weissman & Banich, 1999; Yamaguchi et al., 2000).

In the Roth et al (2002) study, they tested the effect of occluding one eye in an attempt to manipulate attentional asymmetries during a line bisection task. Under binocular viewing conditions, non-impaired participants show an attentional bias towards distant space (Chewring et al., 1998; Jewell & McCourt, 2000). They found that occluding the left eye led to an increased bias towards near, low space suggesting that the activity of the right hemisphere had been suppressed and that the activity of the left hemisphere had been increased leading to an attentional bias for near space. Occluding the right eye showed a bias in line bisection for distant, upper space, similar to that of binocular viewing. Under normal reading conditions, the left hemisphere is dominant for language processing in right-handed English speakers suggesting that in a task that requires lexical processing there will be a right visual field advantage for lexical stimuli. This leaves the unanswered question; is it possible to influence left hemispheric dominance for a linguistic task using monocular occlusion?

Visual Field Projections

Related to the above question, we also ask: how does occluding one of the eyes influence hemispheric processing when information from both of the visual fields is received by both of the eyes? Under normal, binocular reading conditions, the brain receives two representations of each visual field, one from each eye. When one eye is occluded, only one representation of the visual field is transmitted to the brain. The retina is vertically split. Each eye receives visual input from both the right and the left visual fields. The nasal hemi-retina of each eye receives input from the ipsilateral visual field and the temporal hemi-retina of each eye receives input from the contralateral visual field (because the retinal image is inverted). The connections from the nasal hemi-retina to the brain cross over to the contralateral cerebral hemisphere at the optic chiasm and the connections from the temporal hemi-retina project to the ipsilateral hemisphere (they do not cross over at the optic chiasm). This results in the left hemisphere receiving a complete representation of the right visual field and the right hemisphere receiving a complete representation of the left visual field.

The first target of the projections from the eye to the brain is the lateral geniculate nucleus (LGN). There are six distinct layers in each hemisphere’s LGN and the nasal and temporal hemi-retinae project to different groups of these layers. The nasal hemi-retina projects to layer 1 (magnocellular), and layers 4 and 6 (parvocellular) of the contralateral LGN and the temporal hemi-retina project to layer 2 (magnocellular), and layers 3 and 5 (parvocellular) of the ipsilateral LGN. (Note that input from the parvocellular retinal ganglion cells in each hemi-retina is represented in two layers in the LGN: input from the magnocellular retinal ganglion cells is only represented in one layer in the LGN giving a total of four parvocellular representations and two magnocellular representations in each hemisphere when input from both eyes is combined). Nasal and temporal input from the two different eyes is separated in the six layers of the LGN and continues to be separate in the projections to primary visual cortex (area V1) preserving ocularity and preserving information about visual field of origin. The six layers in each hemisphere's LGN combine to depict a complete representation of the contralateral visual field. Given that occluding one eye can alter hemispheric dominance in the line bisection task even when both of the visual fields are projected onto the retina of both of the eyes, we propose that one half of the retina is particularly important in transmitting visual information from the eye to the brain. Based on anatomical and physiological evidence we propose that the nasal half of each retina is the dominant source of visual input to each brain hemisphere. This is the question that we will now investigate.

Importance of the Nasal Hemi-retina in Visual Processing

The nasal hemi-retina receives visual input from a wider span of the visual field than the temporal hemi-retina. Input to the nasal hemi-retina includes the monocular zone of the visual field. The monocular zone lies at the extremes of the perceivable area of visual space and can only be viewed by the ipsilateral eye. The remainder of the discernible area of the visual field (the binocular zone) that lies between the two monocular zones can be perceived by both eyes. The nasal hemi-retina receives the input from the monocular and the binocular zones. The temporal hemi-retina receives only the binocular zone.

Connections from the nasal hemi-retina to the brain are more numerous and have a faster conductance rate than those from the temporal hemi-retina to the brain (Hubel & Wiesel, 1962: Perry et al., 1984). However, this is not entirely due to the fact that they receive a larger part of the visual field (Perry et al., 1984). Connections from the nasal hemi-retina to the brain are more densely packed compared to those from the temporal hemi-retina (Osterberg, 1935: Perry et al., 1984). The receptive fields in the nasal hemi-retina are smaller than those in the temporal hemi-retina. This, coupled with the fact that the connections are more densely packed, allows for greater spatial resolution in the nasal hemi-retinal ganglion cells (Spillmann et al., 1987). Connections from the nasal hemi-retina have a larger diameter and a greater amount of myelination than those from the temporal hemi-retina which gives a faster rate of transmission of the visual signal (Bishop et al., 1953). Rains (1963) showed that reaction times to flashes of light were faster when the flashes were presented to the nasal hemi-retina compared to when they were presented to the temporal hemi-retina. In summary, the nasal hemi-retina has greater spatial resolution and faster, more numerous connections to the brain.

As a consequence of the faster connections from the nasal hemi-retina to the brain, visual information that is received by the nasal hemi-retina will reach the brain, and therefore the next stage of visual processing, before the visual information that is received by the temporal hemi-retina. The nasal hemi-retina of the right eye may play a crucial role in the processing of linguistic stimuli. Not only does this area of the retina project directly to the language-dominant left hemisphere but also as English is read from left to right, previously unseen information first appears in the right visual field. Therefore, it follows that attention moves to the right of a fixated word once that word has been encoded. We propose that the greater spatial resolution and faster transmission rate of the nasal hemi-retina suggests that the nasal hemi-retina of the right eye (which receives the right visual field and projects to the language-dominant left hemisphere) is a vital source of input to the brain for processing fine-grain visual stimuli (for example, written words).

The Effect of Monocular Occlusion on Visual Field Perceptions

To test if it is possible to influence hemispheric attentional dominance for a linguistic task and also to test if there is a particular role of the nasal hemi-retina in linguistic processing, we used the paradigm of monocular occlusion. This paradigm involves comparing performance on a task when participants either use both eyes to complete the task or have one of their eyes occluded using an eye patch. Occluding one eye means that only a single representation of the visual hemifield is transferred from the non-occluded eye to the LGN whereas under normal reading conditions, two representations of each visual hemifield are transmitted to the brain: one from each eye. Under binocular conditions, the left hemisphere receives two representations of the right visual field: one from the temporal hemi-retina of the left eye and one from the nasal hemi-retina of the right eye. The right hemisphere normally receives two representations of the left visual field: one from the temporal hemi-retina of the right eye and one from the nasal hemi-retina of the left eye. Blocking input to the right eye means that the left hemisphere only receives temporal input from the right visual field and the right hemisphere only receives nasal input from the left visual field. If nasal input does dominate temporal input then we predict that occluding the right eye would result in increased right hemisphere activity. Blocking input to the left eye means that the left hemisphere only receives nasal input from the RVF and the right hemisphere only receives temporal input from the LVF. We would predict that this would result in increased left hemisphere activity.

The word Length Effect

In order to test these predictions we chose to examine the word length effect as word length normally produces asymmetries in performance between the two visual fields when both eyes are used. In readers of English where direction of reading is from left to right, the perceptual span (the area of the visual field where meaningful information can be extracted) is asymmetrical: It is greater to the right of fixation (14 – 15 characters) than to the left (3 – 4 characters) (McConkie & Rayner, 1975; Rayner, 1998). Under binocular viewing conditions, word length has a greater affect on performance on word recognition in the left visual field with shorter words being recognised faster and more accurately than longer words (Ellis, 2004; Ellis et al., 1988; Faust et al., 1993; Malamed & Zaidel, 1993; Young & Ellis, 1985, 1987). The time to correctly recognise a word in the left visual field has been estimated to increase by 20 to 30 ms for each additional letter (Ellis 1988). There is much less impact of word length in the right visual field under normal, binocular viewing conditions.

Ellis et al. argued that the length effect is not caused by the smaller area of perceptual acuity in the left visual field but instead reflects different methods of lexical access by the two brain hemispheres. Ellis (2004) found that word recognition was more affected by case alteration in the right visual field than in the left visual field and so proposed that only the left hemisphere (which is dominant for language and is where the right visual field is projected to) processes the letters of a word in parallel. The right hemisphere processes letters in an incremental, non-parallel way leading to an observable length effect in the left visual field but not in the right visual field.

However, there is an increasing amount of evidence against the idea that the two hemispheres process words in different ways. Nazir (2000) argues that hemispheric dominance cannot offer a complete explanation of the length effects. Word length effects are found regardless of visual field position in children who are learning to read and these length effects only disappear from the right visual field after a high level of reading skill has been reached (Aghababian & Nazir, 2000). They argue that this implies that reading experience contributes to the right visual field advantage. Also, in support of this theory, readers of Hebrew, which is read from right to left, tend to have a reduced perceptual asymmetry even with a dominant left hemisphere (Osaka & Oda, 1991; Pollatsek et al., 1981). Therefore, the right visual field advantage cannot be entirely due to the fact that the left hemisphere is dominant for language. Reading direction also influences the asymmetries between the left and right visual fields.

Nazir (2003) argues that different methods of lexical access between the two hemispheres cannot account for the length effect in the left visual field. Visual acuity has been found to influence word length effects. There is a word length effect in the right visual field when the stimuli are presented at large eccentricities (2 - 3°) from the fixation point (Nazir 2003). They argue that the length effect is caused by an interaction between low-level perceptual learning and lexical knowledge. Words are recognised faster when they are presented in the position in the visual field where you have most frequently viewed them on previous occasions (Nazir, 2003; Nazir, 2000; Nazir et al., 1998; Nazir, 1993). Children who are learning to read show a length effect regardless of where the word appears in the visual field and this length effect only disappears when the reader becomes highly skilled (Aghababian & Nazir, 2000). Children who fail to develop a high level of reading skill still show the length effect (Aghababian & Nazir, 2000) suggesting that there is something gained through exposure to reading that overrides the problems with perceiving longer words. However, the fact that a length effect can still be observed in skilled readers suggests that lexical knowledge cannot be the only influencing factor. There is still a length effect in the left visual field (e.g., Ellis, 2004). Even in the right visual field, length effects can be observed under certain circumstances, such as when the stimuli are pseudowords (Young & Ellis, 1985). Therefore, perceptual learning must also contribute to the absence of the right visual field length effect. When fixating a word in a sentence the eye tends to land slightly left of centre in the word therefore this is the most common position for a word to be viewed in. Nazir argues that this enables perceptual learning to occur which interacts with lexical knowledge to diminish the effect of word length in the right visual field (the area where the words are most commonly viewed).

However, based on Roth et al.'s (2002) findings, it appears that attentional factors influence how stimuli are perceived in the two visual fields. Also, in the case of Hebrew, the perceptual span is not completely reversed, only reduced. This suggests that hemispheric asymmetries do influence visual field effects. We propose that the asymmetry of the perceptual span reflects an attentional bias that has developed through learning to read from left to right. New information initially appears in the right visual field so it follows that attentional resources concentrate on this area of the visual field rather than on what has already been fixated and is now in the left visual field. In addition, the language dominant left hemisphere receives the right visual field leading to an even greater advantage for words presented to the right of fixation.

In the present experiment, we test the effect of occluding one eye on the recognition of words presented in the left and right visual fields. Based on Roth et al's (2002) study, we hypothesise that covering one eye should lead to an inhibition of the activity of the attentional systems of the brain hemisphere that is contralateral to the patched eye and an increase in the activity of the attentional systems of the brain hemisphere that is ipsilateral to the patched eye. Based on previous findings (e.g., Ellis, 2004), we predict that under binocular viewing conditions there will be a larger effect of word length in the left visual field compared to in the right visual field or at the central presentation point with 4 letter words being recognised faster than 7 letter words. Extending Roth et al, we predict that occluding the left eye will result in a reduction in the activation of the right hemisphere and an increase in the activation of the left hemisphere leading to the same pattern of results as the binocular condition with 4 letter words being recognised faster than 7 letter words in the left visual field.

However, when the right eye is occluded, we predict that the activity of the left hemisphere attentional system will be inhibited and the activity of the right hemisphere will be increased leading to a reduction of the attentional resources allocated to the right visual field and an increase in the attentional resources allocated to the left visual field. This should result a reduction of the length effect that is normally found in the left visual field under binocular viewing conditions. We predict that there will be a reduced length effect between four and seven letter words in the left visual field when the right eye is occluded. If this prediction is upheld by the results then it is support for the idea that the nasal hemi-retina is a more dominant source of visual input to the brain than the temporal hemi-retina as losing the nasal input would be sufficient to alter hemispheric attentional dominance in a task. If the length effect in the left visual field is found to be reduced when the right eye is covered then the length effect cannot be explained by different methods of lexical access of the two hemispheres as suggested by Young and Ellis (1985). These results would also cast doubt on the proposal by Nazir that perceptual learning combined with lexical knowledge causes the large length effect in the left visual field. As lexical knowledge is not in itself sufficient to override the length effect (there is still a large length effect in the left visual field) then we assume that perceptual learning is necessary. If there is a reduced effect of word length in the left visual field when the right eye is occluded then Nazir’s account cannot be supported. There is little benefit from perceptual learning for words presented entirely in the left visual field as it is very rare for the eyes to land on the last letter of a word during reading. If the length effect in the left visual field is reduced then perceptual learning cannot be the answer to the reduced effect of word length in the right visual field.

4.1.1 Method

Design

This experiment used a lexical decision task to investigate the effect of losing the input of one eye on the recognition of words presented in the left visual field, the right visual field, or at a central fixation point. We examined the effect of three variables: Eye, Visual field and Word length which were fully crossed leading to a 3 (Eye) x 3 (Visual field) x 2 (Word length) design. There were three levels of the variable “Eye”: “LC” (left eye covered), “Both” (both eyes used), and “RC” (right eye covered). The variable of “Eye” was crossed with the variable of “Visual field” which also had three levels: “LVF” (left visual field presentation), “RVF” (right visual field presentation) and “CPP” (central presentation point). The variable of “word length” had 2 levels: “4” (four letter words) and “7” (seven letter words). Each participant was exposed to all 18 conditions. The order of presentation of these conditions was randomised across participants.

Apparatus

A RM innovator Pentium 4 computer connected to an Iiyama Vision Master Pro 413 monitor with a 17-inch screen (refresh rate 74.999 Hz) was used to present the stimuli. A Psychology Software Tools Inc serial response box (model 200A) was used to record participants’ responses.

Materials

The stimuli were varied by length and consisted of letter strings that were either four or seven letters long. Using a counterbalanced design, the letter strings of each length were presented either on a central fixation point, in the right visual field parafovea, or in the left visual field parafovea.

Word Stimuli Words were taken from the British National Corpus (BNC). We excluded those that were plurals, proper nouns, or that were inflected. Each word list consisted of seven 4-letter words and seven 7-letter words. Within each list, there were three nouns, two adjectives and two verbs to counterbalance any effect of word class. Each participant saw 504 stimuli across the three conditions. Of these, 252 were experimental items (real words) and the other 252 were non-word filler items.

Non-word Stimuli An equal number of non-words were also presented. The order with which the words and non-words appeared was randomised. Non-words were taken from the ARC non-word database (Rastle, Harrington, & Coltheart 2002). Non-words were either 4 or 7 letters long. They were chosen so that they were as similar to the real words as possible. All non-words had orthographically legal onsets and orthographically legal bodies and were composed only of legal bigrams.

Presentation Positions

The stimuli were presented in lower case Courier New font. Each letter measured 3mm wide. Participants sat at a distance of approximately 60cm from the screen. The four letter words were approximately 14mm long and the seven letter words were approximately 25mm long. All of the stimuli were presented in courier new font to ensure that all words of equal number of letters were also of the same length in millimetres. At this distance, 10mm is equal to approximately 1° of visual angle. Words that were presented in the left or right parafovea were presented outside the central 2.5° of the visual field (fovea) to ensure that initially the stimulus would only be viewed by the parafovea. When the seven letter words were presented centrally, they covered 2.5° of the foveal area. The four letter words took up 1.4° of the foveal region.

Participants

There were 18 participants in total. All of the participants were right handed and had normal or corrected-to-normal vision. None of them had any history of reading or visual problems. All were undergraduates at the University of Edinburgh.

Procedure

The task was to look at letter strings that appeared on the screen and to make a decision as to whether the letters formed a real word or a non-word. There were three blocks in the experiment: in one block the participant used both eyes to view the stimuli, in the second block the right eye was covered using an eye-patch and in the third block the left eye was covered. The order of presentation of the blocks was randomised across participants. The participants were instructed to fixate on a gap between two vertical lines in the centre of the screen. This is thought to encourage a more stable fixation than a cross in the centre of the screen (e.g., Brysbaert 1994). The fixation point was present on the screen for 3000ms. The words and non-words were then individually presented for 10,000ms leaving time for an eye-movement after initially viewing the stimulus in the parafovea. The stimuli remained on the screen until after the participant had responded. Participants made a decision as to whether the letter strings made a real word or a non-word by pressing a button on the button box. Half of the participants pressed the left button to indicate a real word and the right button to indicate a non-word. The other half pressed the left button to indicate a non-word and the right button to indicate a real word. Participants used the index finger of each hand. As soon as the participant made their response the fixation point for the next trial appeared. There were 10 practice trials to begin to make sure that the participant had correctly understood the procedure. Reaction times in milliseconds and error rates were recorded.

4.1.2 Results

The data were analysed using analysis of variance (ANOVA). There were two repeated-measures within-participants and within-items factors: “Eye” (left eye covered, both eyes used, right eye covered) and “Visual Field” (left visual field presentation point, central presentation point and right visual field presentation point). There was also one within-participants and between-items factor: “Word Length” (4 letters long and 7 letters long). Reaction time data measured in milliseconds were analysed using a 3 (Eye) X 3 (Visual Field) X 2 (Length) repeated measures ANOVA followed up with Bonferroni corrected related-samples t-tests. Error rates were analysed using a 3 (Eye) X 3 (Visual Field) X 2 (Length) repeated measures ANOVA, followed up with Bonferroni corrected related-samples t-tests. Items that participants made errors on were excluded from the reaction time analysis as were items that had a reaction time that was more than 2.5 standard deviations away from the average for that participant for that particular type of item. These values were replaced by the average reaction time score for all participants across all items (800ms). A total of 249 items were replaced giving a replacement rate of 5.49%.

Reaction Times

Table 1: Mean reaction time scores in milliseconds for 4 and 7 letter words at the left visual field presentation point (LVF), central presentation point (CPP) and right visual field presentation point (RVF) with either the left eye covered (LC), the right eye covered (RC), or with both eyes used (both)

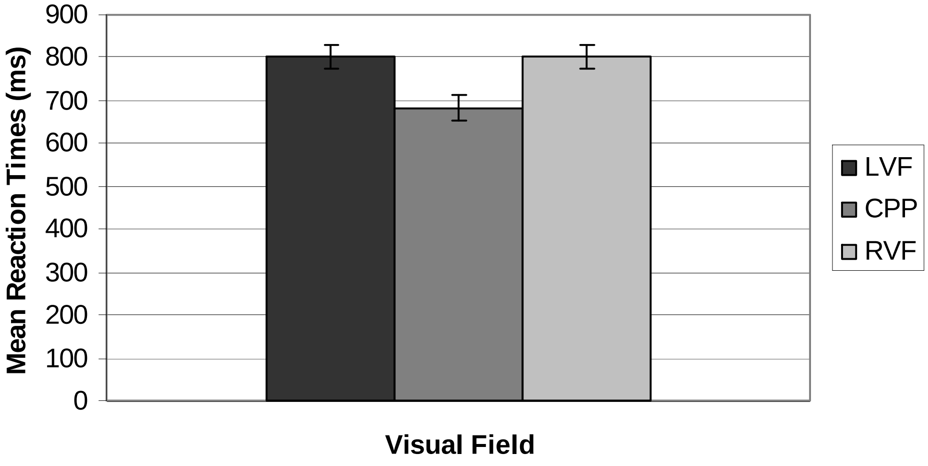
	Visual Field **Word Length**					
	LVF		CPP		RVF	
Eye	4	7	4	7	4	7
LC	787.6	815.3	668.4	694.9	803.2	812.1
Both	764.4	841.8	678.2	677.3	783.3	794.1
RC	799.3	810.9	686.5	687.8	800.2	815.1

Our first prediction was that there would be a larger effect of word length in the left visual field compared to in the right visual field. We failed to find a difference in the word length effect between visual field presentation positions. The interaction between the factors of Visual Field and Length was not significant, either by participants or by items (both *F*s < 1). Overall, there was a trend for four letter words (752.4 ms) to be recognised faster than seven letter words (772.2 ms) but this was not significant for all of the participants. The factor of Length was only significant by-items but not by-participants (F_1 (1, 17) = 1.92, *MSE* = 16561.73, *p*> 0.1; F_2 (1, 40) = 24.36, *MSE* = 4381.52, p< 0.001). However, there was no variation in the difference between four and seven letter words between the left visual field presentation position, the right visual field presentation position, or on the central presentation position. We failed to replicate the findings of (Ellis 2004; Young and Ellis 1985) as we did not find a larger length effect in the LVF compared to in the RVF.

Our second prediction was that there would be a reduced difference in reaction times to four and seven letter words that appeared in the left visual field when the right eye was covered. Our results did not support this hypothesis. The interaction between the factors of Eye and Length was not significant, either by participants or by items (both *F*s < 1) such that covering either the left eye or the right eye or leaving both eyes uncovered did not affect the difference in reaction times between 4 and 7 letter words. The three-way interaction between the factors of Eye, Visual Field and Length was not significant, either by participants or by items (both *F*s < 1) such that there was no variation in the difference in reaction times between four and seven letter words either when they were presented in the left visual field, the right visual field, or at a central presentation point with either the left eye covered, the right eye covered, or with both eyes used for viewing. However, when we look at the mean reaction times for binocular viewing (see Table 1) we can see that there is a trend towards a length effect in the left visual field. Ellis (1988) had shown that word recognition times in the left visual field increased by 20 – 30 ms for each additional letter added to the length of a word. Based on these estimates, we would have predicted a difference of around 60 – 90 ms in reaction times to four and seven letter words. The actual difference in reaction times to four and seven letter words was 77.4 ms in this task. Compare this with a difference of less than 1ms for items presented at a central fixation point, and with a difference of 10.8 ms for items presented in the right visual field and it seems that there may have been a larger effect of word length on items presented in the left visual field. However, as we did not find a significant three-way interaction between Eye, Visual field and Length, we cannot claim that this data supports our hypothesis.

We did find an effect of visual field presentation position. There was a main effect of visual field, significant both by participants and by items (F_1 (2, 34) = 78.98, *MSE* = 6572.89, $p < 0.001$; F_2 (2, 80) = 100.77, *MSE* = 11813.88, $p < 0.001$) such that participants took longer to correctly identify words that were presented in the left visual field (803.2 ms) compared to words that were presented at the central presentation point (682.2 ms) (Bonferroni corrected $t(18) = 163.26$, $p < 0.05$), and were slower at correctly identifying words that had been presented in the right visual field (801.3 ms) compared to when they were presented at the central presentation point (682.2 ms) (Bonferroni corrected *t*(18) = 155.96, *p* < 0.05). There was no difference between the right visual field (801.3 ms) and the left visual field (803.2 ms) for how quickly participants were able to correctly recognise words (Bonferroni corrected *t* (18) = 0.04, *p*> 0.1) (see Figure 3). All other effects and interactions were non-significant.

Figure 3: Mean reaction times in milliseconds (ms) for words presented in the left visual field (LVF), the right visual field (RVF), or at a central fixation point (CPP)



Error Rates

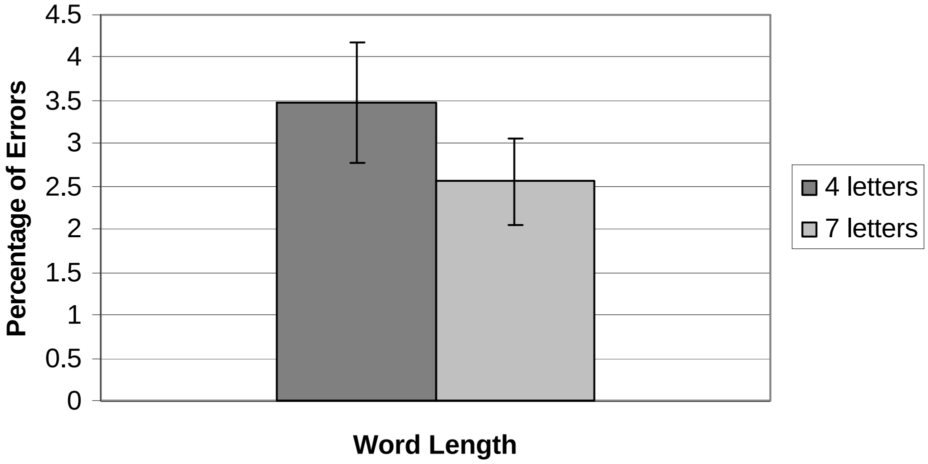
Table 2: Percentages of errors made for 4 and 7 letter words presented in the left visual field (LVF), at the central presentation point (CPP), and in the right visual field (RVF), with either the left eye covered (LC), the right eye covered (RC), or with both eyes used (both)

	Visual Field Word Length					
	LVF		CPP		RVF	
Eye	4	7	4	7	4	7
LC	2.79	2.79	2.79	0.79	8.36	4.00

Both	4.00	4.36	1.57	0.36	6.36	6.29
RC	5.93	1.19	1.57	2.00	5.93	1.19

Our first hypothesis was that there would be a larger effect of word length in the left visual field compared to the right visual field. Our reaction time data did not support this hypothesis and neither did our error data. We found a trend for four letter words (3.47 %) to produce a greater number of errors compared to seven letter words (2.56 %). This was significant by participants but non-significant by items (F_1 (1, 17) = 8.84, *MSE* = 0.59, *p*< 0.01; F_2 (1, 13) = 3.98, *MSE* = 1.22, *p* = 0.067) (see Figure 4).

Figure 4: Percentages of errors made on 4 letter words compared to 7 letter words

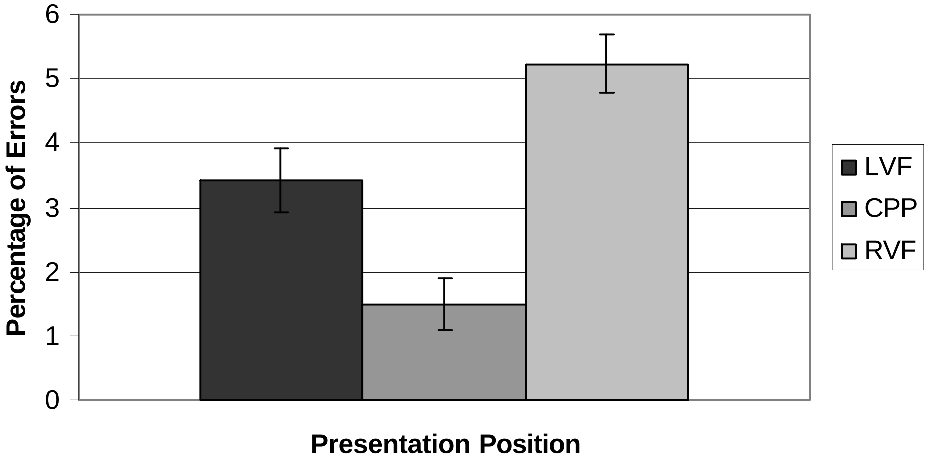


However, there was no variation in this difference between the three presentation positions. The interaction between the factors of Visual Field and Length was non-significant, both by participants and by items (both *F*s < 1) such that there was no variation in the difference in the number of errors made between four and seven letter words between the left visual field, the right visual field, and the central fixation point. We did not find any support for our first hypothesis.

Our second hypothesis was that with the right eye occluded, there would be less of a difference between four and seven letter words. Our reaction time data did not support this hypothesis and neither does our error rate data. The three-way interaction between the factors of Eye, Visual Field and Length was non-significant, both by participants and by items (both *F*s < 1) such that there was no difference for error rates between four and seven letter words in the left visual field, the right visual field, or at a central presentation point, with either the left eye covered, the right eye covered, or with both eyes used for viewing. Covering the right eye did not lead to a reduction in the differences between four and seven letter words. We did not find any support for our second hypothesis.

As with the reaction time data, we found an effect of visual field presentation position on the number of errors made. There was a main effect of visual field, significant both by participants and by items (F_1 (2, 34) = 12.97, *MSE* = 0.60, $p < 0.001$; F_2 (2, 26) = 8.15, *MSE* = 1.08, $p < 0.01$) such that there were more errors made on the lexical decision task when items were presented in the right visual field (5.23 %) compared to when items were presented in the left visual field (3.42 %) (t (18) = 8.38, $p < 0.05$). There were also more errors made when items were presented in the left visual field (3.42 %) compared to when items were presented to the central presentation point (1.49 %) (t (18) = 8.95, $p < 0.05$). Finally, there were more errors made on items presented in the right visual field (5.23 %) than on items presented on the central presentation point (1.49 %) (t (18) = 24.35, $p < 0.01$) (see Figure 5). Our reaction time data showed that words were recognised faster when they were presented centrally compared to when they were presented in either of the lateralised positions (either left visual field or right visual field). Not only did the reaction time data not support the idea that there is a right visual field advantage for recognising words (there was no difference in reaction times between the left visual field and the right visual field) but the error data suggests that words were more easily recognised in the left visual field in this task. All other effects and interactions were non-significant.

Figure 5: Percentages of errors made for items presented in the left visual field (LVF), the right visual field (RVF), or at a central fixation point (CPP)



4.1.3 Discussion

This experiment was designed to test whether occluding one eye would have an impact on visual field attentional asymmetries in a lexical decision task. We predicted that occluding one eye should lead to a decrease in the activation of the cerebral hemisphere contralateral to the eye that is patched which in turn should lead to an increase of activation in the cerebral hemisphere that is ipsilateral to the patched eye. Based on this prediction and the findings of Roth et al. (2002), we predicted that occluding one eye should increase attentional dominance for the hemisphere ipsilateral to the patched eye.

Blocking input from the visual field to the right eye means that the left hemisphere only receives temporal input from the right visual field and the right hemisphere only receives nasal input from the left visual field. If nasal input does dominate temporal input then we predict that occluding the right eye would result in increased activity of the right hemisphere attentional systems leading to a reduction in the left visual field word length effect. Blocking input to the left eye means that the left hemisphere only receives nasal input from the right visual field and the right hemisphere only receives temporal input from the left visual field. We predicted that this would result in the same pattern of results as binocular viewing with there being a large length effect in the left visual field.

We did not find any effect of having one eye covered when completing a lexical decision task on items presented in the left visual field, in the right visual field, or at a central fixation point. Looking at the reaction time and error rates data, there was no significant effect of the variable of Eye. If our hypothesis had been upheld, under binocular viewing conditions, we should have found the right visual field advantage with a larger length effect in the left visual field compared to the right visual field. This would have replicated the results of Ellis (2004). When the left eye was patched, the left hemisphere attentional systems would have still been maximally activated for this language-based task. Therefore, we predicted that occluding the left eye would have resulted in the same pattern of results as that found under binocular viewing conditions.

Roth et al.’s (2002) study predicts that when the right eye is occluded, there would be a decrease in the activation of the left hemisphere attentional system, and the right hemisphere attentional system should have become maximally activated. This in turn would have reduced or eliminated the length effect in the left visual field. However, our results do not support this hypothesis. Viewing the letter strings with either the left eye or the right eye alone produced the same pattern of results as binocular viewing.

Overall we did not find an effect of word length. We had predicted that we would find that four letter words would be recognised faster than seven letter words based on previous findings (e.g., Ellis 2004). The fact that we failed to replicate this finding suggests that perhaps the failure to find a significant word length by eye interaction may have been caused by the choice of stimuli. We did not control for the frequencies of the words that we chose for the four and seven letter word lists. It is possible that differences in frequency ranges masked any effects of word length. We will investigate this idea further in the next experiment.

We did find an effect of visual field presentation with words being identified faster and more accurately in the central presentation position compared to the left or right visual field presentation positions. There were no differences between the left visual field presentations and the right visual field presentations for reaction times. This finding supports Nazir’s idea of the role of perceptual learning being a facilitating factor in word recognition. Nazir proposed that words are recognised faster when they are viewed in a position of the visual field where they have been most frequently viewed on previous exposures (Nazir, 1993). Words presented at the central fixation point are optimally positioned for faster word recognition compared to those that were presented completely in the left visual field or completely in the right visual field as words are most often fixated slightly to the left of centre. Words are rarely fixated on at the first or last letter. Our finding that words were recognised faster when they were presented centrally supports the idea of the importance of visual familiarity when recognising words. However, there were more errors made on words presented in the right visual field compared to words presented in the left visual field. This finding does not support the idea of perceptual learning being the vital factor in word recognition. If it were simply a case of familiarity of presentation position that facilitated word recognition then there should have been less accuracy in the left visual field as words are very rarely fixated on at the last letter. The least frequent view of a word is therefore to see it completely in the left visual field. This should have led to a greater amount of errors when the words were viewed in the left visual field compared to in the right visual field.

There was no significant difference in reaction times between four letter words and seven letter words although marginally more errors were made on four letter words compared to seven letter words. There was a marginally significant effect of visual field by eye such that under binocular viewing conditions, more errors were made in the left visual field and the right visual field presentation positions compared to the central presentation positions. All other effects and interactions were non-significant.

The next experiment will further investigate the impact on lexical decisions of losing the input from one eye. However, in the next experiment we will control for word frequency and also we will concentrate on the impact of losing the input of the right eye on words presented in the left visual field as the word length effect is normally found to be strongest here (Ellis, 2004).

4.2 The Influence of Monocular Occlusion on the Word Length Effect in the Left Visual Field

The previous experiment failed to show any effects of occluding one eye on the recognition of words presented in the left and right visual fields. The present experiment further investigates the questions posed in the previous study by also taking into account the factor of word frequency. It is possible that in the previous experiment, the effect of word length was masked by not having stimuli words that were controlled for frequency. In this experiment we concentrate on words presented in the left visual field as this is the area of the visual field where the largest effect of word length is normally found (e.g., Ellis, 2004). The present experiment uses a lexical decision task similar to that in the previous experiment to test whether losing the nasal hemi-retinal input of the right eye to the left cerebral hemisphere would affect hemispheric attentional asymmetries in a word recognition task. We were particularly interested in the impact of losing the nasal hemi-retinal input from the right eye as we propose that the nasal hemi-retina is a more dominant source of visual input to the brain than the temporal hemi-retina. The nasal hemi-retina of the right eye inputs directly to the language-dominant left hemisphere (see Section 4.1) so blocking right eye nasal hemi-retinal input should most affect linguistic tasks. This effect should be most obvious in the left visual field as the right visual field is received by the nasal hemi-retina of the right eye.

The word length effect is greater in the left visual field than in the right visual field under binocular viewing conditions (e.g., Ellis 2004). We propose that one of the factors that contribute to this effect is that attentional resources are allocated to the right visual field (the right visual field is where new visual information appears first when reading sentences and is received by the language-dominant left hemisphere). If this is the case, blocking nasal hemi-retinal input from the right eye should decrease the activation of the left hemisphere’s attentional resources and increase the attentional resources of the right hemisphere leading to an increase in the working perceptual span of the left visual field. If the perceptual span of the left visual field is increased, there should be no length effect. There should be no difference between short and long words as all of the words will fall within the increased perceptual span. We also investigate the effect of occluding the right eye on the perception of high and low frequency words that are presented in the left visual field. We will now look at this effect in more detail.

The Word length Effect

When reading English, the eye makes saccades along the line of text from left to right. The area of the visual field where useful information can be extracted is called the perceptual span. Originally investigated by McConkie and Rayner (1975), the perceptual span is found to be asymmetric: it expands approximately 14 to 15 characters to the right of fixation and approximately 3 to 4 characters to the left of fixation. A greater amount of visual information can be extracted from the area to the right of fixation compared to from the left. This may reflect an attentional bias developed through the habit of reading from left to right (Binder, Pollatsek, & Rayner, 1999). When new information appears in the visual field during sentence reading, it initially appears to the right of fixation in the right visual field so it follows that attentional resources concentrate on the right visual field rather than on information that is in the left visual field that has already been fixated and received attention. Not all attention is focused on the right visual field however: Binder et al. (1999) demonstrated that skipped words may still receive attention and that even when a word is fixated it may still receive some attention while the reader begins to fixate the next word.

Perhaps as a consequence of the asymmetry of the visual span, under binocular reading conditions there is a large word length effect in the left visual field with shorter words being recognised faster than longer words (e.g., Ellis 2004). The right eye receives temporal input from the left visual field and nasal input from the right visual field. As previously mentioned the nasal hemi-retina has faster, more densely packed connections to the brain and also has greater spatial resolution compared to the temporal hemi-retina. In addition to this, the nasal hemi-retina of the right eye projects directly to the language-dominant left hemisphere. One would predict, therefore, that this would lead to more efficient and faster processing of information from the parafoveal area of the right visual field compared to that from the parafoveal area of the left visual field. The dominance of the left cerebral hemisphere for language and reading habits may lead to a greater amount of attention being allocated to the right visual field in language-based tasks such as reading or word recognition.

The effect of monocular occlusion on word length effects

The current experiment tests whether blocking the input to the right eye, and therefore blocking the nasal hemi-retina input to the left hemisphere influences hemispheric attentional asymmetries in lexical processing. Covering the right eye should lead to an inhibition of the attentional systems of the left hemisphere and an increase in activation of the attentional systems of the right hemisphere.

In addition, the work of Ellis and others (e.g., Ellis, 2004; Faust et al., 1993; Malamed & Zaidel, 1993) inspires more detailed predictions about lexical items of different length. Under binocular viewing conditions, a large length effect should be found in the left visual field with four letter words being recognised faster than seven letter words. Occluding the right eye should reduce the activity of the left cerebral hemisphere by blocking the dominant source of visual input (the nasal hemi-retina) to the left hemisphere. This should increase the activity of the non-language dominant right cerebral hemisphere. If the asymmetry in the perceptual span is due to the dominance of the attentional systems of the left hemisphere in this task then inhibiting the activity of the left hemisphere and therefore increasing the activity of the right hemisphere should reduce these asymmetries. As the activity of the attentional systems of the right hemisphere is increased, the perceptual span of the left visual field should also be extended leading to a decrease in the time it takes to respond to seven letter words as they now lie within the perceptual span. There should be a reduction in the length effect in the left visual field when the right eye is covered. If the data support this idea then the length effect cannot be due to different methods of lexical access by the two cerebral hemispheres as proposed by Ellis and others. If the length effect can be explained by different methods of lexical access then the length effect should still be present when the right eye is occluded. This experiment is a replication of the previous experiment except that in experiment 4.2 we also control for word frequency.

4.2.1 Method

Design

This experiment used a lexical decision task to investigate the effect of monocular occlusion on the word frequency and the word length effects that are found in the left visual field under binocular viewing conditions. I looked at the effect of three variables: Word Frequency, Word Length and Eye which were fully crossed leading to a 2 (Frequency) x 2 (Length) x 2 (Eye) design. There were two levels of the variable “Frequency”: “HF” (high frequency words), and “LF” (low frequency words). The variable of Frequency was crossed with the variable of “Length” which also had two levels: “4” (four letter words) and “7” (seven letter words). The variable of “Eye” had two levels: “Both” (participant used both eyes) and “RC” (participant had their right eye covered). Each participant was exposed to all 8 conditions.

Apparatus

A RM innovator Pentium 4 computer connected to an Iiyama Vision Master Pro 413 monitor with a 17-inch screen (refresh rate 74.999 Hz) was used to present the stimuli. This was connected to a Psychology Software Tools Inc serial response box (model 200A) which was used to record the participants’ responses.

Materials

The stimuli items consisted of letter strings that were either four or seven letters long. An equal number of words and non-words of 4 and 7 letters were presented. The real word stimuli were varied by frequency as well as by length. Using a counterbalanced design, the words of each length-frequency combination were presented in the left visual field parafovea. These stimuli were crossed with the two levels of the variable ‘Eye’: Both eyes used or right eye covered.

Word Stimuli Words and word frequencies were taken from the British National Corpus (BNC). Plurals, proper nouns, or words that were inflected were excluded from stimuli lists. An equal number of words of either four or seven letters long were chosen to test the length effect. There should be a sufficient difference in the length between these two word groups to enable a length effect to occur but seven letter words are not so rare as to create a difference in the availability of words of an equal frequency range as the four letter words. The word groups (4 letters long and 7 letters long) were matched on the range of frequencies. All of the low frequency words were below 20 occurrences per million and all of the high frequency words had above 100 occurrences per million (4-letter high frequency word group *mean* = 269.1, *standard deviation* = 75.7, *range* = 143 - 372. 7-letter high frequency word group *mean* =255.5, *standard deviation* = 126.6, *range* = 100 – 473, 4-letter low frequency word group *mean* =13.0, *standard deviation* =3.2, *range* = 10 – 20, 4-letter low frequency word group *mean* =11.7, *standard deviation* =1.3, *range* = 10 - 14). The stimuli lists were compiled with a mixture of nouns, verbs and adjectives that were counterbalanced to control for any effect of word class. The majority of the four letter words had one syllable and the seven letter words had between one and three syllables. The words were a mixture of regular and exception words. There were an equal number of words and non-words presented to each participant. The order of stimuli presentation was randomised across participants.

Non-word Stimuli The non-words were chosen to closely resemble real words. The non-words were taken from the ARC non-word database (Rastle, Harrington, & Coltheart, 2002). All non-words had legal bigrams, orthographically legal onsets, and orthographically legal bodies. These parameters were used in order to ensure that the non-words were as similar to real words as possible. The non-words were either 4 or 7 letters long.

Presentation Positions

All of the stimuli were presented in lower-case Courier New font to ensure that all words of equal number of letters were also of the same length in millimetres. Using this font, each letter measured 3mm wide. Participants sat at a distance of approximately 60cm from the screen. The four letter words were approximately 14mm long and the seven letter words were approximately 25mm long. At this viewing distance, 10mm is equal to approximately 1° of visual angle. All of the experimental items were presented in the left visual field parafoveal region. Words that were intended for presentation in the left parafovea were presented outside the central 2.5° of the visual field (foveal area) to ensure that initially the stimulus would only be viewed by the parafovea. An equal number of non-experimental real words were presented to the right visual field parafovea and to a central presentation point so that the participants did not begin to anticipate where in the visual field the stimuli would appear.

Participants

There were 18 participants in total. All of the participants were right handed. All were undergraduates at the University of Edinburgh. All had normal or corrected-to-normal vision. None of them had any history of reading or visual problems.

Procedure

Participants completed a lexical decision task. There were two blocks in the experiment: in one block the participant used both eyes to view the stimuli, in the other block the right eye was covered using an eye-patch. The order of the blocks was randomised across participants. The task was to look at the letter strings that appeared on the screen and make a decision as to whether the letters formed a real word or a non-word. Participants sat at a distance of approximately 60cm from the screen. They were instructed to fixate on a gap between two vertical lines in the centre of the screen. This fixation point was present on the screen for 3000ms. The words and non-words were then individually presented until the participant responded up to a maximum of 10,000ms. Participants made a decision as to whether the letter strings made a real word or a non-word by pressing a designated button on the button box. Participants used the index finger of each hand. They pressed the left button to indicate a real word and the right button to indicate a non-word. As soon as the participant made their response, the fixation point for the next trial appeared. There were 10 practice trials to begin to make sure that the participant had correctly understood the procedure. Reaction times and error rates were recorded.

4.2.2 Results

The data were analysed using analysis of variance (ANOVA). There were two repeated-measures within-participants and between-items factors: Frequency (High frequency words and low frequency words) and Length (4 letters long and 7 letters long). There was also one within-participants and within-items factor: Eye (Both eyes used and Right eye covered). Reaction time data measured in milliseconds were analysed using a 2 (Frequency) X 2 (Length) X 2 (Eye) repeated measures ANOVA followed up with Bonferroni corrected related-samples t-tests. Error rates were analysed using 2 (Frequency) X 2 (Length) X 2 (Eye) repeated measures ANOVA followed up with Bonferroni corrected related-samples t-tests. Items that participants made errors on were excluded from the reaction time analysis as were items that had a reaction time that was more than 2.5 standard deviations away from the mean for that particular type of item for that participant. These values were replaced by the average reaction time score for that participant for that item type. A total of 42 items were replaced across participants giving a replacement rate of 5.56%.

Reaction Times

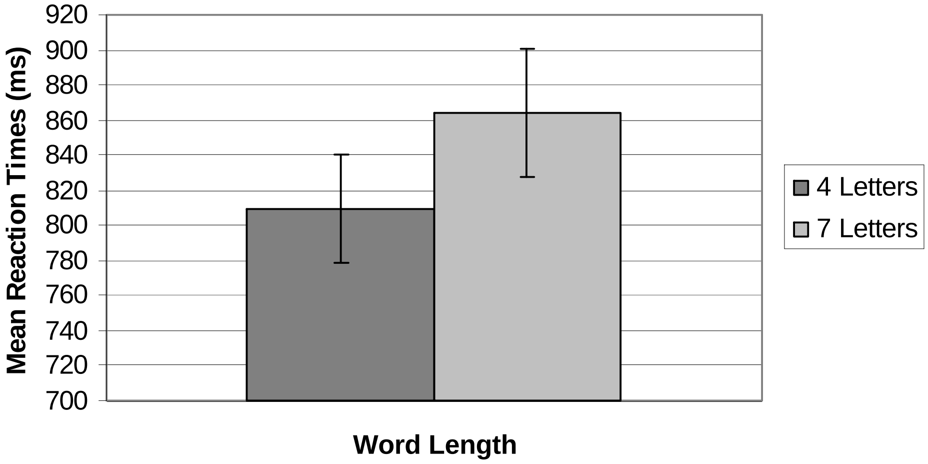
Table 3: Mean reaction time (RT) scores in milliseconds for high and low frequency 4 letter words and high and low frequency 7 letter words presented in the left visual field using either both eyes (both) or with the right eye covered (RC)

	Word Frequency Word Length			
	High		Low	
Eye	4	7	4	7
Both	757.3	839.0	824.2	928.9
RC	802.1	815.7	852.6	873.0

Table 3 shows the mean reaction times for high and low frequency words of 4 and 7 letters in the left visual field with either the right eye covered or both eyes used. We found a main effect of word length, significant both by-participants and by-items (F_1

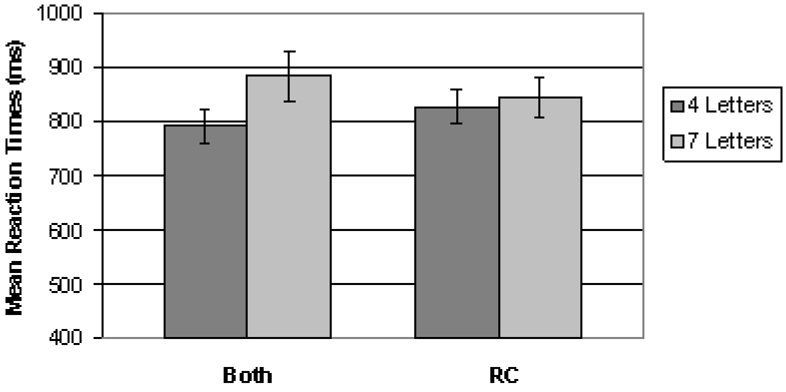
(1, 17) = 6.890, *MSE* = 15859.57, $p < 0.02$; F_2 (1, 20) = 6.45, *MSE* = 18915.04, $p < 0.02$) such that four letter words (809.1 ms) were recognised faster than seven letter words (864.2 ms) when they were presented in the left visual field (see Figure 6).

Figure 6: Mean reaction times in milliseconds (ms) to 4 and 7 letter words presented in the left visual field



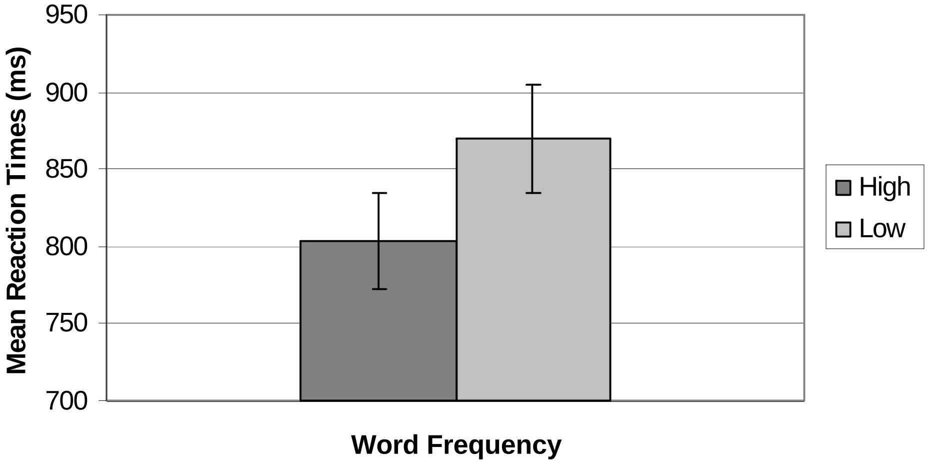
Supporting our hypothesis, there was a significant interaction (both by-participants and by-items) between eye and word length (F_1 (1, 17) = 4.66, *MSE* = 11215.70, $p < 0.05$; F_2 (1, 20) = 4.43, *MSE* = 12940.89, $p < 0.05$). When the words were viewed binocularly, there was the predicted length effect in the left visual field with four letter words (790.8 ms) being recognised significantly faster than seven letter words (883.9 ms) (t (35) = 7.56, $p < 0.05$). When the right eye was occluded we found that there was not a significant difference in reaction times between four letter words and seven letter words that were presented in the left visual field (t (35) = 1.22, $p > 0.1$) (see Figure 7).

Figure 7: Mean reaction times in milliseconds (ms) for 4 and 7 letter words viewed in the left visual field either with both eyes (both) or with the right eye covered (RC)



We also found a significant effect of word frequency, significant both by-participants and by-items (F_1 (1, 17) = 20.08, *MSE* = 7842.29, $p< 0.001$; F_2 (1, 20) = 9.97, *MSE* = 19080.11, $p= 0.005$) such that high frequency words (803.5 ms) were recognised faster than low frequency words (869.7 ms) when they were presented in the left visual field (see Figure 8).

Figure 8: Participants' Reaction Times in milliseconds (ms) to high frequency words and low frequency words presented in the left visual field



However, word frequency did not interact with any of the other variables. The interaction between the factors of Frequency and Length was non-significant both by-participants and by-items (both *F*s < 1) such that the frequency of the words did not influence the difference in reaction times between long (7 letter) words and short (4 letter) words. There was also no interaction between frequency and eye in that there was no difference in reaction times between high and low frequency words when the right eye was occluded compared to when the words were viewed binocularly. The three-way interaction between the factors of Frequency, Length and Eye was also non-significant both by-participants and by-items (both *F*s < 1) such that although there was a significant difference in reaction times to four and seven letter words between using both eyes and using only the left eye, it made no difference to reaction times if the words were high or low frequency.

Error Rates

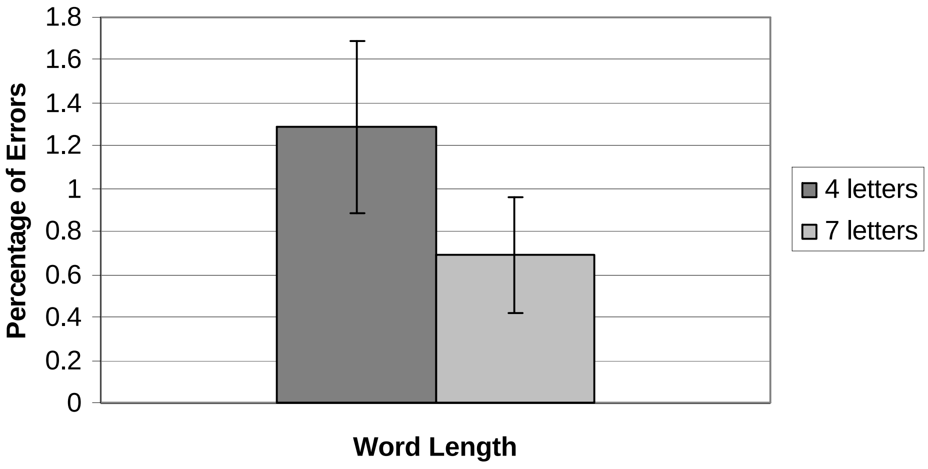
Table 4: Percentages of Errors made on high and low frequency 4 letter words and high and low frequency 7 letter words in the left visual field presentation point, using both eyes and with the right eye covered

	Word Frequency

	Word Length			
	High		Low	
Eye	4	7	4	7
Both	1.59	3.97	6.35	4.76
RC	4.76	1.59	7.94	0.79

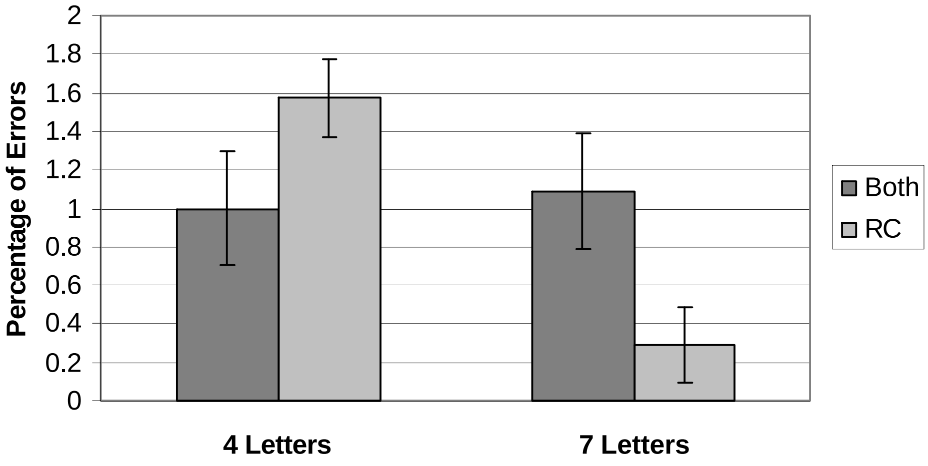
Although we found that four letter words were recognised faster than seven letter words when they were presented in the left visual field, there was a trend for four letter words to elicit more errors compared to seven letter words. There was a main effect of word length, significant only by-participants but non-significant by-items (F_1 (1, 17) = 4.86, MSE = 0.21, $p < 0.05$; F_2 (1, 20) = 2.87, MSE = 0.21, $p > 0.1$) such that (by-participants only) there were more errors on four letter words (1.29 %) compared to seven letter words (0.69 %) (see Figure 9). This suggests the possibility of a speed-accuracy trade off.

Figure 9: Percentages of errors made on four letter words and seven letter words presented in the left visual field



As with the reaction times, the interaction between word length and eye was significant both by-participants and by-items (F_1 (1, 17) = 4.99, *MSE* = 0.27, $p< 0.05$; F_2 (1, 20) = 5.71, *MSE* = 0.20, p< 0.05) such that when both eyes were used to view the stimuli, there was not a significant difference in the number of errors made on four letter words compared to seven letter words (t (18) = 0.08, $p > 0.1$). When the right eye was occluded, there was a significant difference in the number of errors made on four letter words and seven letter words with four letter words (1.57 %) producing significantly more errors compared to seven letter words (0.29 %) (t (18) = 8.09, $p < 0.05$) (see Figure 10). Although four letter words were recognised faster than seven letter words when the stimuli were viewed binocularly, there was no difference in the number of errors made on four letter words compared to seven letter words. However, with the right eye occluded there was no difference in the reaction times to four letter words compared to seven letter words but there was a significant difference in the amount of errors made with four letter words eliciting more errors than seven letter words. This suggests that there was a speed-accuracy trade-off. The recognition of four letter words appeared to be affected more by having the right eye occluded than the recognition of seven letter words.

Figure 10: Percentages of errors made on 4 and 7 letter words when viewed with both eyes compared to with the right eye covered (RC)



Overall, word frequency did not affect the number of errors made. The factor of frequency was non-significant both by-participants and by-items (both *F*s < 1) such that there was no difference between the number of errors made on high frequency words compared to on low frequency words. Recall that high frequency words were recognised faster than low frequency words.

The interaction between the factors of word frequency and word length was marginally significant by-participants but not significant by-items (F_1 (1, 17) = 4.21, *MSE* = 0.17, *p* = 0.056; F_2 (1, 20) = 2.31, *MSE* = 0.26, *p*> 0.1). However, further Bonferroni corrected t-test showed that there was no significant difference in the number of errors made between high frequency seven letter words and low frequency seven letter words (*t* (18) = 0.00, *p* > 1.00) and no significant difference between the number of errors made on high frequency four letter words and low frequency four letter words (*t* (18) = 5.06, *p* > 0.06). All other effects and interactions were non-significant.

4.2.3 Discussion

This experiment used a lexical decision task to investigate the effect of losing the input to the brain from the right eye when making lexical decisions to high and low frequency words of either four or seven letters in the left visual field. We examined the impact of losing the input from the right eye (and therefore the proposed dominant source of visual input to the left hemisphere) on the word length effect

(Ellis, 2004; Ellis et al., 1988; Faust et al., 1993; Malamed & Zaidel, 1993; Young & Ellis, 1985, 1987) that is normally found in the left visual field under binocular viewing conditions.

If nasal hemi-retinal input to the brain is dominant over temporal hemi-retinal input then blocking the nasal hemi-retinal input of the right eye to the language dominant left hemisphere should affect the asymmetries that are normally present in this task under binocular viewing conditions. If the asymmetries in the perceptual span (as demonstrated by the word length effect) are due to the dominance of the left hemisphere attentional systems in the task then inhibiting the activity of the left hemisphere should reduce these asymmetries.

Based on the findings of Ellis and others (e.g., Ellis, 2004) it was predicted that there would be a word length effect in the left visual field when the stimuli were viewed binocularly with shorter words being recognised faster than longer words. This is indeed what we found: There was a robust word length effect in the left visual field when the stimuli were viewed with both eyes with four letter words being recognised significantly faster than seven letter words. Critically, however, we extended the findings of Ellis (2004) to predict that the word length effects that are found in the left visual field under binocular viewing conditions should be attenuated when the right eye is occluded. Our results bear out this prediction. When only the left eye is used to view the stimuli, we found that there was not a significant effect of word length in the left visual field. Under these viewing conditions, there was no difference in reaction times between four and seven letter words. We propose that this is because occluding the right nasal hemi-retina removes the dominant source of visual input to the left hemisphere reducing the activity of the attentional systems of the left hemisphere and increasing the activity of the attentional systems of the right hemisphere. This leads in turn to an increase in the effective perceptual span of the left visual field and a reduction in the word length effect. This result does not support Ellis et al’s assertion that the length effect in the left visual field reflects different methods of lexical access of the left and right hemispheres. If the length effect in the left visual field did reflect differences in lexical processing between the left and right hemispheres then the length effect should still be present even with the right eye occluded as the left visual field is still received by the right hemisphere.

Ellis and others (e.g., Ellis, 2004; Ellis et al., 1988) proposed that the presence or absence of word length effects in reading is reflective of the process of lexical access. The largest word length effect is found in skilled readers when a word is presented completely in the left visual field and the recognition of words that are presented completely in the right visual field is more affected by alternating case than words presented in the left visual field (Ellis, 2004). They interpret these findings as evidence that the two hemispheres access words in different ways. They argue that the left hemisphere processes letters in parallel and the right hemisphere processes letters in a non-parallel way. These processes require that graphemic information is stored in a short-term memory buffer. Ellis et al. proposed that words that are presented to the left visual field are also processed in this way, giving rise to the length effect in the left visual field. However, the results of the present experiment suggest that this might not be the whole story.

Under normal reading conditions the effects of word length are less obvious for skilled readers. However, young children who are learning to read show large word length effects but this disappears as reading skill develops (Aghababian & Nazir, 2000). In skilled readers word length only becomes an obvious factor when items are presented completely in the left visual field. Length effects arise in the right visual field when either processing non-words or real words that are presented in an unusual format (for example, alternating case) where word forms are distorted. Nazir (2000) argues that a better explanation for word length effects is that it is not reflective of hemispheric asymmetries in processing styles but instead it reflects a combination of lexical knowledge and perceptual learning. Words are recognised more efficiently when they are viewed in the position in which they are most commonly encountered. Length effects are most obvious in the left visual field because it is very rare for a word to be fixated on at the final letter. As a consequence of this, it is very rare for a word to be viewed completely in the left visual field. However, the results of the present experiment do not support this idea.

Occluding the right eye should not have affected the word length effect in the left visual field if the length effect was purely a product of perceptual learning.

This experiment does support the hypothesis of Binder, Pollatsek, and Rayner (1999) who argue that the asymmetry in the perceptual span (and therefore the word length effect) is due to attentional factors. If attention to the right visual field is decreased (by occluding the right eye), and attention to the left visual field increases as a consequence, then it would be expected that there would be a reversal in the perceptual span asymmetry and the length effect would be reduced in the left visual field. This is what we found.

An alternative explanation for the absence of the left visual field length effect could be that visual acuity was decreased by covering one eye. However, if this was the case then it would be expected that seven letter words would show the greatest impact as they extend further into the periphery than four letter words. This would have lead to an increase in the length effect, not a reduction of the length effect. Also, there were more errors made on four letter words than on seven letter words when the right eye was covered. There was no difference in error rates between four and seven letter words when both eyes were used. Again, it would be expected that seven letter words would suffer more from a reduced perceptual span than four letter words.

Aghababian and Nazir (2000) demonstrated that word length effects are most obvious when learning to read. The participants in this experiment were all undergraduate students who presumable are highly skilled readers. It would be interesting for future research to replicate this experiment using a less skilled reading group (for example, developmental dyslexics) to test whether there are any parallels between the less skilled dyslexic group and children who are learning to read.

4.3 Implications for reading and further questions to be addressed

In these two experiments we have shown that blocking the input to the left hemisphere from the nasal hemi-retina of the right eye reduces the word length effect that is normally found in the left visual field under binocular viewing conditions. The results suggest that occluding the right eye led to an increase in attention to the left visual field and as a result, an increase in the perceptual span in the left visual field. This supports the idea of the perceptual span asymmetry being due to attentional factors that have developed through reading a line of text from left to right (Binder, Pollatsek, & Rayner, 1999). The data reported here do not support the explanation of visual field asymmetries that attributes them to different methods of lexical access between the two hemispheres (e.g., Ellis, 2004). We also found evidence against the explanation of the word length effect offered by Nazir (e.g., Nazir, 2000; 2003). Nazir proposes that the word length effect arises through an interaction between lexical knowledge that has been gained through reading practice and low-level, perceptual learning. Our data do not fully support Nazir’s hypothesis as we found an absence of the length effect in the left visual field when the right eye was occluded. If the assumptions of Nazir were correct then the length effect should always be present in the left visual field as it is very rare for a word to be fixated on the final letter. As a consequence, there is a lack of retinal exposure for words that are solely presented in the left visual field.

We propose an alternative explanation for the effects of word length in the left visual field that is based on the proposal of Binder et al. (1999) that the asymmetry in the perceptual span is caused by a rightward bias that has developed through the habit of reading from left to right. Reading from the left to the right means that new information initially appears in the right visual field and so it follows that attention is focused on the area of the visual field where new input is appearing. The right visual field is transmitted to the left hemisphere through both the left and the right eyes. It is projected onto the nasal hemi-retina of the right eye and to the temporal hemi-retina of the left eye. As previously mentioned, the nasal hemi-retina has stronger, faster connections to the brain compared to the temporal hemi-retina and it also enables greater spatial resolution due to the smaller receptive fields of the cells. It appears from the two experiments reported here that blocking the nasal hemi-retinal input from the right eye to the left hemisphere is sufficient to reduce hemispheric attentional dominance in lexical processing. This lends support to the idea that the input to the nasal half of the retina has more of an influence on lexical processing than input to the temporal half of the retina.

In addition to the overall faster transmission rate of the nasal hemi-retina, there are two different types of retinal pathway arising from this area of the retina: the magnocellular and parvocellular pathways. As discussed in chapter 1, the magnocellular pathway arises mostly from the extra-foveal area of the retina and has a faster transmission rate than the parvocellular pathway which arises mostly from the foveal area of the retina. This means that the fastest route from the visual field to the brain is the magnocellular pathway connections from the nasal hemi-retina of the right eye to the LGN. These retinal ganglion cells sample the right visual field parafoveal area which is exactly where new portions of text appear when reading. The remaining six experiments go on to explore this idea further. Based on this anatomical information, we propose that it is the nasal hemi-retina of the right eye that allows parafoveal preview benefits to occur in sentence reading. The high speed transmission of right visual field parafoveal input to the language-dominant left hemisphere allows for fast processing of new information that appears in the right visual field.

Monocular occlusion effects compared to binocularity in reading

It has traditionally been assumed by researchers in the area of eye-movements during reading that both eyes fixate on the same point in the text when reading sentences. However, recent work has shown that this is not the case (Heller & Radach, 1999; Juhasz et al., 2006; Liversedge et al., 2006a; Liversedge et al., 2006b). Liversedge and others have shown that almost half (47%) of all fixations made during sentence reading are "non-aligned". A fixation is characterised as being non-aligned when the eyes fixate more than one character apart (after vergence movements have been completed). Of these unaligned fixations 26% are uncrossed (the left eye is fixating to the left of the fixation point of the right eye) and 15% are crossed (the left eye is fixating to the right of the fixation point of the right eye). Importantly, this non-alignment of the eyes does not increase the difficulty of word recognition (Juhasz et al., 2006). As long as the representations from each eye are available for further processing then it does not appear to matter if they are not identical. When one eye is occluded, one of the two representations of each visual field is blocked from reaching the brain and the next stage of visual processing. This adversely affects lexical processing. In binocular reading, the two representations may not be identical but this appears to enhance lexical processing, at least in the right visual field. Occluding one eye does not make reading easier suggesting that the visual system is well adapted to reconciling two disparate images.

4.4 Chapter Summary

In this chapter we have shown that occluding the input to the left hemisphere from the nasal hemi-retina of the right eye leads to a reduction in the word length effect that is normally found in the left visual field under binocular viewing conditions. It has been argued that the large word length effect (Ellis, 2004) that is found in the left visual field is the result of different methods of lexical access by the left and right hemispheres. The results of the two experiments reported here do not support these claims. Also, these results do not support the alternative account of the length effect as proposed by Nazir (2000, 2003). The word length effect cannot be due to either hemispheric asymmetries in lexical processing or perceptual learning as the effect is not present when the right eye is occluded. Instead, we propose an account that is based on the proposal by Binder et al. (1999) that asserts the importance of attentional factors in contributing to the asymmetry of the perceptual span. We have shown in these two experiments how this asymmetry can be reversed by inhibiting the attentional systems of the left hemisphere.

We have also shown that it is faster and easier to identify words that appear directly on the fixation point (in foveal vision) compared to those that are presented to only one visual field (in parafoveal vision). This finding does lend support to the proposal that perceptual learning is important for fast, accurate word recognition (Nazir, 2000; 2003). It is more common for words to be fixated slightly left of centre than it is for them to be fixated wholly in the left or right visual fields. Therefore, the perceptual learning hypothesis would predict that words are more easily recognised when they are centrally fixated than when they appear in either the left or right visual fields. Our data partially support this hypothesis. However, perceptual learning cannot account for all of the findings. We found no significant word length effect in the left visual field when the right eye was occluded. This cannot be accounted for by the perceptual learning hypothesis. The next set of experiments goes on to explore the effects of visual field presentation position on the recognition of words that are varied by regularity. We will also further develop the idea that the magnocellular pathway might influence the parafoveal preview benefit in sentence reading.

Chapter 5

The Relationship between Reading Skill and Lexical and Sub-lexical processing in Word Recognition

5.0 Chapter Overview

The previous chapter looked at how the influence of word length effects in different areas of the visual field could be manipulated. In this chapter we examine how the length of a word affects the reading of dyslexics and we relate this to the proposal that dyslexic readers rely on a sub-lexical reading route and are unable to utilise the lexical reading route. In Section 5.1 we test the hypothesis that dyslexics are unable to use the lexical reading route by investigating the differences between dyslexic and non-impaired readers when recognising both regular and exception words. The experiment in section 5.2 extends this investigation by looking at how visual field presentation position affects these differences. In section 5.3 we show how the ability to detect phonological information in parafoveal vision is impaired in dyslexic readers and in section 5.4 we relate the findings of the three experiments to parafoveal processing and reading in general.

5.1 The Effects of Reading skill on the Recognition of Regular and Exception Words

The previous chapter investigated the influence of word length on word recognition times. Skilled readers show a larger effect of word length when the words are presented completely in the left visual field. Large word length effects are also seen in skilled readers when they are reading non-words with short non-words being recognised faster than long non-words (Juphard et al., 2004). Skilled readers show lesser effects of word length in the right visual field (when most of the fixated word falls in the right visual field as is the case in a fixation on a word in a sentence). Less proficient readers, including dyslexics and children who are learning to read, show a much greater effect of word length. This usually lessens as reading skill develops (Aghababian & Nazir, 2000) but it remains large for dyslexic readers (De Luca et al., 2002; Spinelli et al., 2005; Ziegler et al., 2003; Zoccolotti et al., 2005).

When learning to read, a sub-lexical strategy is used to identify a word (Aghababian & Nazir, 2000; Zoccolotti et al., 2005). This strategy involves incrementally mapping phonemes onto graphemes and building a representation of the word. When reading skill develops, a faster lexical-based strategy is adopted which enables the recognition of words as whole units. The large word length effects shown by dyslexics and beginner readers reflect a reliance on the sub-lexical route where a greater number of letters in a word corresponds to longer processing times. Dyslexics fail to develop the lexical strategy and so continue to show large word length effects even as adults. Martens and de Jong (2006) used a lexical decision task which they argued emphasises the importance of orthographic, rather than phonological processing. The nature of a lexical decision task (decide whether a letter string is a real word or not) requires lexical knowledge. If dyslexic readers are employing a sub-lexical strategy to recognise words then this will be more apparent in a task that emphasises the need for lexical knowledge. They compared dyslexics with chronologically and reading-age matched control groups. They found that word length effects were much more evident in the dyslexic group. They argue that this supports the idea that dyslexics continue to use the sub-lexical route to word recognition and that there is an increased switch to the lexical route as reading skill develops.

Further support for the idea that dyslexics rely on a less efficient sub-lexical strategy comes from studies with dyslexics in languages that have transparent orthographies (for example, Spanish) which have regular grapheme-to-phoneme correspondence. The reading of dyslexics is still slower than non-impaired readers but word recognition is more accurate than in languages with less transparent orthographies (Zoccolotti et al., 1999). Zoccolotti et al. argue that this reflects the reliance of dyslexic readers on a sub-lexical strategy. This leads to more accurate word recognition than in deep orthography languages (for example, English) but reading is still slower because letters in the word need to be phonologically coded in succession. Related to this is the finding that non-impaired readers take longer to process words that are presented letter-by-letter compared to words that are presented as a whole (Osswald, Humpreys, & Olson, 2002; Rayner & Johnson, 2005).

Using both a standard lexical decision task (participants have to decide whether a letter string is a real word or a non-word) and a phonological lexical decision task (participants have to decide whether a letter string sounds like a real word), Unsworth and Pexman (2003) showed that less proficient readers showed an effect of word regularity whereas skilled readers did not. They concluded that poorer readers did not access phonology as efficiently as the more proficient readers. The skilled readers appeared to be using the lexical route in order to identify exception words whereas the less skilled readers rely on the sub-lexical route which cannot accurately process exception words as these words do not have regular grapheme-to-phoneme correspondence. Therefore, the skilled readers do not show an effect of word regularity and the poorer readers find exception words more difficult than regular words as they cannot access the correct pronunciation of exception words as they are unable to use the lexical route to access the whole phonological representation.

In recent years, neurological models of word recognition have been developed in order to account for the differences between lexical and sub-lexical word recognition strategies (Borowsky et al., 2006; Posner & Raichle, 1994; Pugh et al., 1996, 2000; Sandak et al., 2004). These models propose that efficient, accurate word recognition relies on an interaction between two left hemisphere cortical processing streams: the ventral and the dorsal streams. Both processing streams arise from occipital cortex (where visual feature analysis occurs) but then project to different brain areas. The ventral stream arises from visual cortex and projects to the temporal lobe. This is termed the “lexical route”. Representations of whole words that have been encountered before are stored in lexical memory. These whole word lexical representations map onto whole word phonological representations. The dorsal stream also arises from visual cortex but projects to the parietal lobe and then onto the frontal lobe. This is the “sub-lexical route”. Word recognition is achieved incrementally by this route through mapping individual sounds onto individual sub-lexical orthographic units. This route is also thought to contribute to the development of semantic representations of words.

Support for these models comes from a study by Pugh et al. (1996) who used fMRI to study the regions of the brain that became activated when making same/different judgements on stimuli that were developed specifically to isolate visuo-spatial, orthographic, phonological and semantic processing. The results of this study showed that, in visual word recognition with single words, sub-component processes (such as orthographic processing) activated different brain areas corresponding to the proposed dorsal and ventral pathways.

The dorsal stream, which decodes words incrementally, mapping graphemes to phonemes, is thought to be the route that is used when learning to read (Aghababian & Nazir, 2000; Zoccolotti et al., 1999; Zoccolotti et al., 2005). Without reading experience lexical representations of words cannot be present and so the lexical route cannot be used. If word recognition relies on this route then there will be large effects of word length. If the words are processed by increments then shorter words will be recognised faster than longer words. People who are learning to read show length effects which lessen as reading skill develops (and the ventral pathway comes into use). The lexical route only comes into use when an adequate level of reading skill has been attained and words can be recognised as whole (Pugh et al., 2000; Sandak et al., 2004). If words are recognised as whole units then there will be less effect of word length. This explains why there are reduced length effects in the right visual field for skilled readers; they are able to use the lexical processing route. Dyslexics, however, continue to show large length effects in the right visual field (De Luca et al., 2002; Martens & De Jong, 2006; Spinelli et al., 2005; Ziegler et al., 2003; Zoccolotti et al., 2005). This suggests that dyslexics fail to develop the lexical processing route and remain largely reliant on the sub-lexical processing route.

The dorsal pathway can process regularly spelled words by mapping spelling to sounds. Exception words cannot be processed in this way as there is no one-to-one mapping between spelling and sound. Exception words have to be recognised as a whole and therefore will rely exclusively on processing by the ventral stream. In contrast, phonologically-legal non-words cannot be processed by the ventral stream as there can be no representation in lexical memory of a non-word. Non-word processing must therefore rely exclusively on the dorsal stream. If dyslexics continue to rely on the dorsal stream then we can predict that they will have difficulty in recognising exception words.

The present experiment investigates the effects of word regularity on both dyslexic participants and a control group consisting of skilled readers. We present single word items on a central fixation point in order to assess whether dyslexic participants would differ from the non-impaired group in their ability to efficiently recognise exception words that rely on ventral stream processing. Firstly, we predict that the dyslexic group will be slower to make lexical decisions compared to the control group. If the dyslexics are restricted to using the dorsal stream then all lexical processing will be incremental and therefore slower. The control group will be faster as they utilise the ventral route to process words as whole units. Secondly, as the control group are able to process words as units, we predict that they will show a word frequency effect with high frequency words being recognised faster than low frequency words. We predict that the dyslexic group will not show a word frequency effect as all processing must be incremental if they are relying completely on the dorsal route. If there is no recognition of the word as a whole unit, then we do not expect an effect of word frequency. Finally, we predict that the dyslexic group will show an effect of word regularity with regular words being recognised faster, and more accurately than exception words. The recognition of exception words relies on ventral processing so we predict that if the dyslexics are relying on dorsal stream processing they will make more errors on exception words. The control group participants will not show an effect of word regularity as they can utilise the ventral stream.

5.1.1 Method

Design

The experiment used a lexical decision task to investigate the effects of word regularity and word frequency in dyslexic and non-impaired readers. We looked at the effect of two item variables: word regularity and word frequency which were fully crossed leading to a 2 (Regularity) x 2 (Frequency) design; and one participant variable (Group Type) with two levels (Dyslexic group and Control group). There were two levels of the variable “Regularity”: Regular words and Exception words. The variable of “Regularity” was crossed with the variable “Frequency” which also had two levels: High frequency and Low frequency. The variables of Regularity and Frequency were crossed with the variable of Group Type which had two levels: “Control” which was made up of non-impaired readers and “Dyslexic” which was made up of dyslexic readers. Each participant was exposed to all four conditions. Using a fully counterbalanced design, participants were shown eighty letter strings consisting of four or five letters. Forty of these were real words (experimental items) and forty were non-words (filler items). The participants had to decide whether the letter strings were real words or not. The experimental words were presented on a central fixation point. We compared developmental dyslexics with non-reading impaired participants.

Apparatus

A RM innovator Pentium 4 computer connected to an Iiyama Vision Master Pro 413 monitor with a 17-inch screen (refresh rate 74.999 Hz) was used to present the stimuli. A Psychology software Tools Inc serial response box (model 200A) was used to record participants’ responses.

Materials

Word Stimuli There were four different types of real word stimuli: High frequency exception words, low frequency exception words, high frequency regular words and low frequency regular words.

Defining Frequency The frequency values of the words were taken from the BNC corpus. We calculated the upper and lower frequency quartiles for nouns, verbs and adjectives. Only words from the upper frequency quartile were used to compile the stimuli for the high frequency word lists and only words from the lower frequency quartile were used to compile the stimuli for the low frequency word lists. This ensured that there was a significant difference in the frequencies of the words in each of the two stimuli groups. All of the low frequency words were below 17 occurrences per million and all of the high frequency words had 200 to 400 occurrences per million. These were counterbalanced across word length (4 or 5 letters) and word class (nouns, verbs and adjectives). The word groups (High and Low frequency) were matched on the range of frequencies for each word type (regular and irregular) (Regular high frequency word group *mean* = 299.9, *standard deviation* = 157.9, *range* = 147. Irregular high frequency word group *mean* = 249.4, *standard deviation* = 102.4, *range* = 142. Regular low frequency word group *mean* = 13.2, *standard deviation* = 1.80, *range* = 6. Irregular low frequency word group *mean* = 11.7, *standard deviation* = 1.64, *range* = 6.).

Defining Regularity The definition of regularity was that given by the Southwest Educational Development Laboratory. Words had to meet two criteria before they were considered to be exception words. Firstly, they had to have a different pronunciation from other words that shared the same spelling. Secondly, the pronunciation of the exception word had to be less common (less words are pronounced this way) than the alternative pronunciation. The regular word list was compiled by taking words that had the same letter clusters as the exception words but were pronounced in the same way as the majority of words that shared that same letter cluster.

Non-word stimuli (filler items) There were 40 non-word stimuli items presented in total. Twenty of these were four letters long and the other twenty were five letters long. These were fully counterbalanced across conditions. All of the non-words were taken from the ARC non-word database (Rastle, Harrington, & Coltheart, 2002). The non-words were all pronounceable. All had orthographically existing onsets, orthographically existing bodies and were composed of legal bigrams. All had the same number of syllables and had a similar number of phonological neighbours (range: 10 – 15). The aim was to make them as similar to real words as possible.

Presentation Positions

Participants sat at a distance of approximately 60cm from the screen. At this distance, 10mm is equal to 1° of visual angle. Each letter measured 3mm wide making the four letter words approximately 14mm long and the five letter words approximately 18mm long. All of the stimuli were presented in lower case courier new font to ensure that all words with an equal number of letters were also of the same length in millimetres. Words were presented in the centre of the screen ensuring that all of the words fell within the central 2.5° of the visual field (the foveal region).

Participants

There were 18 participants in total. Nine of these had been previously diagnosed as having developmental dyslexia when at school. These participants completed further pre-tests (see next section). The first 9 participants that met pre-determined criteria for reading impairment made up the dyslexic group. The nine participants that made up the control group had no history of visual or reading impairments. The control group and the dyslexic group were matched for chronological age and for education level. All of the participants were right handed. All were undergraduate students at the University of Edinburgh. All had normal or corrected-to-normal vision.

Dyslexia Pre-tests

All of the participants in the dyslexia group had been previously diagnosed as having developmental dyslexia. To further test the extent of their deficit all nine dyslexic participants completed the Adult Dyslexia Checklist (Vinegrad, 1994). They also completed the tan spelling section of the WRAT-3, and the tan reading section of the WRAT-3.

Adult Dyslexia Checklist

According to Vinegrad, more than nine positive responses to the twenty questions included in the Adult Dyslexia Checklist is a good indicator that dyslexia is present. All participants included in the dyslexic group gave more than nine "yes" responses out of a possible twenty. Of the twelve questions that are classified as key questions by Vinegrad, all of the dyslexic participants included in the analysis gave "yes" responses to more than 50% of these questions.

Reading and Spelling Performance

Reading performance was measured by the WRAT-3 tan reading test. Spelling performance was measured by the WRAT-3 tan spelling test. Table 5 shows a summary of the results.

Table 5: Summary of dyslexia pre-test results

	Chronological age	Reading age	Spelling age
Mean	20.6	18.1	16.1
Range	19 - 24	17.0 – 19.11	16.0 – 16.11

Procedure

The participants were instructed to fixate on a gap between two vertical lines in the centre of the screen. This fixation point was present on the screen for 2000ms. The stimuli were presented individually at the central fixation point for 300ms. After the stimulus had been on the screen for 300ms, a mask consisting of "XXXXX" appeared. The mask remained until the participant had made a response. As soon as the participant made their response, the fixation point for the next trial appeared. Participants had to indicate whether the stimulus that they had just viewed was a real word or a non-word. Nine of the participants used the index finger on their dominant hand to indicate a "word' response and the index finger on their non-dominant hand to indicate a “non-word’ response. This was counterbalanced across the other nine participants who indicated a ‘word’ response with their non-dominant index finger and a non-word response with their dominant index finger. There were 10 practice trials to begin to make sure that the participant correctly understood the procedure. Reaction times and error rates were recorded.

5.1.2 Results

The data were analysed using repeated-measures analysis of variance (ANOVA). Frequency (High frequency words and low frequency words) and Regularity (Regularly spelled words and exception words) were within-participants and between-items. There was also one between-participants and within-items factor: Group Type (Control group and dyslexic group). Reaction time data measured in milliseconds were analysed using a 2 (Frequency) X 2 (Regularity) X 2 (Group Type) repeated measures ANOVA. This was followed up by two separate 2 (Frequency) X 2 (Regularity) repeated measures ANOVAs on each of the participant groups. Error rates were analysed using a 2 (Frequency) X 2 (Regularity) X 2 (Group Type) repeated measures ANOVA. This was followed up by two separate 2 (Frequency) X 2 (Regularity) repeated measures ANOVAs on each of the participant groups. Items that participants made errors on were excluded from the reaction time analysis as were items that had a reaction time that was more than 2.5 standard deviations away from the average for that participant for that particular type of item. These values were replaced by the average reaction time score for that participant for that type of item. A total of 32 scores were replaced giving a replacement rate of 4.44%.

Reaction Times

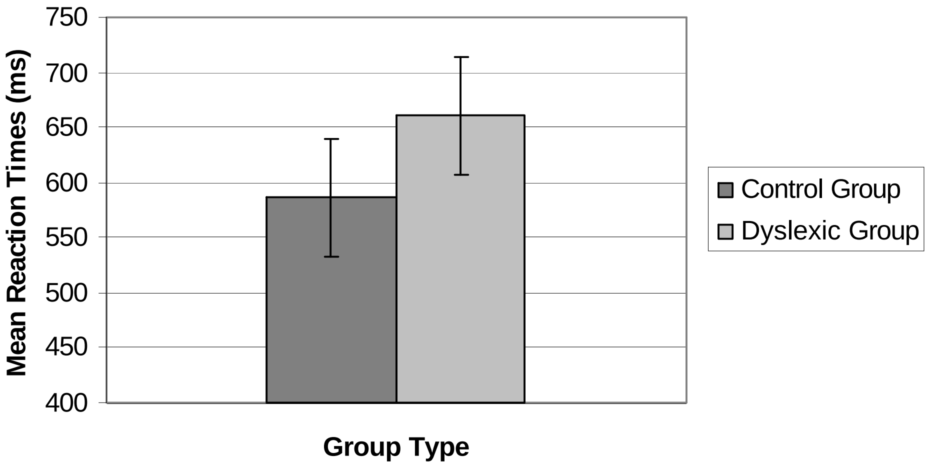
Table 6: Mean reaction time scores in milliseconds for words varied by frequency and regularity for each of the two groups: dyslexic and control

	Word Frequency Word Regularity	
	High Frequency	Low Frequency

Group	Regular	Exception	Regular	Exception
Control	571.4	574.6	590.5	608.2
Dyslexic	702.5	598.0	692.7	648.2

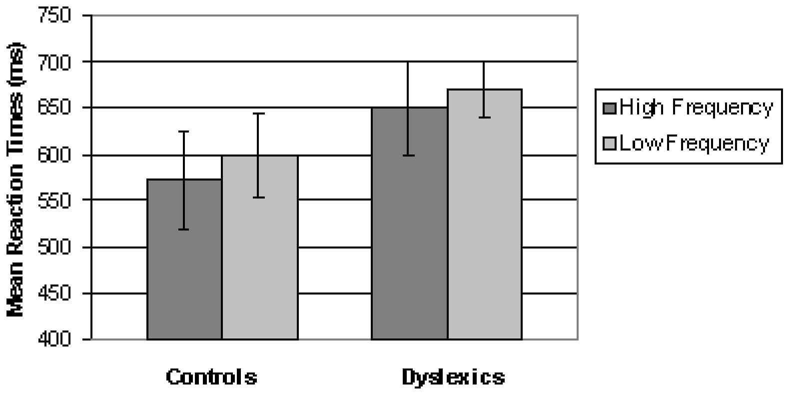
As predicted, we found that the non-impaired control group (586.2 ms) were faster at making lexical decisions compared to the dyslexic group (660.4 ms) (F_1 (1, 16) = 8.77, *MSE* = 8004.88, $p < 0.02$; F_2 (1, 9) = 39.22, *MSE* = 86218.15, $p < 0.001$). We had predicted that this would be the case if the dyslexic readers were relying exclusively on the slower dorsal stream whereas the non-impaired readers were able to utilise the faster ventral processing stream (see Figure 11).

Figure 11: Mean reaction times in milliseconds (ms) to centrally-presented words for the control group and the dyslexic group



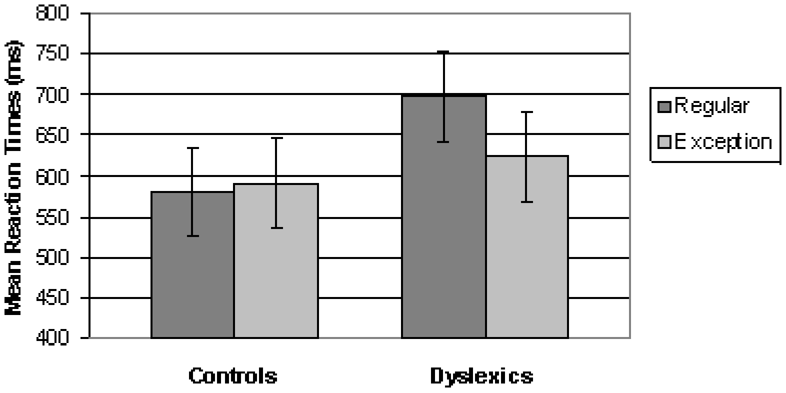
Our second prediction was that the non-impaired readers would be affected by word frequency but that the dyslexic readers would not. In the overall initial analysis (the Frequency x Regularity x Group ANOVA), the interaction between word frequency and group type (dyslexic or control) was non-significant, both by-participants and by-items (both *Fs* <1). The frequency of the words did not appear to be sufficient to produce a difference in reaction times between participant groups. However, the pattern of results was different when the two participant groups were analysed separately. For the control group participants we found an effect of frequency (significant by-participants and approaching significance by-items) (F_1 (1, 8) = 5.22, *MSE* = 1605.59, $p < 0.05$; F_2 (1, 9) = 4.83, *MSE* = 1449.84, $p = 0.056$) with high frequency words (572.9 ms) being recognised faster than low frequency words (599.3 ms). This is the effect that was predicted based on previous studies. Participants in the dyslexic group did not show a significant frequency effect in the separate analyses (both *Fs* <1). However, as there was no interaction between frequency and group type in the overall analysis, we cannot conclude that there were different effects of word frequency between the two groups. As can be seen in Figure 12, there is a great deal of variance within the two groups.

Figure 12: Mean reaction times measured in milliseconds (ms) to high frequency words and low frequency words for both the control group and the dyslexic group



Finally we predicted that the dyslexic participants would show an effect of word regularity but that the non-impaired participants would not be affected by regularity. Contrary to what we predicted, overall we found that exception words (607.3 ms) were recognised faster than regular words (639.3 ms) (F_1 (1, 16) = 4.98, MSE = 3701.99, $p < 0.05$; F_2 (1, 9) = 4.81, MSE = 1911.11, $p = 0.056$). However, we found that this effect was specific to the dyslexic group. The interaction between word regularity and group type was significant, both by-participants and by-items (F_1 (1, 16) = 8.77, $p < 0.01$; F_2 (1, 9) = 10.85, MSE = 1399.76, $p < 0.01$) (see Figure 13). Further analyses that looked at the two groups separately reveal that the participants in the dyslexic group showed a significant word regularity effect (F_1 (1, 8) = 8.88, MSE = 5624.30, $p < 0.02$; F_2 (1, 9) = 9.23, MSE = 2599.19, $p < 0.05$) with exception words (623.1 ms) being recognised faster than regularly spelled words (697.6 ms). The control group participants failed to show a significant effect of word regularity (both Fs <1). We had predicted that this interaction would be significant and that only the participants in the dyslexic group would show an effect of word regularity in this task. However, they were predicted to be slower at judging exception words compared to regular words. The opposite pattern of results was found with exception words being recognised faster than regularly spelled words.

Figure 13: Mean reaction times in milliseconds (ms) to regularly spelled words and exception words for dyslexic and control group participants



All other effects and interactions were non-significant. The factor of frequency was non-significant and there were no significant interactions between frequency and any of the other factors.

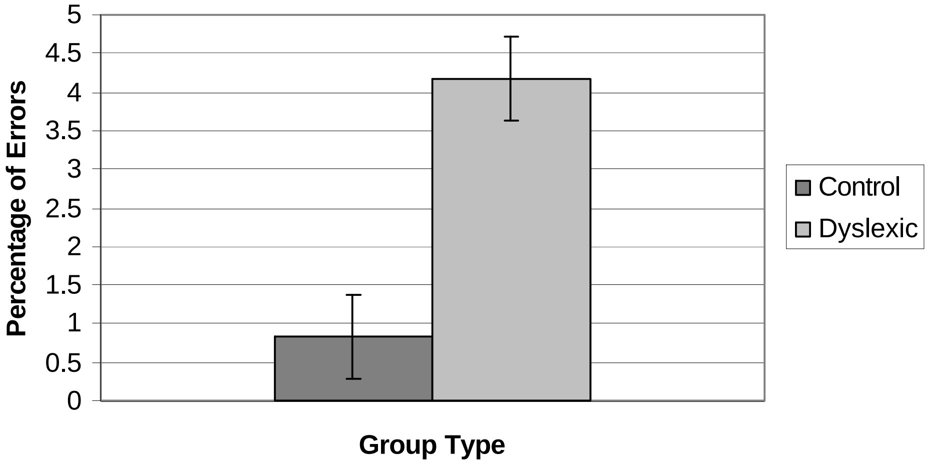
Error Rates

Table 7: Percentage of errors made by participants for words varied by regularity and frequency for each of the two groups: dyslexic and control

	Word Frequency Word Regularity			
	High Frequency		Low Frequency	
Group	Regular	Exception	Regular	Exception
Control	0.0	0.0	1.1	2.2
Dyslexic	0.0	5.6	3.3	7.8

Not only were the dyslexic participants slower at making lexical decisions, they also made more errors. Overall, dyslexic participants (1.04 %) made significantly more errors compared to control group participants (0.21 %). There was a main effect of group type, significant by-participants but non-significant by-items (F_1 (1, 16) = 7.70, MSE = 0.23, $p<$ 0.01; F_2 (1, 9) = 3.16, MSE = 0.67, $p>$ 0.1) (see Figure 14).

Figure 14: Percentage of errors made by control group participants compared to dyslexic group participants



Even though we found that the reaction times of the dyslexic participants were affected by word regularity (while the control group participants were not), neither of the two participant groups were affected in terms of response accuracy by the regularity of the words. The interaction between word regularity and group type was non-significant, both by-participants and by-items (both *Fs* <1). Further analyses which looked at the error rates of both groups separately also failed to show any significant effects. Neither the control group (both *Fs* < .1) or the dyslexic group (both *Fs* < .1) showed any affect of word regularity. However, if we look at the percentage of errors made by the dyslexic group for each word type we can see that there are signs of a speed-accuracy trade off that may help to account for the "reverse" regularity effect that we found in the reaction times (see Table 7). There was a trend for the dyslexics to make more errors on the exception words (6.72%) compared to the regularly spelled words (1.65%). Although this result was non significant, there is a trend towards poorer accuracy for exception word recognition by the dyslexic group. Although they were faster overall at recognising exception words compared to regular words there was a tendency for them to be less accurate at recognising exception words.

The error data for the factor of frequency showed a similar pattern of results as the reaction time data. The interaction between word frequency and group type was non-significant, both by-participants and by-items (both *Fs* <1). Further analyses which looked at the error rates of both groups separately still failed to show any significant effects. The number of errors made was not affected by word frequency for either the control group (both *Fs* < .1) or the dyslexic group (both *Fs* < .1). All other effects and interactions were non-significant.

5.1.3 Discussion

This experiment was designed to investigate the claim that dyslexic readers fail to utilise the lexical-based ventral processing stream during word recognition and that they continue to rely on the sub-lexical dorsal processing stream. Based on previous research (e.g., Martens & de Jong, 2006), we predicted that if this was the case, the dyslexic readers would be slower overall compared to the non-impaired readers at making lexical decisions. This is what we found. Given that the dorsal stream processes words incrementally, we predicted that reliance on this stream would result in longer processing times. We also found that the dyslexic participants were less accurate in their decisions. The faster word recognition times of the non-impaired group compared to the dyslexic group suggests that these participants were able to utilise the ventral processing stream to recognise words as lexical units.

When we analysed the two participant groups separately, we found that only the control group participants were affected by the frequency of the word. We had predicted that if the skilled readers in the control group are able to utilise the ventral stream to processes words by accessing them as lexical representations in lexical memory then recognition times would be influenced by word frequency. Greater exposure to a word (with high frequency words) makes the word more familiar and therefore easier to recognise. We had predicted no such effect of frequency for the dyslexic group participants. If the dyslexic readers were relying on the dorsal stream for word recognition then they must be accessing the words incrementally. If words are not recognised as whole units then we do not expect a word frequency effect. However, in the overall analysis we found no interaction between frequency and group type so we cannot conclude that the two groups are affected differently by the frequency of a word.

The results also show that there was an effect of word regularity for the participants in the dyslexic group but not for the participants in the control group. There was no difference for the participants in the control group between regularly spelled words and exception words, in either reaction times or number of errors made. Sereno and Rayner (2000) had shown that non-impaired readers only show a regularity by frequency interaction when the target word had previously been viewed in parafoveal preview. The absence of an effect of word regularity indicates that the skilled readers were able to use the ventral processing stream to recognise exception words as familiar lexical items. The dyslexic readers did show an effect of word regularity. However, the results are in the opposite direction to the predictions made. The dyslexic group were faster at recognising exception words compared to regular words although there was a trend for the dyslexics to make a greater number of errors on the exception words suggesting that there was a speed-accuracy trade-off. As the dorsal stream only processes letters in an incremental, serial way we predicted that there would be a greater number of errors made on exception words as these words do not have regular grapheme-to-phoneme correspondence. However, this did not reach significance. If the dyslexic readers were reliant on the dorsal stream in order to recognise words then we would have expected that they would be impaired at recognising exception words. Only the ventral stream has the ability to correctly recognise exception words as these words cannot be recognised by incrementally mapping phonology onto orthographic units.

One possible explanation for effect may be that the participants that were included in the dyslexic group were all reasonably high-functioning university undergraduates. Even though the dyslexics in this study had been previously diagnosed as being dyslexic at school and had a significantly lower spelling-age than the control group, they had a reading-age that was only approximately two years behind age-matched control readers. It is possible that these participants may have overcome their difficulties with exception words but with varying degrees of success. We did not record the age at which they were diagnosed as being dyslexic. If they had been diagnosed at an early age then it is possible that they received some targeted training throughout their schooling which enables them to recognise words that would have otherwise proved difficult for them. If this were the case then any differences between the non-impaired group and the dyslexic group would be more likely to emerge in the reaction time data rather than the error data. They would recognise the words that they are more likely to make errors on (exception words) and would be able to correctly identify them but would still be slower overall when compared to the participants in the control group who would presumably be able to rely on lexical processing for most of the words. The overall slowness of the dyslexic group compared to the control group suggests that for most of the responses, the dyslexic group were still forced to rely on slower, sub-lexical processing.

The rate of errors made by all participants in the experiment (including both the dyslexic group and the control group) was very low (mean = 1.98%). This suggests that maybe the task was too easy to produce a sufficient number of errors to show a reliable pattern. There were only three errors made in total by the participants in the control group (across all word types) and only sixteen errors were made by the participants in the dyslexic group (across all word types). We would have expected the dyslexic group to make more errors on the exception words compared to the regularly spelled words. The dyslexic group made more errors overall compared to the control group but there was no pattern to the errors made. The task may not have been difficult enough to elicit enough errors to reveal an underlying pattern. If the task had been more difficult (for example, using a shorter stimulus presentation duration than 300ms) then perhaps there would have been more errors and a pattern may have emerged that showed exception words were more difficult to process for the dyslexic group. Also, we were limited in the number of stimuli that we could use in this task. As we had to match the words for length, frequency, number of syllables etc, we were left with a limited choice of words (especially for the exception word lists). It is possible that we simply did not have enough items to uncover patterns in the errors made.

The main finding was that the participants in the dyslexic group were slower to recognise regularly spelled words compared to exception words when the prediction had been that these participants would show the opposite pattern of results. There was no difference between regularly spelled words and exception words, in either reaction times or error rates for the control group. This suggests that these non-impaired participants were equally efficient at detecting both regular and exception words in a lexical decision task where the words were all presented to the centre of the visual field. The dyslexic participants were slower to recognise regularly spelled words suggesting that something about these words made them more difficult to recognise than the exception words. However, we did find a suggestion of a speed-accuracy trade off with exception words producing a greater number of errors compared to regular words although this was not significant. As we used quite a small number of words in this experiment, it is possible that they differed on another dimension that we did not control for.

Sereno and Rayner (2000) showed that non-impaired readers show an effect of word regularity for low frequency words but only when the target word had initially been viewed in parafoveal vision when reading a sentence. Under these conditions, non-impaired readers appear to be able to extract some information from the target word before it is fixated that facilitates subsequent processing of the word. Chace, Rayner, and Well (2005) demonstrated that a homophone preview of the target word facilitated recognition of the target word in skilled readers but not in less accomplished readers. They concluded that only highly skilled readers were able to extract phonological information from the parafoveal preview. When dyslexics are reading, a portion of them have been found to have irregular patterns of eye movements (e.g., Ram-Tsur et al., 2006). They tend to make shorter saccades and have longer fixation times when compared to skilled readers. This suggests that they are not equally as able as skilled readers to extract information from the parafoveal preview. We will examine this hypothesis in greater detail in the next section. The next experiment looks at the ability to extract information from the parafoveal area of the visual field by both dyslexics and non-impaired readers.

5.2 The Effect of Word Regularity and Word Frequency in Isolated Words Presented to the Fovea and to the Parafovea

Sereno and Rayner (2000) looked at the effect of having a parafoveal preview of the target word on the interaction of word regularity and word frequency. They found that when readers had access to a parafoveal preview of the word, there was an interaction between word regularity and frequency. When there was a non-matching preview word the regularity by frequency interaction was absent. The interaction between regularity and frequency is only present when readers have previously seen the target word in the parafoveal preview. It can therefore be concluded that some aspect of the information received during the parafoveal preview is responsible for producing the regularity by frequency effect in a sentence reading context.

The interesting question is: what aspect of parafoveal preview information allows the interaction between regularity and frequency to occur? As this interaction only occurs when there has been a parafoveal preview of the target word, Sereno and Rayner (2000) proposed that phonological codes are accessed at an early stage of lexical access, possibly in the parafoveal preview. In a replication of Pollatsek et al.'s (1992) result, Miellet and Sparrow (2004) demonstrated that processing of a target word was facilitated by a homophone preview more than when the preview was orthographically similar to the target word. They also found facilitation of target word processing from homophone preview words that were not orthographically similar to the target word. They concluded that phonological access of a word in parafoveal preview facilitates subsequent processing of that word when it is fixated (see also Tsai et al., 2004 and Pollatsek et al., 2000 for replications using Chinese language reading). Chace et al., (2005) compared the eye movements of skilled readers and less skilled readers using the boundary paradigm (see section 3.3.2 for details) while viewing sentences that contained a designated target word. The preview word was varied the so that it was either identical to the target word, was a homophone of the target word, was orthographically similar to the target word, or was a consonant string. Their results show that skilled readers were able to efficiently extract information from the parafoveal preview. There was a greater amount of facilitation was from homophone previews compared to the orthographically similar previews. The less skilled readers did not show this effect. The authors concluded that only highly skilled readers were able to efficiently utilise the preview information and that the less skilled readers were unable to extract the phonological information that was available in the parafoveal preview. They also concluded that the ability to efficiently access phonological codes is a good indication of level of reading skill.

Unsworth and Pexman (2003), using a lexical decision task, found that less skilled readers were more likely to wrongly judge pseudo-homophones to be real words compared to non-homophonic non-words. Skilled readers did not show this effect. They concluded that the less skilled readers were less efficient at performing grapheme-to-phoneme mapping. Although the Chace et al. (2005) study and the Unsworth and Pexman (2003) study limited their investigations to non-dyslexic readers' skill levels these results may be extendable to dyslexic readers also. Dyslexic readers have been found to have comparable reading performance with younger non-dyslexic readers. Related to this is the finding that foveal processing difficulty influences the degree of information that can be extracted from parafoveal preview. When the foveal processing load is high, there is less preview benefit (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens et al., 1999; Vitu et al., 1999; White, Rayner, & Liversedge, 2005). Therefore, we propose that, in line with the findings of Chace et al. (2005) for less skilled readers, as dyslexics find processing written words difficult, the foveal processing demands are too high to enable the dyslexic readers to allocate spare attention to the preview word and therefore they are not as efficient as non-impaired readers at extracting information from the parafoveal preview.

If a reader is unable to efficiently extract phonological information from the parafoveal preview (for example, if the preview is masked or if the reader cannot access phonological information in the preview) then reading will be slowed down with shorter saccades and longer fixations. This is similar to the pattern of eye-movements that a portion of dyslexics show. Dyslexics have been found to make more frequent and shorter saccades and have longer fixation times compared to skilled readers (De Luca et al., 1999; Pavlidis, 1985; Ram-Tsur et al., 2006). The shorter saccades and longer fixation times suggest that the dyslexic readers are not retrieving an adequate amount of information from the parafoveal preview. We propose that it is an impairment in phonological processing that underlies the faulty eye-movement pattern exhibited by a sub-group of these readers and that this can be linked to a deficit in the magnocellular pathway, the visual pathway that is responsible for the fast transmission of parafoveal and peripheral visual stimuli. In non-impaired readers the initial rapid magnocellular response to stimuli in the parafoveal area of the retina may modulate subsequent processing of the slower parvocellular stream that transmits visual information from the foveal area of the retina (Vidyasagar, 2005). The magnocellular response may "prime" the visual system to enable faster recognition of the stimuli when fixation occurs as the eye moves to position the fovea directly on the stimulus. A portion of dyslexics have been found to have an impairment in the magnocellular visual pathway (e.g., Stein & Walsh, 1997). If this were the case then we would predict that there would be no priming of the visual system by the magnocellular pathway for this type of dyslexic and that they would not be able to utilise parafoveal information as efficiently as the skilled readers.

When a word has initially been viewed in parafoveal vision, words with regular spelling receive facilitation (phonological and orthographic processing has occurred in the parafoveal preview) which enables faster recognition when they are fixated (Sereno & Rayner, 2000). Exception words cannot be facilitated to as great an extent as they do not have regular grapheme-phoneme correspondence. Exception words do not sound the same as they are spelled and therefore can only receive orthographic priming from parafoveal preview. Regular words can be primed by both orthography and phonology and will therefore be recognised faster. If the ability to extract phonological information from the parafoveal area is impaired then regular words would not be primed in this way and there would be no regularity by frequency interaction for the dyslexic readers. Skilled readers only show an effect of word regularity when there has previously been a parafoveal preview of the word (Sereno & Rayner, 2000). However, we predict that the dyslexic readers will show a word regularity effect even when words are viewed in isolation (without a parafoveal preview) as we propose that they have impaired ventral stream processing and exception words can only be processed by this stream.

This experiment is designed to investigate whether the differences in responses between regularly spelled words and exception words that dyslexic readers experience will be attenuated when the words are viewed in parafoveal vision. Firstly, we predict that overall the dyslexic participants will be slower to make lexical decisions compared to the control group as we propose that the dyslexics are relying on sub-lexical processing whereas the skilled readers can use both lexical and sub-lexical processing. Secondly, we predict that if the dyslexic participants have an impairment in ventral stream, or lexical processing then they will find it more difficult to correctly recognise exception words compared to regular words as exception words rely exclusively on ventral stream processing whereas regular words can be processed by either stream. There should be no difference in reaction times or number of errors made between exception words and regular words for the control group as the skilled readers in the control group are able to utilise both the dorsal and ventral streams efficiently. Thirdly, if the dyslexic participants in this experiment do have a magnocellular impairment which prevents the extraction of phonological information from the parafoveal area of the visual field then we predict that there will be an attenuation of the response time differences between regularly spelled words and exception words when these words are viewed in parafoveal vision. If the dyslexics cannot efficiently extract phonological information from the parafovea then we predict that the responses to regular words will be slowed to be similar to that of the exception words. The control group will not show any effects of word regularity regardless of where the words appear in the visual field as skilled readers only show regularity effects when there has been a preview of the word (Sereno & Rayner 2000). In addition to comparing foveal and right visual field parafoveal viewing, we also included left visual field presentations of words because previous work has demonstrated that non-impaired readers show a right visual field advantage for words (e.g., Faust et al., 1993; Malamed & Zaidel, 1993; Mohr et al., 1994). Including left visual field presentations as well as right visual field presentations (where parafoveal preview benefit is obtained when reading left to right) allows us to see whether there are any visual field effects for words and whether this is different for dyslexics compared to non-impaired readers.

5.2.1 Method

Design

This experiment used a lexical decision task to investigate the interaction of word regularity and stimuli presentation position (parafoveal vs. foveal). We looked at the effect of two item variables: Regularity and Visual Field which were fully crossed leading to a 2 (Regularity) x 3 (Visual Field) design; and one participant variable (Group Type) with two levels (Dyslexic group and Control group). There were two levels of the variable “Regularity”: Regular words and Exception words. All of the words used in this experiment were low frequency as the regularity by frequency effect is more likely to occur with low frequency words. The variable of “Regularity” was crossed with the variable “Visual Field” which had three levels: “LVF” in which stimulus items were presented to the left visual field parafovea, “CPP” in which stimulus items were presented on a central fixation point to fall within the foveal region of the retina, and “RVF” in which stimulus items were presented to the right visual field parafovea. The variables of Regularity and Visual Field were crossed with the variable of Group Type which had two levels: “Control” which was made up of participants in the non-impaired group, and “Dyslexic” which was made up of dyslexic participants. Each participant was exposed to all six conditions.

Using a fully counterbalanced design, participants were shown 120 letter strings consisting of four or five letters. Sixty of these were real words (experimental items) and sixty were non-words (filler items). There were 10 low frequency exception words and 10 low frequency regular words presented to each of the three viewing positions giving a total of 60 real words. The letter strings were presented either in the left visual field parafovea, the right visual field parafovea, or on a central presentation point that would ensure that the stimuli were only viewed with the fovea. The participants had to decide whether the letter strings were real words or not. We compared developmental dyslexics with non-reading impaired participants.

Apparatus

A RM innovator Pentium 4 computer connected to an Iiyama Vision Master Pro 413 monitor with a 17-inch screen (refresh rate 74.999 Hz) was used to present the stimuli. A Psychology Software Tools Inc serial response box (model 200A) was used to record participants’ responses.

Materials

Word Stimuli All of the real word experimental items were low frequency. There were two different types of real word stimuli: Low frequency regular words and low frequency exception words. We used words of both four and five letters long to ensure that there were a sufficient amount of suitable words available to compile the stimuli lists. Word length was counterbalanced across the two levels of the regularity variable.

Defining Frequency We used the same definition of high and low frequency as in the previous experiment. All of the low frequency words were below 17 occurrences per million. These were counterbalanced across word length (4 or 5 letters) and word class (nouns, verbs and adjectives).

Defining Regularity The definition of word regularity was the same as in the previous experiment (see section 5.1.1). We only used words that had not appeared in the previous experiment in order to avoid practice effects as we were using the same participants for both experiments. The two word groups (regular and exception) were matched for range of frequencies (Regular word group *mean* = 11.2, *mean deviation* = 1.65, *range* = 7; Irregular word group *mean* = 10.7, *mean deviation* = 1.10, range = 10).

Non-word Stimuli (filler items) In total, there were 60 non-word stimuli items presented. We chose non-words that had not been included in the previous experiment so that we did not get any effects of practice. Thirty of these were four letters long and the other 30 were five letters long. These were fully counterbalanced across conditions. All of the non-words were taken from the ARC non-word database (Rastle, Harrington, & Coltheart, 2002). The non-words were all phonologically legal. All had orthographically existing onsets, orthographically existing bodies and only legal bigrams. All had the same number of syllables and had a similar number of phonological neighbours (range: 10 – 15). The aim was to make them as similar to real words as was possible to maximise task difficulty.

Presentation Positions

All of the stimuli were presented in lower-case Courier New font to ensure that all words of the same amount of letters were of the same length in millimetres. With this font, each letter was approximately 3mm wide. The four letter words were approximately 14mm long and the five letter words were approximately 18mm long. At this viewing distance, 10mm is equal to approximately 1° of visual angle. Words that were intended for parafoveal presentation in either the left or the right visual field were presented 2.5° away from the fixation point to ensure that they were not initially viewed by the fovea. Words that were intended for foveal presentation were presented in the centre of the screen ensuring that they fell within the central 2° of the visual field and so were only displayed to foveal vision when the participant was fixating on the central fixation point.

Participants

The same participants that took part in the previous experiment also took part in this experiment. There were 18 participants in total (see section 5.2.1 for details).

Procedure

Participants sat at a distance of approximately 60cm from the screen. They were instructed to fixate on a gap between two vertical lines in the centre of the screen. The fixation point was present on the screen for 2000ms. When the fixation point disappeared the stimuli were individually presented for 300ms. The letter stings could either appear in the left visual field parafovea, in the right visual field parafovea, or on the central fixation point within foveal range. After the stimulus had been on the screen for 300ms, a mask consisting of “XXXXX” appeared on the screen covering the area where the stimulus item had been. The mask remained on the screen until the participant had made a response. As soon as the participant made their response, the fixation point for the next trial appeared. Participants had to indicate whether the stimulus that they had just viewed was a real word or a non-word. Using the index finger of each hand, the participants had to press one of two buttons to indicate whether the stimulus was a word or a non-word. The hand that each individual participant used to respond to a particular type of stimuli (word or non-word) was counterbalanced across participants so that some used the index finger of the left hand to indicate a “word” and the index finger of the right hand to indicate a “non-word” and the others used the index finger of the right hand to indicate a word and the index finger of the left hand to indicate a non-word. There were 10 practice trials to begin to make sure that the participant correctly understood the procedure. Reaction times and error rates were recorded.

5.2.2 Results

The data were analysed using analysis of variance (ANOVA) followed up with Bonferroni corrected related-samples t-tests. Regularity (regularly spelled words and exception words) was within-participants and between-items. Visual Field (left visual field presentation point, central presentation point and right visual field presentation point) was within-participants and within-items. There was also one between-participant and within-items factor: Group Type (control group and dyslexic group). Reaction time data measured in milliseconds were analysed using a 2 (Regularity) X 3 (Visual Field) X 2 (Group Type) repeated measures ANOVA followed up with Bonferroni corrected related-samples t-tests. Error rates were analysed using a 2 (Regularity) X 3 (Visual Field) X 2 (Group Type) repeated measures ANOVA followed up with Bonferroni corrected related-samples t-tests. Items that participants made errors on were excluded from the reaction time analysis as were items that had a reaction time that was more than 2.5 standard deviations away from the average for that participant for that particular type of item. These values were replaced by the mean reaction time score for that participant for that particular type of item. A total of 221 items were replaced giving a replacement rate of 15.3%.

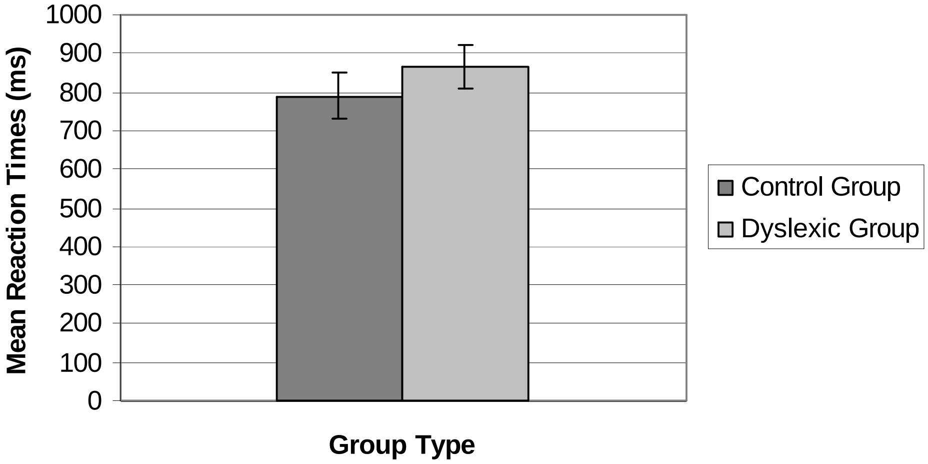
Reaction Times

Table 8: Mean reaction time scores in milliseconds (ms) for regularly spelled words and irregularly spelled words in the left visual field (LVF), on a central presentation point (CPP) and in the right visual field (RVF). Control group and dyslexic group are shown.

	Group Type Word Regularity			
	Control Group		Dyslexic Group	
Visual Field	Regular	Exception	Regular	Exception
LVF	830.8	893.7	854.8	887.3
CPP	673.7	724.5	748.8	840.1
RVF	798.9	815.6	843.6	1020.3

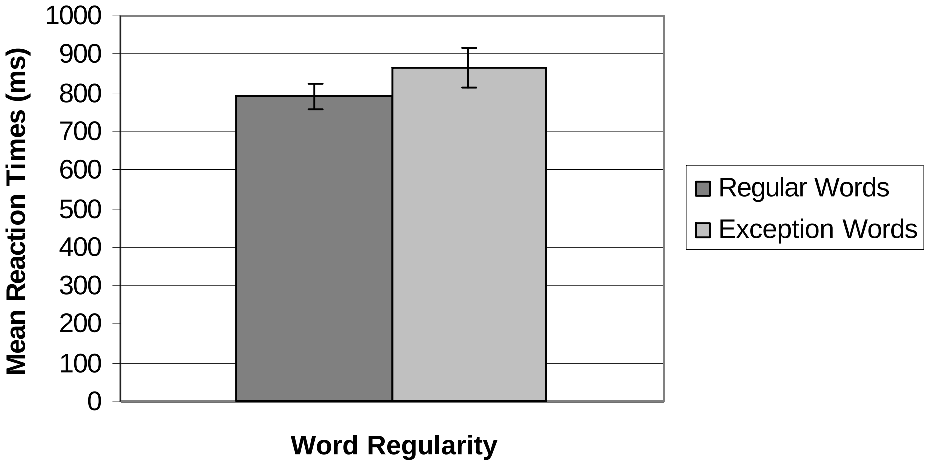
Supporting our first prediction we found that overall, participants in the control group (789.5 ms) were significantly faster to make correct lexical decisions compared to participants in the dyslexic group (865.8 ms) (see Figure 15) (F_1 (1, 16) = 11.83, *MSE* = 27563.22, $p <$ 0.001; F_2 (1, 29) = 9.41, *MSE* = 34674.67, $p <$ 0.005). This is what we predicted would be the case if the dyslexic participants were relying exclusively on the slower dorsal processing stream whereas the control group were able to utilise the faster ventral processing stream.

Figure 15: Mean reaction times measured in milliseconds (ms) for the control group and the dyslexic group



Our second prediction was that only the dyslexic participants would show an effect of word regularity with regularly spelled words taking longer to recognise compared to exception words. In the overall analysis we found that the interaction between word regularity and group type was not significant, either by-participants or by-items (both *Fs* <1). However, the pattern of results was different when the two participant groups were analysed separately. For the dyslexic group participants, the factor of word regularity was marginally significant by-participants and significant by-items (F_1 (1, 8) = 4.69, *MSE* = 24446.07, $p = 0.053$; F_2 (1, 29) = 4.50, *MSE* = 65046.63, $p < 0.05$) with regularly spelled words (815.8 ms) being recognised faster than exception words (915.9 ms). Participants in the control group failed to show a significant effect of word regularity (both *Fs* <1) such that there was no significant difference between regularly spelled words and exception words for the non-impaired participants. However, as there was not a significant interaction between regularity and group type in the three-way ANOVA we cannot conclude that there were any differences in responses to regular and exception words between the two groups. Overall, in the three-way analysis we found an effect of word regularity. Regularly spelled words (791.8 ms) were recognised faster than exception words (863.6 ms) (F_1 (1, 16) = 6.26, *MSE* = 22250.16, $p < 0.05$; F_2 (1, 29) = 4.36, *MSE* = 55626.58, $p < 0.05$) suggesting that it is generally easier to recognise regularly spelled words compared to exception words. However, the larger error bar on the exception words suggests that there is greater variability in how easily these words are recognised between participants (see Figure 16).

Figure 16: Mean reaction times measured in milliseconds to regular and exception words

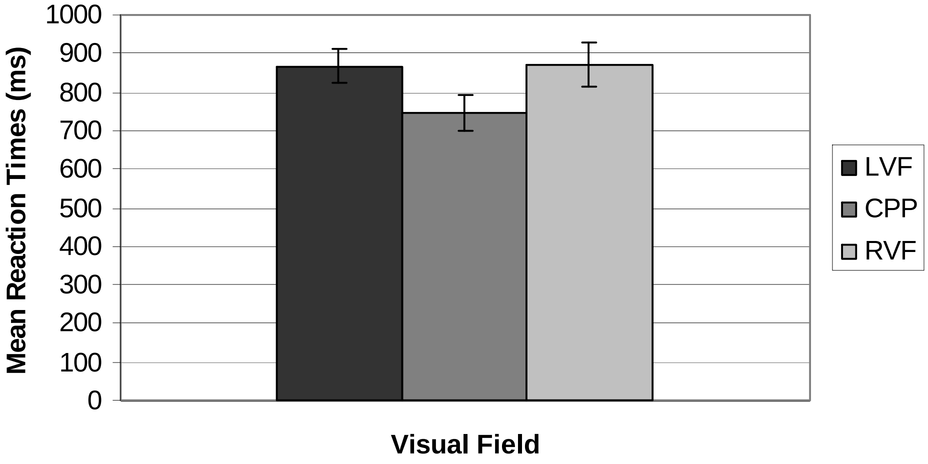


Our third prediction was that the difference in reaction times to regular and exception words for the dyslexic participants would be less when the words had been presented parafoveally. However, we found that the three-way interaction between word regularity, visual field presentation and group type was not significant, either by-participants or by-items (both *Fs* <1). The pattern of results was the same when the two participant groups were analysed separately. Neither the control group (both *Fs* < .1) or the dyslexic group (both *Fs* < .1) showed a significant effect of visual field on the recognition of regularly spelled words compared to exception words. We had predicted that if the dyslexics had an impairment in processing the phonology of words that appeared in parafoveal vision that there would be less of a difference between regular and exception words for the dyslexic participants when the words were viewed parafoveally compared to foveally. Our results do not support this hypothesis.

We also found no differences between the dyslexic and the non-impaired groups between foveally or parafoveally viewed words. The interaction between visual field presentation and group type was non-significant both by-participants and by-items (both *Fs* <1). Viewing the words either foveally or parafoveally did not affect regular and exception words differently either. The interaction between word regularity and visual field presentation was not significant, either by-participants or by-items (both *Fs* <1) such that there was no effect on lexical decisions at the three different presentation positions (left visual field, central presentation position, or right visual field) of words having regular spelling or irregular spelling.

With regards to visual field presentation position, we found that words were recognised faster when they were directly fixated compared to when they were viewed in either the left or right visual fields. There was a main effect of visual field, significant both by-participants and by-items (F_1 (2, 32) = 4.35, *MSE* = 40643.68, $p< 0.05$; F_2 (2, 58) = 51.40, *MSE* = 18335.44, $p< 0.001$). Post hoc t-tests showed that word recognition was slower in the left visual field (866.7 ms) than at the central presentation point (746.8 ms) ($t = 22.18$, $p < 0.001$, n = 18), and also slower in the right visual field (869.6 ms) compared to at the central presentation point (746.8 ms) ($t = 16.84$, $p < 0.001$, n = 18), but there was no significant difference between the right visual field and the left visual field ($t = 0.479$, $p> 0.1$, n = 18) (See Figure 17).

Figure 17: Mean reaction times measured in milliseconds (ms) to regular and exception words viewed in left visual field presentations (LVF), central presentations (CPP), and right visual field presentations (RVF)



Error Rates

Table 9: Percentage of errors made by dyslexic and control group participants for regular and exception words in the left visual field presentation point (LVF), central presentation point (CPP) and right visual field presentation point (RVF)

	Group Type Word Regularity			
	Control Group		Dyslexic Group	
Visual Field	Regular	Exception	Regular	Exception
LVF	15.6	20.0	10.0	18.9
CPP	3.3	4.4	13.3	15.6
RVF	8.9	10.0	11.1	17.8

Overall, there was not a significant difference in the amount of errors made between the dyslexic group and the control group. The factor of group type was non-significant both by-participants and by-items (both *Fs* <1) so that although the dyslexic group had been slower to make lexical decisions, they were just as accurate as the non-impaired group when they did make the decisions.

Our second prediction was that only the dyslexic participants would be impaired at recognising exception words: There would be no difference between regular and exception words for the control group. However, we found that neither the dyslexic group nor the non-impaired group were affected by word regularity in terms of number of errors made. The interaction between regularity and group type was non-significant, both by-participants and by-items (both *Fs* <1). There was no difference in the number of errors made between the control group and the dyslexic group on the correct identification of either regularly spelled words or exception words. The pattern of results was the same when the two participant groups were analysed separately: the dyslexic group participants still did not show an effect of word regularity. Regularity was only marginally significant by-participants and non-significant by-items for the dyslexic group (F_1 (1, 8) = 4.53, *MSE* = 0.60, $p = 0.057$; F_2 (1, 29) = 0.70, *MSE* = 1.79, $p < 0.1$). Participants in the control group failed to show a significant regularity effect when the data for this group was analysed separately in a post-hoc analysis (both *Fs* < 1). There had also been no interaction between word regularity and group type for the reaction times either. However, in the separate group analyses the dyslexics were found to be slower to correctly recognise exception words compared to regularly spelled words whereas there was no effect of regularity for the control group participants. Although the group by regularity interactions were non-significant, there are suggestions that there is a trend for exception words to be more difficult to process for the dyslexic readers. Overall we found that regularity was significant only by-participants but not by-items (F_1 (1, 16) = 8.03, *MSE* = 0.56, $p < 0.02$; F_2 (1, 29) = 1.19, *MSE* = 1.96, $p > 0.1$) such that, by-participants only, there was a trend for exception words (7.22 %) to produce more errors compared to regularly spelled words (5.19 %).

Our third prediction was that for the dyslexic participants, there would be less of a difference between regular and exception words when they were presented parafoveally compared to when they were presented to the central fixation point. We predicted that the control group would not be affected by word regularity regardless of where in the visual field the words were viewed. However, the three-way interaction between regularity, visual field and group type was non-significant, both by-participants and by-items (both *Fs* < 1). Neither our reaction time data nor our error rate data supports this hypothesis.

With regards to the differences between the processing of words that are presented in the left visual field compared to in the right visual field we found that visual field presentation position had no effect on the number of errors made. The factor of visual field was only significant by-items and non-significant by-participants (F_1 (2, 32) = 1.77, *MSE* = 2.48, $p > 0.1$; F_2 (2, 58) = 4.17, *MSE* = 0.45, $p < 0.03$). There was no difference in the number of errors made between items presented in the left visual field, at the central presentation point, and in the right visual field. Again, as with the reaction time data, this does not support the idea that words are more easily recognised when they are presented in the right visual field than when they are presented in the left visual field. All other effects and interactions were non-significant.

5.2.3 Discussion

This experiment investigated whether, for dyslexic readers, there is a greater difference in the speed and accuracy of word recognition between regularly spelled and exception words when they are presented centrally (foveally) compared to when they are presented parafoveally. We compared the effect of stimuli presentation position on both dyslexic and non-impaired readers. Firstly, we predicted that the dyslexics would be slower to make correct lexical decisions compared to the control group. Our data support this hypothesis. We propose that the dyslexics are slower than the non-impaired group to process words because they continue to rely on the slower, sub-lexical dorsal stream whereas the non-impaired control group have developed an efficient lexical-based ventral stream that enables them to process words faster and more efficiently (e.g., Borowsky et al., 2006).

We also predicted that only the dyslexic group would show an effect of word regularity with regularly spelled words being recognised faster than exception words. The non-impaired control group should show no effect of word regularity. This was partially supported by the data. In the initial analysis, where we looked at the data from both the dyslexic group and the control group we found no interaction between regularity and group type suggesting that the two groups were not affected differently by word regularity. However, when we analysed the two groups separately, we found that the dyslexic participants showed an effect of word regularity with regular words being recognised faster than exception words. There was no significant difference in error rates between regularly spelled words and exception words for the dyslexics suggesting that given slightly longer to make the decision, as reflected in the reaction time data, dyslexic readers were able to be as accurate as the non-impaired readers in recognising that these stimuli items were real words. As predicted, there was no significant difference in either reaction times or error rates for regularly spelled words and exception words for the non-impaired control group.

Our third prediction was that if the parafoveal deficit in dyslexic readers is due to a difficulty in extracting phonological information from the parafoveal area of the visual field then dyslexics should have greater difficulty in correctly identifying words that require phonological processing (particularly regular words) when they appear in the parafoveal area of the visual field. However, our results do not support this hypothesis. We found no interaction for word type and visual field presentation position. Neither exception words nor regularly spelled words were affected by viewing position.

We had predicted that the dyslexic participant group would show an effect of word regularity with regularly spelled words being recognised faster than exception words. We predicted that this effect would be greatest when the stimuli times were viewed at the central fixation point. When the words were viewed in the parafoveal area of the right visual field we predicted that this difference between regular and exception words would be reduced. If the dyslexic participants have difficulty in extracting phonological information from the parafoveal view then their performance on regular words should suffer when these words are viewed in the parafovea. Regular words can be identified through either lexical access or phonological access. We predicted that there would be no difference in the reaction times to exception words between presentation positions. Exception words cannot be identified through grapheme-to-phoneme matching and so should not suffer under conditions where phonological processing is not possible. Our results did not support this hypothesis. In order to investigate our hypothesis further, in the next experiment we use a task that requires more explicit phonological processing.

Also interesting to note, there was an effect of visual field presentation position on the time required to correctly identify a word. Words were recognised faster when they were directly fixated compared to when they were viewed parafoveally (in either the left or right visual fields). This suggests that the faster ventral stream may have been involved in processing foveated words but that parafoveal word processing may have involved the slower dorsal stream. However, the control group participants did not show an interaction of word regularity and visual field presentation position. If the control group were using incremental phonological processing to aid the recognition of parafoveally presented regular words we would have expected that regular words would have been recognised faster than exception words in parafoveal vision. This was not supported by the results. An alternative explanation is that the control group participants were using ventral stream lexical processing to identify both regular words and exception words regardless of where they appeared in the visual field. If this was the case we would not predict an effect of word regularity since the regular words are not being accessed through phonological assembly. Instead, all of the words are being recognised as whole units as proposed by previous research (e.g., Pugh et al., 2000; Sandak et al., 2004). We go on to investigate this further in chapter 6.

The reaction time data indicate that the dyslexic participants have problems identifying exception words compared to regularly spelled words regardless of where in the visual field the words are presented. These findings lends support to the idea that dyslexic readers are unable to access words as lexical units and instead continue to rely on the sub-lexical route to word recognition (De Luca et al., 2002; Spinelli et al., 2005; Ziegler et al., 2003; Zoccolotti et al., 2005).

Previous work has demonstrated that non-impaired readers show a right visual field advantage for words (e.g., Faust et al., 1993; Malamed & Zaidel, 1993; Mohr et al., 1994). Our results did not support this hypothesis. We found that words were recognised faster in foveal compared to parafoveal vision but that there were no differences in either reaction times or error rates between the left visual field and the right visual field presentation positions. One explanation for this is that it has previously been demonstrated that this right visual field advantage is greater for longer words compared to short words (Brysbaert & d'Ydewalle, 1990b). The words used in this experiment were relatively short: all were four or five letters long. It is possible that the words used were not long enough to induce this effect. One other possibility is that the types of words used in this experiment were not of the ideal lexical category to elicit this effect. Mohr et al. (1994) showed that the right visual field advantage was greater for function words rather than content words. The words used in this experiment were a mixture of both. The stimuli words were chosen so that lexical category was counterbalanced across word lists. This may have prevented the right visual field advantage from emerging.

In this experiment only the dyslexic participants showed an effect of word regularity. This effect was found to be independent of where in the visual field the stimuli appeared. As stated previously, it is possible that the dyslexic participants in these two experiments had developed strategies for dealing with exception words and so were more practiced at reading them. As all of the participants were university students it can be assumed that they have largely overcome any real difficulties with reading. It is possible that this training may have focused on exception words as it is known that these are the type of words that are likely to cause the most problems for them. As a consequence of this the participants in these studies may be fully able to recognise the exception words used in the present experiment simply through practice. One way to get around this potential use of strategy and practice effects is to employ a task that requires more than simply recognising a word. In the next experiment a task is used that requires full phonological processing of the stimuli in order to make a correct judgement. This should be a more accurate measure of the ability to extract phonological information from words. Also, when dyslexics attempt to fixate on a target (such as a fixation point in the middle of the screen) their eyes tend to dart around the intended target and they have trouble locating the point they are attempting to fix on (Eden et al., 1994; Evans et al., 1994). The posterior parietal cortex, the superior colliculus, and the cerebellum all play an important role in vergence behaviour (Rae et al., 1998; Sparks, 1986; Stein, 1992). Input to these three brain areas is dominated by the magnocellular system which suggests that the deficit that we are investigating is likely to lead to difficulties in maintaining fixation. In order to ensure that the stimuli falls in the intended visual field presentation position we use an eye tracker to make sure that the participants are fixated on the central fixation point before the trial is initiated. This technique will be used in the next experiment to further investigate the question of dyslexics’ ability to access phonological information in the parafovea.

5.3 The Extraction of Phonological Information from the Parafoveal Area of the Visual Field

The previous experiment showed that dyslexic readers are affected by the regularity of the spelling of a word regardless of where in the visual field the word is viewed. Skilled readers did not show an effect of word regularity regardless of whether they were directly fixating the word or if the word was viewed in parafoveal vision. This result suggests that dyslexic readers have a general difficulty in recognising exception words possibly because they cannot process words as a whole and are forced to rely on a sub-lexical route to word identification. Skilled readers do not show effects of word regularity suggesting that they are able to efficiently use the lexical route to word identification and are not forced to rely on the sub-lexical route.

It has recently been shown that when the eye is fixated on a particular word in a sentence, information is also being encoded about the next word in the sentence (Rayner, Liversedge, & White, 2006). Previous research had shown that the reader only has to be able to see a fixated word for 50-60ms in order to have encoded sufficient information for recognition of that word to proceed as normal (Liversedge et al., 2004; Rayner et al., 2003; Rayner et al., 1989). Rayner et al. (2006) demonstrated that although recognition of the fixated word is not affected when it disappears after 60ms, when the word directly to the right of the fixated word disappears after 60ms, reading is disrupted. Masking or disappearance of the parafoveally presented word (the word directly to the right of the fixated word) after a fixation duration of 60ms led to a significant disruption of reading. They showed that both basic visual information (e.g. word length) and orthographic encoding of the parafoveally presented word occurs during fixation on the previous word. They suggest that this extraction of information from the parafoveal word continues past the initial 60ms of viewing and possibly for the entire fixation duration. These findings suggest that two processes of lexical access are occurring at the same time. As recognition of the fixated word is not affected by disruption of the stimulus after 50-60ms but that recognition of the parafoveal word is disrupted even after 60ms exposure, foveal word recognition appears faster than parafoveal word recognition. Based on this, we propose that skilled readers are able to use lexical access to recognise the foveally presented words and as this processing occurs, information about the parafoveal word is encoded through the sub-lexical route. If the dyslexic readers are not able to recognise the foveated word through lexical access and are relying on sub-lexical processes, this may disrupt the encoding of the parafoveally viewed word as both words are relying on the same processes.

Developmental dyslexics have been found to have different patterns of eye-movements to non-impaired readers. Dyslexics tend to have shorter saccades and longer fixations (Biscaldi et al., 1998). This may reflect a problem with perceiving or encoding visual information that appears in the parafoveal preview. If the amount of visual information that can be extracted from the parafoveal preview is less than that which is normally available to non-impaired readers then dyslexics would have to make fixations more often. Disruption of the perception of parafoveal information may also occur if foveal processing is difficult (Henderson & Ferreira, 1990; White, Rayner, & Liversedge, 2005). If the dyslexic readers are unable to use the lexical route to word recognition, even when words are fixated directly, then presumably the more arduous sub-lexical processing leaves less cognitive resources to allocate to processing the next (parafoveally viewed) word in the sentence. However, in the previous experiment we showed that the dyslexic readers showed a similar pattern of results as the skilled reading group (and were therefore faster at recognising words that were directly fixated compared to those that were viewed parafoveally suggesting processing by the ventral stream). These dyslexics still showed an effect of word regularity (when the skilled readers did not) which suggests dorsal stream processing. In order to investigate this further, and to attempt to separate a possible problem with parafoveal perception from a deficit in lexical processing, the next experiment uses a task that is a more direct test of the ability to extract phonological information from words that are only viewed in the parafovea.

The present experiment was designed to test whether people with developmental dyslexia have more difficulty than non-impaired readers in extracting phonological information of a word when the word is presented to the parafovea. We compare the abilities of non-reading-impaired participants and those with developmental dyslexia. Participants were required to make a rhyme judgment about a pair of words that were presented either to the right visual field parafovea or to a central (foveal) point. The stimuli were presented in both the fovea and in the parafovea to attempt to isolate a specific parafoveal preview deficit in the participants who had dyslexia.

We propose that in the absence of a foveal stimulus, skilled readers will be able to use the lexical route to word recognition when words appear in the parafoveal area of the visual field. Dyslexic readers will not be able to do this. We test this by presenting word pairs in both central and parafoveal vision and asking the participants to make a judgment about whether the two words rhyme or not. Word pairs were selected in an attempt to separate phonology and orthography. The words that rhymed either shared the same letter clusters (both were regular words) or had different spellings. The words that did not rhyme either shared the same letter clusters (one was a regular word and the other an exception word) or had different spellings. In order to make correct rhyme judgments the participants have to be capable of accessing a word through the lexical route as some of the words (in the orthographically similar rhyming pairs) are exception words. Orthographic information alone is not sufficient to correctly judge phonological similarity. A comparison was made between a foveal presentation (items presented on a fixation point) and the right visual field (outside the central 3° of visual angle) because in English the parafoveal preview is obtained from the right visual field.

In this experiment we make four predictions: Firstly, we hypothesise that skilled readers will be able to efficiently extract phonological information from both the regular and the exception words (by using the lexical route). The skilled readers in the control group will be able to make correct rhyme judgements regardless of whether the phonology of the words is predictable from the orthography. We also predict that if the dyslexic group have an impaired lexical route and are forced to rely on the sub-lexical route then they will not be able to correctly process exception words. This will lead to difficulties in detecting the presence of a rhyme when the phonology of the words is not predictable from the orthography (when one of the words in the pair is an exception word and the two words look alike but are pronounced differently). Thirdly we predict that in the absence of a foveal stimulus, skilled readers will be able to employ the lexical route to word recognition when words are presented parafoveally. We predict that there will be no difference between orthographically similar and orthographically dissimilar word pairs in the central and parafoveal presentations for the skilled reading group. Finally we predict that the performance of the dyslexic readers in detecting rhyme in word pairs that do not look alike will be worse when the word pairs are presented to parafoveal vision compared to when they are presented centrally. We predict that their word recognition problems (difficulties processing exception words caused by a deficient ventral processing stream) will be exacerbated by a deficit in the ability to efficiently extract phonological information from parafoveal vision.

5.3.1 Method

Design

This experiment employed a rhyme-matching task to test the effect of orthographic similarity on judgements of phonological similarity in the parafovea and the fovea. We looked at the effect of three item variables: Phonology, Orthography, and Visual Field which were fully crossed leading to a 2 (Phonology) x 2 (Orthography) x 2 (Visual Field) design; and one participant variable (Group Type) with 2 levels. There were two levels of the variable “Phonology”: “PS” in which the two words in the pair were phonologically similar (the two words rhymed), and in level “PD” the two words in the pair were phonologically dissimilar (they did not rhyme). The variable of “Phonology” was crossed with the variable of “Orthography” which also had two levels: “OS” in which the two items in the pair looked similar (they had similar letter clusters and they looked as though they should be pronounced in the same way), and “OD” in which the two items in the pair looked dissimilar (they did not share similar letter clusters and they looked like they should not be pronounced in the same way). The variables of “Phonology” and “Orthography” were crossed with the variable of “Visual Field” which had two levels: RVF (right visual field) and CPP (central presentation point). The variable “Group Type” had two levels: “CON” in which the participants were all non-impaired readers and “DYS” in which the participants all had developmental dyslexia. Each participant was exposed to all eight stimulus conditions.

Apparatus

The stimuli were presented using a Generation 6 DPI eye tracker connected to a 486 PC with a 15” RM VGA monitor (refresh rate 74.999 Hz). Participants’ responses were recorded using a Psychology Software Tools Inc serial response box (model 200A).

Materials

Stimuli were pairs of 5 letter words. The word pairs were varied by phonological similarity and orthographic similarity. Using a counterbalanced design, seventy-two experimental word pairs were created. These word pairs consisted of 4 different types of pairs:

(OS/PS) These word pairs were orthographically and phonologically similar (e.g. “boost” and “roost”). Words in these pairs rhymed and looked as though they should rhyme based on comparisons of the letter clusters of each word. Words were judged to be orthographically similar when they shared the exact same final three letters (in five letter words).

(OD/PS) These word pairs were orthographically dissimilar but phonologically similar (e.g. “wares” and “lairs”). They looked as though they should not rhyme based on comparisons of the letter clusters of each word but they did rhyme. Words were judged to be orthographically dissimilar when they did not share similar final letter clusters.

(OS/PD) These word pairs were phonologically dissimilar but shared the same final letter clusters (they had the same final three letters in the same order) and so looked as if they did rhyme (e.g. “prove” and “drove”). They looked as though they should rhyme based on comparisons of the letter clusters of each word but they did not rhyme.

(OD/PD) These word pairs did not rhyme and did not look the same (e.g. “month” and “learn”). These pairs did not look as though they should rhyme based on comparisons of the letter clusters of each word and they were not pronounced the same.

To ensure that the rhyming pairs were phonologically similar (that they were pronounced the same and they rhymed with each other), the word pairs were compiled by matching the phonemes of each word using a dictionary (Collins English dictionary) that provided standard pronunciations for the words. Orthographic similarity was defined as the two words in each pair having, at a minimum, exactly the same final three letters in the same order. Orthographic dissimilarity was defined as the two words in each pair having a maximum of one letter the same in the same position of the word (as in “wares” and “lairs”).

Filler items

Filler items that consisted of 72 word pairs were also presented. These fillers were compiled in the same way as the experimental items. The filler items were presented at the same positions in the visual field as the experimental items but they were also presented in the left visual field so that participants did not begin to anticipate where the experimental word pairs would appear.

Presentation Positions

Items intended for parafoveal presentation were presented outside of the central 3° of visual angle around the fixation point to ensure that they were only presented to the parafovea and could not be perceived by foveal vision. Items intended for foveal presentation were presented within the central 2° of visual angle to ensure that they were presented only to the fovea. Words were presented using white letters on a black background. All of the words were presented in lower case courier new font. Pairs were presented (one above the other) either in the left visual field (filler items only - so that participants did not begin to anticipate the appearance of experimental word pairs to the right of fixation), the right visual field, or on the central fixation point. Filler items were presented at all three presentation positions; experimental items were only presented at the central presentation point or to the RVF parafovea.

Participants

There were thirty-four participants in total. These participants had not taken part in either of the previous experiments. All were undergraduates at the University of Edinburgh. Twenty-four were not reading impaired and 10 had been previously diagnosed with developmental dyslexia. All of the participants were right handed. All had normal or corrected-to-normal vision.

Procedure

Word pairs were presented in the right visual field (RVF) (parafovea) or on a central fixation point (CPP) (fovea). The task was to indicate whether the two words in each pair rhymed. The participants were instructed to fixate on a fixation point in the centre of the screen. An eye-tracker was used to ensure that participants were always looking at the fixation point when the word pairs were presented. When the fixation point screen was visible, a red dot indicated the eye position of the participant. The fixation point was present until the experimenter pressed a button on the response box to make a stimulus item appear. This was done when the experimenter had ensured that the participant was fixating on the central cross. Each trial consisted of a fixation cross, followed by the presentation of a word pair. The word pair remained on the screen until the participant had made a response. Using a “Go – no-go” paradigm, the participant had to press a button on the button response box to indicate the presence of a rhyme. No response was required if no rhyme was perceived. Participants used the index fingers of both hands to make the response. This was done to ensure that there could be no bias for responding faster with their dominant hand. As soon as the participant made their response the fixation point for the next trial appeared. Once fixation had been established, the button was pressed to initiate the next trial. There were 10 practice trials to begin to ensure that the participant had correctly understood the procedure. Reaction times and errors rates were recorded.

5.3.2 Results

The data were analysed using analysis of variance (ANOVA). Reaction time data measured in milliseconds were analysed using a 2 (VF) X 2 (similarity) X 2 (Group Type) repeated measures ANOVA. Visual Field (central presentation point (CPP) and right visual field presentation point (RVF) was within-participants and within-items. Similarity (orthographically similar (OS) and orthographically dissimilar (OD) was within-participants and between-items. There was also a between-participants and within-items factor of Group Type (dyslexic group (DYS) and control group (CON)). Only the rhyming pairs could be analysed for the reaction time data as a "go - no-go" paradigm was used. Participants only made a response if they thought that the word pair matched. For this reason we could only look at the RT data for the rhyming pairs.

When looking at the errors made on items in the eye-tracking task it was possible to look at both the rhyming and non-rhyming pairs as a non-response was taken to indicate that the participant did not think that the two words in the pair rhymed. Because the question of interest is whether there was a difference in responses when the phonology of the words was not predictable from the orthography of the words when compared to when the phonology was predictable from the orthography, the two distinct types of word pair could be collapsed. In this case, rhyming word pairs that were orthographically similar and non-rhyming pairs that were orthographically dissimilar were grouped into a set called "Match" meaning that it was possible to tell from the orthography of the words whether or not the two words rhymed without any phonological processing. Items in the Match category either looked the same and sounded the same or looked different and sounded different. Non-rhyming pairs that looked as though they should rhyme and rhyming pairs that looked as though they should not rhyme were grouped into a set called "Non-match" meaning that it was not possible to correctly decide from looking only at the orthography of the words whether they rhymed or not. Phonological processing was required to correctly judge these word pair types.

Error rates were analysed using a 2 (VF) X 2 (Match) X 2 (Group Type) repeated measures ANOVA. Visual Field (central presentation point (CPP) and right visual field presentation point (RVF) was within-participants and within-items. Match (Match (M) and Non-match (NM) was within-participants and between-items. There was also a between-participants and within-items factor of Group Type (dyslexic group (DYS) and control group (CON)).

Items that participants made errors on were excluded from the reaction time analysis. Items that had a reaction time that was more than 2.5 standard deviations away from the average for that participant for that particular type of item were also excluded from the final analysis. These values were replaced by the average reaction time score for that participant for that type of item. A total of 169 items were replaced giving a replacement rate of 6.90%.

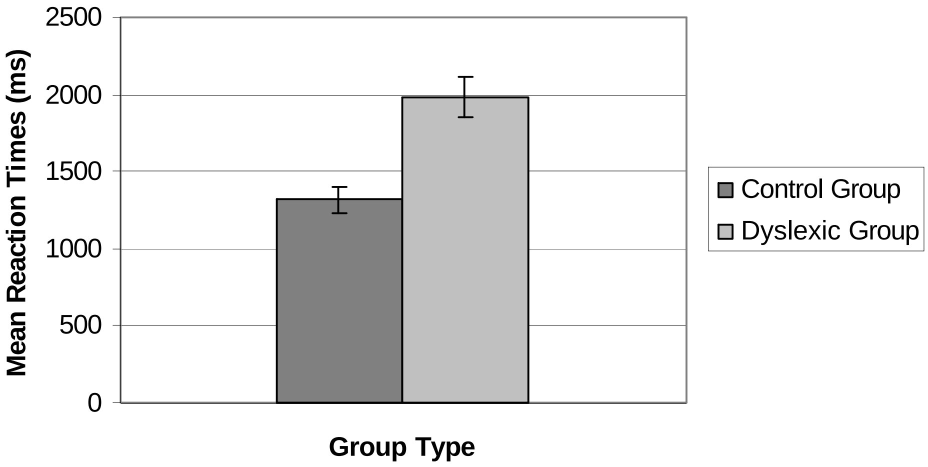
Reaction Times

Table 10: The mean reaction time scores (rhyming pairs only) in milliseconds (ms) for dyslexic and control group participants for orthographically similar (OS) and orthographically dissimilar (OD) items at the central presentation point (CPP) and right visual field presentation point (RVF)

	Visual Field Presentation Position Similarity			
	Central		Right visual Field	
Group Type	OS	OD	OS	OD
Dyslexic	1782	1972	1703	2466
Control	1225	1352	1297	1385

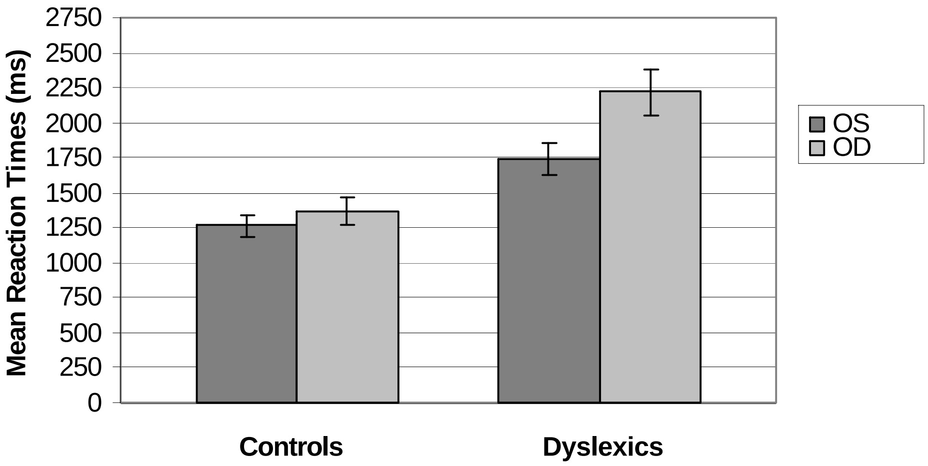
Overall, we found that the control group (1315.1ms) were faster at making rhyme judgements compared to the dyslexic group (1981.0 ms) (F_1 (1, 32) = 24.52, *MSE*= 368479.88, *p*< 0.001; F_2 (1, 5) = 116.06, *MSE*= 53522.94, *p*< 0.001) (see Figure 18).

Figure 18: Mean reaction times in milliseconds (ms) for rhyme judgements (for rhyming pairs only) by the control group and the dyslexic group



For the rhyming pairs, items that were orthographically similar (both were regular words. They had similar spellings and they sounded the same) were recognised faster (1501.8 ms) than pairs that were orthographically dissimilar (1793.8 ms). The factor of similarity was significant by-participants and approaching significance by-items (F_1 (1, 32) = 21.16, *MSE*= 113909.26, $p < 0.001$; F_2 (1, 5) = 4.69, *MSE*= 155606.88, $p = 0.083$). Supporting our first hypothesis, there was no difference between orthographically similar word pairs and orthographically dissimilar word pairs for the control group. However, the dyslexic group took longer to recognise orthographically dissimilar pairs (2219.0 ms) compared to orthographically similar pairs (1742.5 ms) which is what we predicted in our second hypothesis. The interaction between similarity and group type was significant by-participants and by-items (F_1 (1, 32) = 8.46, $p < 0.01$; F_2 (1, 5) = 6.58, *MSE*= 96628.82, $p < 0.05$) (see Figure 19).

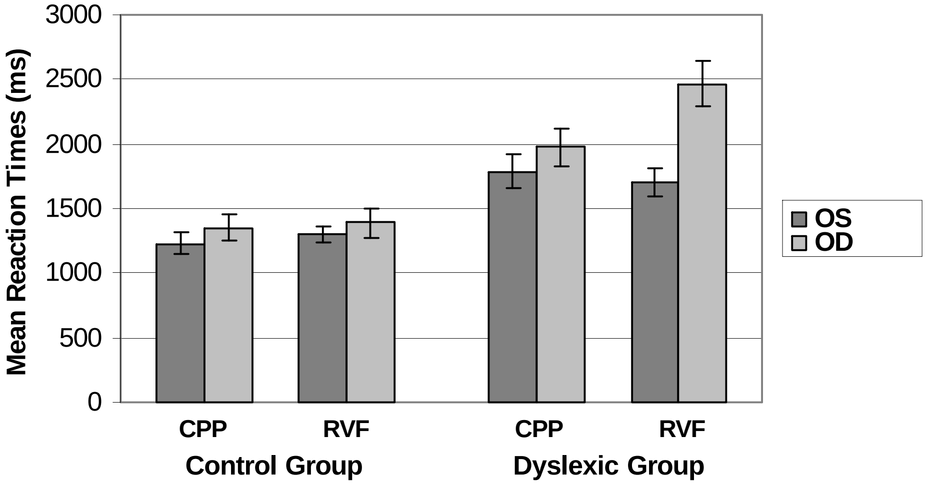
Figure 19: Mean reaction times in milliseconds (ms) for orthographically similar pairs (OS) and orthographically dissimilar pairs (OD) (rhyming items only) for the control group and the dyslexic group



In hypotheses three and four we predicted that the performance of the dyslexics would be worse when the word pairs were presented parafoveally compared to when they were presented foveally. We also predicted that there would be no difference between foveal and parafoveal presentations in the performance of the control group. Our data supports both of these hypotheses. The interaction between Visual Field and Group Type was marginal by-participants and non-significant by-items (F_1 (1, 32) = 3.75, $p < 0.062$; F_2 (1, 5) = 1.11, $MSE = 30118.62$, $p > 0.1$) such that the dyslexic group were marginally slower to make correct rhyme judgements when the stimuli appeared in the RVF parafovea. However, the three-way interaction between Visual Field x Similarity x Group Type was significant by-participants and by-items (F_1 (1, 32) = 24.94, $p < 0.001$; F_2 (1, 5) = 9.11, $MSE = 25179.32$, $p < 0.03$). Further analyses (two 2 x 2 ANOVAs, one on each participant group) showed that the interaction was not significant for the control group (F_1 (1, 23) = 0.49, $MSE = 17976.27$, $p > 0.1$; F_2 (1, 5) = 0.07, $MSE = 8717.05$, $p > 0.1$) but that there was a significant interaction for the dyslexic group (F_1 (1, 9) = 17.065, $MSE = 48069.325$, $p < 0.005$; F_2 (1, 5) = *7.870*, $MSE = 62544.550$, $p < 0.05$). Only the dyslexic participants were slower at making rhyme judgements on rhyming, orthographically dissimilar word pairs (2466 ms) compared to rhyming, orthographically similar word pairs (1703 ms) in the RVF (see Figure 20).

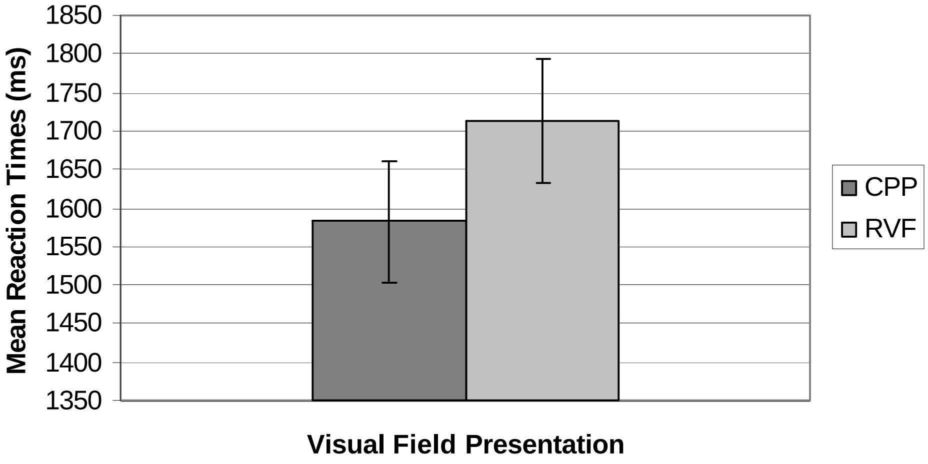
Figure 20: Mean reaction times in milliseconds (ms) to orthographically similar (OS) and orthographically dissimilar (OD) items (rhyming pairs only) that were

presented at a central fixation point (CPP) or in the right visual field parafovea (RVF): Dyslexic and control groups shown



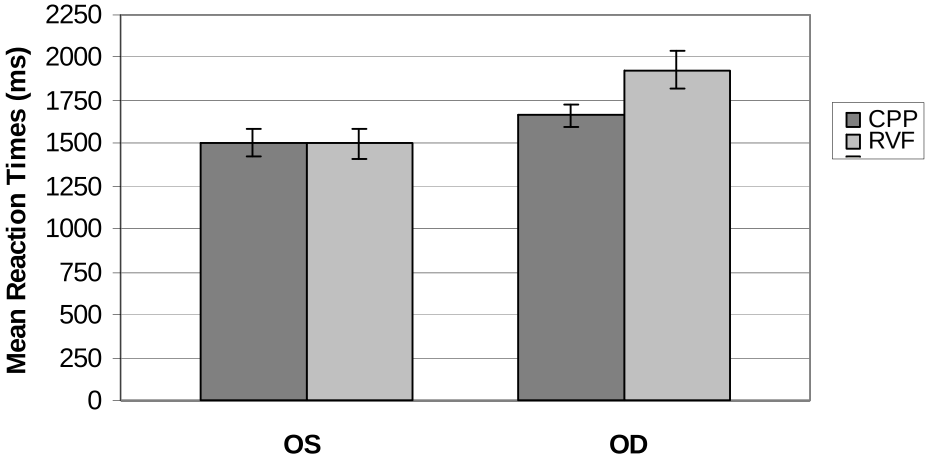
We also found that word pairs that were presented at the CPP (fovea) were judged more quickly (1582.8 ms) than word pairs that were presented to the RVF (parafovea) (1712.8 ms). There was a main effect of Visual Field, significant both by-participants and by-items (F_1 (1, 32) = 10.59, *MSE*= 45090.74, $p< 0.01$; F_2 (1, 5) = 7.21, *MSE*= 39794.07, $p< 0.05$) (see Figure 21).

Figure 21: Mean reaction times in milliseconds (ms) for items (rhyming pairs only) presented in the centre of the visual field (CPP) and in the right visual field parafovea (RVF)



Rhyming word pairs that had similar orthography (OS/ PS) were judged faster (1500 ms) than phonologically similar - orthographically dissimilar word pairs (1925.5 ms) (OD/ PS) but only in the parafoveal area of the right visual field (RVF). The interaction between Similarity and Visual Field was significant by-participants and marginal by-items (F_1 (1, 32) = 19.06, *MSE*= 26439.94, *p*< 0.001; F_2 (1, 5) = 5.72, *MSE*= 46082.29, *p*< 0.062) (see Figure 22). All other effects and interactions were non-significant.

Figure 22: Mean reaction times in milliseconds (ms) for orthographically similar pairs (OS) and orthographically *dissimilar* pairs (OD) (rhyming items only) that were presented at the central fixation point (CPP) or in the right visual field parafovea (RVF)



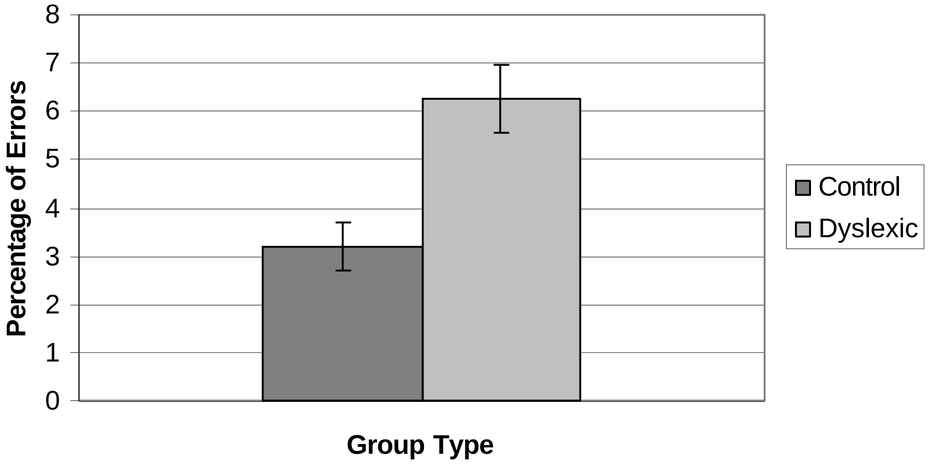
Eye-tracking Errors

Table 11: Percentage of errors made by control and dyslexic group participants for matching pairs and non-matching pairs that were presented at the central presentation point (CPP) and right visual field presentation point (RVF)

	Visual Field Presentation Position Similarity			
	Central presentation		Right visual Field	
Group Type	Match	Non-match	Match	Non-match
Dyslexic	0.00	10.00	2.22	12.78
Control	0.22	6.72	7.22	5.11

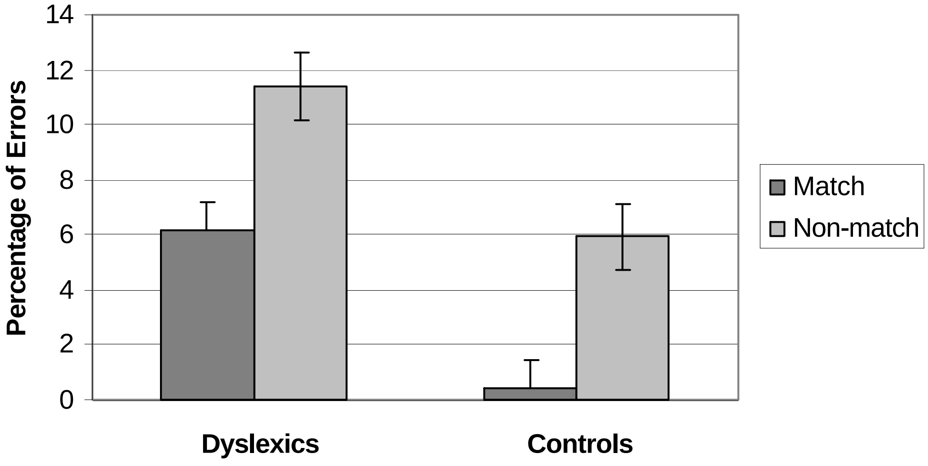
Overall, we found that there was a trend for dyslexic participants (6.25 %) to make more errors compared to control group participants (3.19 %). There was an effect of group type, significant by-participants but not by-items (F_1 (1, 32) = 5.38, MSE= 0.08, p< 0.05; F_2 (1, 11) = 2.96, MSE= 0.01, p> 0.1). Recall that, as well as making more errors, dyslexic participants were found to be slower at making the rhyme judgements suggesting that not only does it take longer for them to make the rhyme judgements but that they are less accurate when they do decide (see Figure 23).

Figure 23: Percentage of errors made by control group participants and dyslexic group participants



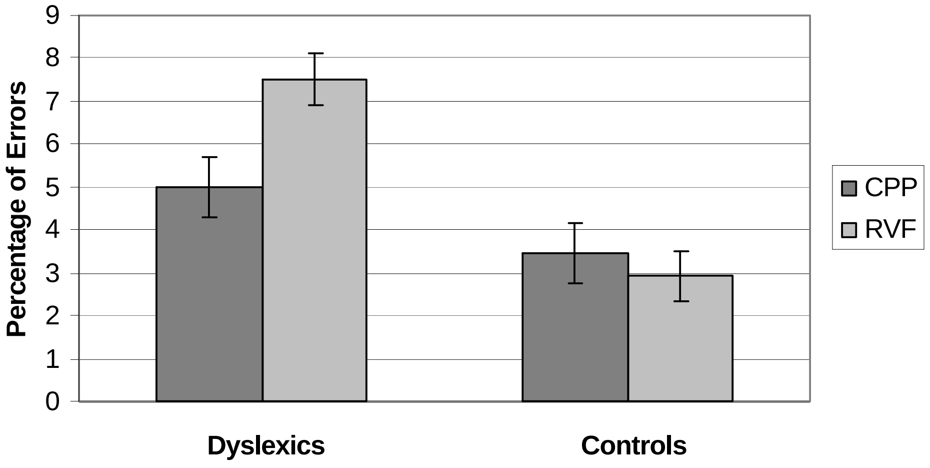
When we look at the error rates for each participant group (control and dyslexic) for matching and non-matching items we see that there was no difference between the number of errors made by the skilled reading group and the dyslexic group on matching word pairs. The interaction between Group Type and Match was significant by-participants but not by-items (F_1 (1, 32) = 5.48, $p < 0.03$; F_2 (1, 11) = 0.71, *MSE*= 1.47, $p > 0.1$). However, we found that there was a tendency for the dyslexic group (11.39 %) to make more errors on the non-matching pairs (where the phonology is not predictable from the orthography) compared to the control group (5.92 %). Both participant groups made more errors on the non-matching pairs but the dyslexic group were impaired compared to the skilled reading group. Not only are the dyslexics slower at judging non-matching pairs but they also make more errors when they do make the decision (see Figure 24).

Figure 24: Percentage of errors made on matching and non-matching word pairs for both the control group and the dyslexic group



There was an interaction between group type and visual field presentation position, significant both by-participants and by-items (F_1 (1, 32) = 6.79, $p < 0.02$; F_2 (1, 11) = 8.29, $MSE = 0.25$, $p < 0.02$) such that the dyslexic group participants made more errors on rhyme judgements on items that appeared in the right visual field (7.50 %) than on items that appeared at a central presentation point (5.00 %). There was no effect of visual field for the control group (see Figure 25).

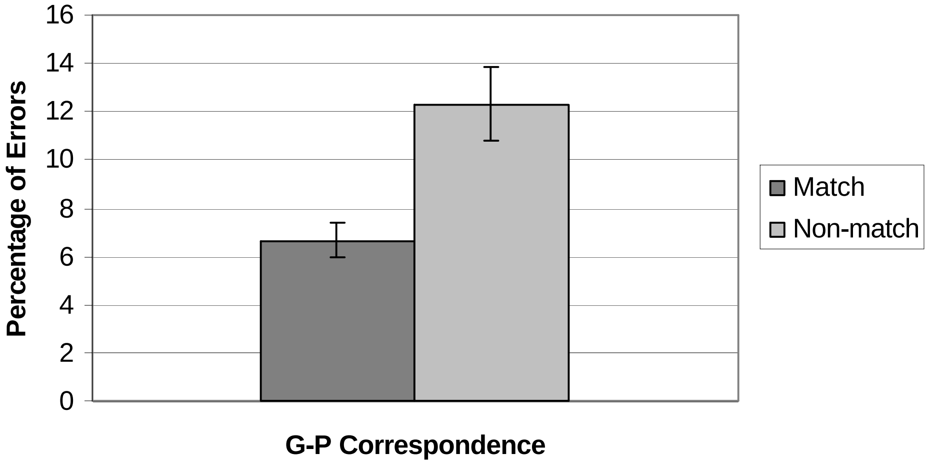
Figure 25: Percentage of errors made by dyslexic and control group participants on word pairs presented at either a central fixation point or in the right visual field parafovea



The 3-way interaction between Group Type, Match and Visual Field was not significant either by-participants or by-items (both *Fs* < 1). The dyslexic group had been slower to make rhyme judgements on non-matching pairs in the parafoveal condition. Although they were slower they did not make significantly more errors on these pairs when compared to the control group. This suggests a speed-accuracy trade-off for the dyslexic group participants: It was taking them longer to make a correct decision.

We also found that there were a greater number of errors made on non-matching items (12.31 %) (items that either looked like they were phonologically similar but did not rhyme (OS/ PD) or looked like they were not phonologically similar but did rhyme (OD/ PS)) than on matching items (6.64 %) (either looked phonologically similar and did rhyme (OS/ PS) or did not look like they were pronounced the same and did not rhyme (OD/ PD)). The factor of similarity was significant both by-participants and by-items (F_1 (1, 32) = 57.83, *MSE*= 0.98, *p*< 0.001; F_2 (1, 11) = 14.00, *MSE*= 5.25, *p*< 0.01) (see Figure 26). There was a significant difference in reaction times between items where the phonology was predictable and items where the phonology was not predictable (see previous section). Not only were more errors made on items that had not predicable phonology, they were also slower to be judged. All other effects and interactions were non-significant.

Figure 26: Percentage of errors made on matching and non-matching word pairs



Questionnaire Study

After the eye-tracking part of the experiment, participants were given a questionnaire containing a list of the words that they had seen in the experiment and were asked to indicate which of the pairs rhymed. This enabled us to get an off-line measurement of their rhyming judgements. There was no time-limit to ensure that the participants were carefully considering their decisions. The questionnaire data measures the effect of orthographic and phonological variation without the factor of visual field and so is, in effect, equivalent to foveal presentation. This data can also be used to help control for a potential “go” bias in the “go-no-go” task. Because participants are required to make a response when they detect the presence of a rhyme, they may make more errors on the items where there is no rhyme present simply because of a bias to make a response. Dyslexic participants in particular have been found to show a bias towards a positive response when completing lexical decision tasks (Hildebrandt et al., 1995). In the questionnaire task, participants are required to make a response to all items, not just the ones where they detect the presence of a rhyme. By eliminating the factor of visual field it is also possible to investigate whether the difference between groups is due to a problem with the eye guidance system. Dyslexics have been found to have problems with eye movements and so any differences between groups that are found in the eye-tracking data may be due to this rather than a specific problem with perceiving phonological information in the parafovea. If there is still an effect of non-predictable phonology in the questionnaire data then it is unlikely to be a problem of simply locating the words.

Questionnaire Results

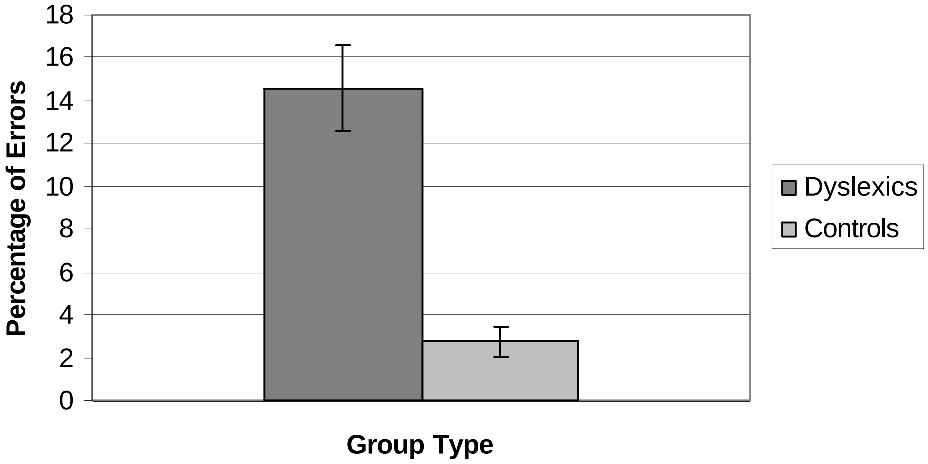
The questionnaire data was analysed using a 2 (Rhyme) x 2 (Similarity) X 2 (Group Type) repeated measures ANOVA. There were two repeated-measures within-participants and between-items factors; Rhyme (phonologically similar (PS) and phonologically dissimilar (PD)) and Similarity (orthographically similar (OS) and orthographically dissimilar (OD)). There was also a between-participants and within-items factor of Group Type (dyslexic group (DYS) and control group (CON)).

Table 12: Percentage of errors made by the control group and the dyslexic group for orthographically similar – phonologically similar (OS/PS), orthographically similar – phonologically dissimilar (OS/PD), orthographically dissimilar – phonologically similar (OD/PS), and orthographically dissimilar – phonologically dissimilar (OD/PD) word pair items

	Rhyme Similarity			
	Rhyming Pairs (PS)		Non-rhyming Pairs (PD)	
Group Type	Similar (OS)	Dissimilar (OD)	Similar (OS)	Dissimilar (OD)
Control	0.5	5.19	6.5	0.25
Dyslexic	8.75	26.25	29.38	1.25

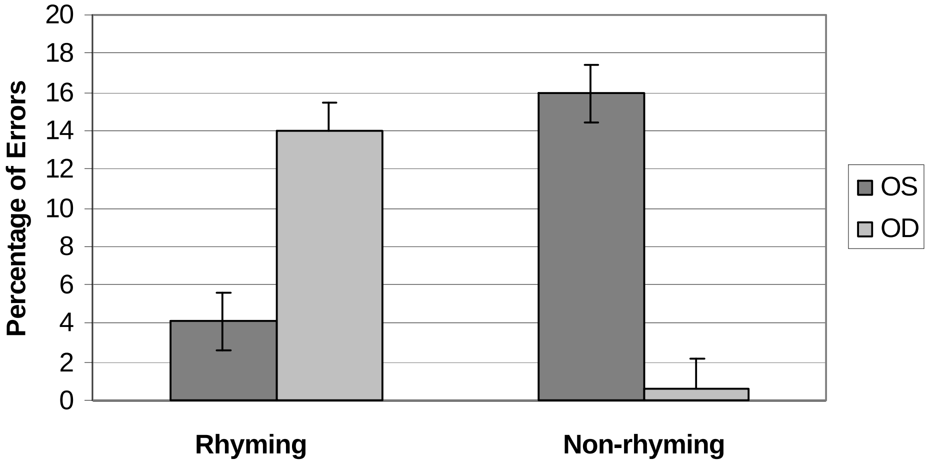
Overall, the dyslexic group (14.58 %) made more errors on the questionnaire study compared to the control group (2.76 %) (F_1 (1, 32) = 12.31, *MSE*= 8.22, $p< 0.001$; F_2 (1, 17) = 36.31, *MSE*= 0.62, $p< 0.001$) (see Figure 27). When compared to the eye-tracking data, dyslexic participants still make more errors when compared to the control group even with the factor of visual field excluded.

Figure 27: Percentage of errors made for control group participants and dyslexic group participants



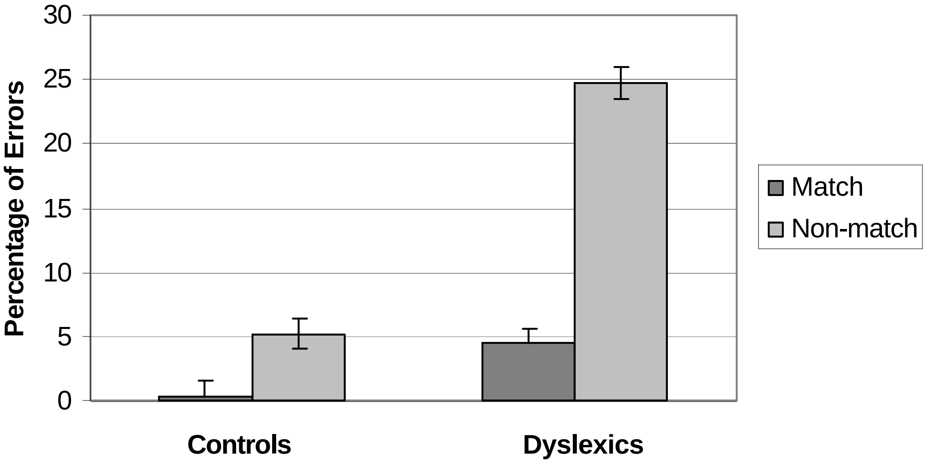
A greater number of errors were made on the item pairs when participants were unable to judge whether or not the two words in the pair rhymed from the way the words were spelled (F_1 (1, 32) = 87.85, *MSE*= 1.65, $p< 0.001$; F_2 (1, 17) = 62.99, *MSE*= 1.46, $p< 0.001$) (see Figure 28). A greater number of errors were made on rhyming items when they were orthographically dissimilar (13.97 %) than when they were orthographically similar (4.11 %) and more errors were made on non-rhyming pairs when they were orthographically similar (15.94 %) than when they were orthographically dissimilar (0.67 %). This is the same pattern of results that was obtained from the eye-tracking data. Participants had greatest difficulty when making rhyme judgements on items where the phonology was not predictable from the orthography of the word pairs. This was the case even when the factor of visual field was excluded.

Figure 28: Percentage of errors made on orthographically and phonologically similar items (OS/ PS), orthographically similar and phonologically dissimilar items (OS/ PD), orthographically dissimilar and phonologically similar items (OD/ PS), and orthographically and phonologically dissimilar items (OD/ PD)



Also, even with the factor of visual field excluded, the dyslexic participants were still worse than the control group at detecting phonological similarity when phonology is not predictable from the way that the words are spelled. The three-way interaction between rhyme, similarity and group type was significant both by-participants and by-items (F_1 (1, 32) = 33.04, $p< 0.001$; F_2 (1, 17) = 16.32, $MSE= 0.41$, $p< 0.001$) such that dyslexic participants made more errors (24.72 %) than control group participants (5.19 %) on items where the orthography and the phonology did not match (pairs that looked as though they should rhyme but did not rhyme and pairs that looked as though they should not rhyme but did rhyme) (see Figure 29). The questionnaire data provides an off line confirmation of the error data. When compared to the eye-tracking data, dyslexic participants still made more errors on items where the phonology of the words is not predictable from the orthography even without the factor of visual field. Based on these findings it appears that dyslexic participants have a problem with making rhyme judgements in general. The eye-tracking data in the previous section shows that this deficit is especially obvious when items are viewed in the parafovea. It is not just a case of dyslexics having difficulty with locating a stimulus in the parafovea. Even when they are allowed to look at the stimulus for an unlimited time they still perform worse than non-impaired participants. All other effects and interactions were non-significant.

Figure 29: Percentage of errors made on items where the orthographically and phonologically do not match (OS/ PD and OD/ PS) and for items where the orthography and the phonology do match (OS/ PS and OD/ PD) for the dyslexic group and the control group



5.3.3 Discussion

This experiment tested the idea that people who have developmental dyslexia find it more difficult to process phonological information when this information appears in the parafoveal area of the visual field. It has been proposed that the phonological information of a word is accessed before fixation on that word occurs (Chace, Rayner, & Well, 2005; Miellet & Sparrow, 2004; Pollatsek et al., 1992; Sereno & Rayner, 2000). The results of this experiment support the idea that dyslexic readers do not get the full preview benefit. We found that dyslexic participants had more difficulty compared to control participants when retrieving phonological information in the parafovea.

Overall, we found that the dyslexic readers were slower and had a tendency to make more errors when making rhyme judgments. The dyslexic participants were slower to recognise the presence of a rhyme when one of the rhyming word pairs contained an exception word and so rhyme judgements could not be correctly made simply by comparing the orthography of the two words. There was no such effect for skilled readers. Skilled readers were equally able to detect the presence of a rhyme in both types of word pair; two regular words or one regular word and one exception word. This finding supports the idea that skilled readers are able to use lexical processing to access words and that dyslexic readers have to rely on sub-lexical processing as proposed by Zoccolotti et al., (2005). Only the lexical route to word recognition is capable of reading exception words accurately (Coltheart et al., 1993). In order to detect the presence of a rhyme in the word pairs that contained an exception word, the phonology of the exception word has to be correctly accessed. The problem that the dyslexic participants experienced with these word pair types suggests that they were not able to do this. The skilled readers showed no difficulty with these word pairs so we can deduce that they were using lexical access to encode the correct phonology of the exception words.

The dyslexic readers were found to be particularly impaired at making rhyme judgments on word pairs that contained words that were not visually similar (therefore, one of them was an exception word) when the pairs were presented in the parafoveal area of the visual field. This was not the case for the skilled readers: they were equally as able to correctly detect rhymes in both types of word pair regardless of whether they were directly fixated or whether they were presented parafoveally. The performance of the two groups did not differ significantly when the word pairs were directly fixated. However, when the word pairs were presented parafoveally, the dyslexic readers were significantly impaired at detecting rhymes when one of the words was an exception word.

The questionnaire data shows that this difficulty in detecting phonological similarity for the dyslexic group is present even when the factor of visual field is excluded. The dyslexic readers still made more errors compared to control group participants in detecting the presence or absence of phonological similarity even when they were allowed unlimited time. From the questionnaire data, it can be seen that dyslexics perform less well when judging the pairs where orthography and phonology do not match (e.g. orthographically similar but non-rhyming or orthographically dissimilar but rhyming). This suggests that the dyslexic readers are judging the likelihood of a rhyme based on the similarities between the orthography of the two words. In the case of the orthographically similar but non-rhyming word pairs, the dyslexic readers appear to assume that the two words rhyme because they look the same and then fail to reject these pairs based on further phonological analysis. The same applies when the words are orthographically dissimilar but do in fact rhyme. The dyslexics do not appear to be engaging phonological analysis in order to detect the presence of a rhyme. This finding supports the hypothesis that dyslexic readers fail to develop a fully functional lexical route for word recognition (De Luca et al., 2002; Spinelli et al., 2005; Ziegler et al., 2003; Zoccolotti et al., 1999, 2005). The eye tracking data shows that this deficit is particularly pronounced in the parafoveal preview suggesting that there might be two underlying deficits; firstly, a problem with lexical access and secondly a problem with parafoveal perception of words.

The right visual field parafoveal presentations led to significantly slower recognition times for participants with dyslexia compared to when the stimuli were directly fixated. This was most obvious for word pairs that contained an exception word. When reading sentences, dyslexics make shorter saccades and longer fixations compared to skilled readers (Biscaldi et al., 1998; Ram-Tsur et al., 2006), suggesting that they do not get adequate preview information. If the dyslexic readers are not able to efficiently extract information from the parafovea they will require more frequent fixations because they perceive less information per fixation. It has been shown that during normal reading, information is received about the word directly to the right of the fixated word while processing continues on the fixated word (Liversedge et al., 2004; Rayner et al., 2006; Rayner et al., 2003; Rayner et al., 1989). The difficulties that dyslexic readers show in perceiving parafoveal input in this experiment suggest that they will not be able to do this as efficiently as skilled readers.

The magnocellular pathway arises from the parafoveal and peripheral regions of the retina whereas the parvocellular pathway arises mostly from the fovea. This suggests that the magnocellular visual pathway may play a significant role in transmitting visual information from the parafoveal area of the visual field. If there is a deficit in the magnocellular pathway, parafoveal vision will be disrupted creating a narrowing of the perceptual span and causing the reader to have to make more frequent fixations. The magnocellular pathway has a faster transmission rate than the parvocellular pathway. Because the right visual field parafoveal and peripheral regions (carried by the faster magnocellular pathway) are transmitted via the nasal hemiretina, to the language dominant left hemisphere, this may be the neurological mechanism that enables parafoveal viewing of a word to occur. The information from these areas of the retina will reach the LGN and therefore the next stage of lexical processing before any other part of the visual field. We propose that the magnocellular visual pathway is largely responsible for the detection of lexical information in the parafoveal preview. If some dyslexics do have a magnocellular pathway impairment as suggested by Stein and others (e.g., Hari, Renvall, & Tanskanen, 2001; Stein, 2001; Stein, Talcott, & Walsh, 2000; Stein & Walsh, 1997), then parafoveal perception will be more affected than foveal perception as the fovea is dominated by parvocellular neurons.

We found that the performance in rhyme detection of the dyslexic readers was affected by the presence of an exception word. This supports the idea that dyslexic have failed to develop a lexical route for reading and are relying on sub-lexical processing. This impairment was more severe when the word pairs were viewed parafoveally. The impairment is most severe for word pairs where the phonology is not predictable from the orthography of the words suggesting that the dyslexics have difficulty in extracting phonological codes from these items. That this was more evident in parafoveal viewing suggests that phonological encoding is particularly important for perceiving parafoveal input (Chace, Rayner, & Well, 2005; Miellet & Sparrow, 2004; Pollatsek et al., 1992) and that a deficit in encoding phonological information may be a result of impairment in the magnocellular pathway.

5.4 Implications for reading and further questions to be addressed

The results of experiment in section 5.1 suggested that dyslexic readers are more affected by word regularity than skilled readers when directly fixating isolated words. The skilled reader control group were not affected by irregularities of grapheme-to-phoneme mapping. This suggests that skilled readers use a lexical strategy to recognise words whereas the dyslexic readers are continuing to rely on a slower, sub-lexical strategy. When words can be recognised as whole units through the lexical route, exception words can be recognised as efficiently as words with regular grapheme-to-phoneme mapping. However, when the sub-lexical route is employed, the recognition of exception words is impaired as these words cannot be identified correctly through G-P rules as the phonology does not map onto the orthography.

The sub-lexical strategy is used when learning to read (Aghababian & Nazir, 2000; De Luca et al., 2002; Martens & De Jong, 2006; Spinelli et al., 2005; Ziegler et al., 2003; Zoccolotti et al., 2005). Dyslexic and beginner readers both show large word length effects. They recognise shorter words faster than longer words suggesting that a sub-lexical strategy is being used to incrementally assemble the words through the mapping of phonemes onto individual graphemes. This length effect lessens as reading skill develops and a lexical-based strategy is adopted. Using this strategy enables words to be identified faster as they are recognised as whole units. Dyslexic readers fail to adopt this lexical strategy (Zoccolotti et al., 2005). They continue to use the sub-lexical route, mapping phonemes onto graphemes, which leads to slower reading and difficulties identifying exception words as these word types cannot be read in this way. An examination of dyslexia in a language with regular orthography shows that Spanish dyslexics are slower than non-impaired Spanish readers but they do not make as many errors in word identification compared to dyslexics reading English which has a less regular orthography (Zoccolotti et al., 1999).

Non-impaired, skilled readers rely on an interaction between the ventral (lexical) and the dorsal (sub-lexical) routes (Borowsky et al., 2006; Pugh et al., 1996; Sandak et al., 2004). The lexical route is faster as words are recognised as whole units. Both regular and exception words can be recognised using the lexical route. The sub-lexical route is slower as words have to be assembled; phonemes are mapped onto individual graphemes. Experiment 5.2 supports the idea that dyslexics fail to adopt the lexical strategy as they were slower overall at recognising all word types compared to the skilled control group. There was also a trend for the dyslexics to have greater difficulty in recognising exception words compared to regular words. Regular words can be recognised using the sub-lexical route but exception words cannot as exception words do not have regular grapheme-to-phoneme correspondence. Non-words, including pseudo-homophones, rely exclusively on sub-lexical processing. There can be no lexical representations of these words as the readers have never encountered them before. Even highly skilled readers show length effects when reading non-words (Juphard et al., 2004) suggesting a reliance on the sub-lexical route.

In Experiment 5.2, neither exception words nor regularly spelled words appeared to be affected by presentation to the parafoveal area of the visual field. To investigate this further we used a more specific task in experiment 5.3 to examine the ability of the dyslexics to extract phonological information from parafoveal vision. In experiment 5.3 we found that the performance in rhyme detection of the dyslexic readers was affected by the presence of an exception word. The impairment demonstrated by the dyslexic readers was most severe for word pairs that contained a word in which the phonology was not predictable from the orthography of the words suggesting that the dyslexics have difficulty in extracting phonological codes from these items. This supports the idea that the dyslexic readers are relying on sub-lexical processing. This impairment was more severe when the word pairs were viewed parafoveally suggesting that phonological encoding is particularly important for perceiving parafoveal input.

Related to this is the finding that, during a lexical decision task, less skilled readers (though not specifically dyslexics) also demonstrated an effect of word regularity. Skilled readers did not (Unsworth & Pexman, 2003). In the same study, poorer readers were found to make more errors on pseudo-homophones (incorrectly identifying them as read words). The authors concluded that the more skilled readers were able to access phonology more efficiently and that poorer readers were less able to perform G-P matching. This finding suggests that the word regularity effects found with dyslexic readers may not be exclusively a symptom of dyslexia. Instead it seems to be symptomatic of a lower level of reading skill.

As the magnocellular visual pathway is the most common type of neuronal pathway that connects the parafoveal area of the retina to the brain we propose that disruption to the transmission of the visual signal along this pathway may underlie some of the reading problems in dyslexics. The shorter saccades and longer fixation times of dyslexics may reflect an inability to efficiently extract information from parafoveal vision. The experiment in section 5.3 demonstrated that dyslexic readers had greater difficulty in extracting phonological information from parafoveally presented word pairs. Previous studies have shown that homophone previews facilitate subsequent word recognition more than orthographically similar preview words (Miellet & Sparrow, 2004; Pollatsek et al., 1992). This difference in preview benefit was not found for less skilled readers (Chace, Rayner, & Well, 2005). Chace et al. concluded that only readers with a high level of skill were able to use phonological information from the parafoveal preview to facilitate recognition of a word when it was fixated. Based on this we propose that dyslexic readers, and non-impaired readers who do not have a high level of reading skill, are unable to extract as much benefit from parafoveal preview as skilled readers. We further propose that in the case of a portion (but not all) of dyslexics that this deficit is explainable in term of magnocellular dysfunction.

5.5 Chapter Summary

In this chapter we have shown that dyslexic readers have greater difficulty in processing words when the phonology of the word does not directly correspond to the orthography of the word when viewing words in isolation. We also showed that high-functioning readers do not show this effect. Skilled readers are equally as able to extract phonology from a word that has regular or irregular spelling. The findings of the first two experiments in this chapter suggest that dyslexic readers rely on a sub-lexical route to word recognition whereas more skilled readers are able to additionally employ a lexical route which allows them to access exception words as efficiently as regular words. We also found evidence for a parafoveal deficit in the dyslexic readers that suggested that they were not as able as skilled readers to efficiently extract information (particularly phonological) from words viewed in parafoveal vision. We relate this to a possible magnocellular dysfunction in at least a sub-type of dyslexic readers. The next set of experiments goes on to explore this idea by using isoluminant stimuli to inhibit the action of the magnocellular pathway in non-impaired readers in an attempt to assess the contribution of this pathway to visual word recognition and to assess whether the parafoveal areas of the visual field are particularly vulnerable to a magnocellular deficit.

Chapter 6

The Effect of Magnocellular Inhibition on Word Recognition

6.0 Chapter Overview

In this chapter we test the contribution made by the magnocellular pathway to the process of word recognition. It has previously been demonstrated that presenting stimuli on a red background inhibits the activity of the magnocellular pathway (e.g., Chapman et al., 2004). In the set of experiments in the current chapter we exploit this methodology to test the impact of magnocellular suppression on both lexical (ventral) and sub-lexical (dorsal) processing. In experiment 6.1 we investigate the effect of magnocellular inhibition on lexical processing. In particular, we investigate whether a magnocellular (dorsal stream) deficit leads to disruption of lexical (ventral) processing. The experiment in section 6.2 examines the impact of magnocellular inhibition on the perception of words and non-words. Section 6.3 investigates the impact of magnocellular inhibition on the ability to recognise both regular and exception words. Experiments 6.2 and 6.3 both also address the differences between stimuli presented in the foveal and parafoveal presentation positions. In section 6.4 we summarise the results of these three experiments and discuss what the findings imply about reading in general.

6.1 The effect of magnocellular inhibition on Lexical Processing

In the previous chapter (section 5.2) we demonstrated that dyslexic readers showed a tendency to have difficulty in recognising exception words. The non-impaired control group readers showed no differences in either speed or accuracy in the recognition of exception words compared to regularly spelled words. We hypothesised, based on previous research (De Luca et al., 2002; Martens & de Jong, 2006; Spinelli et al., 2005; Ziegler et al., 2003; Zoccolotti et al., 2005) that this finding indicates that dyslexic readers fail to adopt a lexical strategy for word recognition and instead continue to rely on sub-lexical processing. The dyslexic group were slower compared to the non-impaired group even at recognising regularly spelled words indicating that the non-impaired group were able to recognise words as whole units but that the dyslexic group still had to rely on a slower, incremental, sub-lexical strategy even when viewing regularly spelled words. In experiment 5.3 we demonstrated that the dyslexic readers appeared to have difficulty in extracting phonological information from words that were presented to parafoveal vision. We related this finding to a possible magnocellular dysfunction as the magnocellular pathway is the predominant pathway to arise from the parafoveal area of the retina and a magnocellular deficit has been proposed to underlie the reading difficulties of a portion of dyslexics (e.g., Facoetti, Paganoni, & Lorusso, 2004; Hari, Renvall, & Tanskanen, 2001; Stein, 2001; Stein, Talcott, & Walsh, 2000; Stein & Walsh, 1997). If parafoveal processing of a stimulus is not as efficient in these readers then this may be the reason why many dyslexics show abnormal patterns of eye-movements (Biscaldi et al., 1998; Ram-Tsur et al., 2006).

We propose that not only do dyslexics have a deficit in ventral stream process that disrupts their ability to read exception words but that a sub-group of them may also have a deficit in dorsal stream processing. We propose that a deficit in dorsal stream processing underlies the problem in extracting phonological information from words viewed in parafoveal vision. In order to investigate this further we present the stimuli on a red background. This has been shown to inhibit the functioning of the magnocellular pathway.

It was initially demonstrated by Wiesel and Hubel (1966) that the activity of magnocellular retinal ganglion cells could be inhibited by red light. This finding was replicated by work in the 1970’s (Dreher, Fukuda, & Roedieck, 1976; Kruger, 1977; Schiller & Malpeli, 1978). The M channel is particularly sensitive to longer wavelengths of light (Livingstone & Hubel, 1984). Magnocellular retinal ganglion cells have a centre-surround organisation with the majority of them having an inhibitory surround that is maximally responsive to red light as the colour red has the longest wavelength of the visible spectrum (De Monasterio & Schein, 1980; Dreher, Fukada, & Roedieck, 1976; Kruger, 1977; Lee, 1996; Livingstone & Hubel, 1987; Shapley, 1990; Wiesel & Hubel, 1966). Therefore, using a background of red should impair the functioning of the magnocellular pathway. Many researchers have used isoluminant stimuli with red backgrounds and have shown results that are consistent with a magnocellular deficit (Bedwell, Brown, & Miller, 2003; Breitmeyer & Breier, 1994; Breitmeyer & Williams, 1990; Brown & Koch, 2000; Chapman et al., 2004; Edwards et al., 1996; Pammer & Lovegrove, 2001).

In the first experiment we test whether inhibiting a previously functional magnocellular pathway (and therefore inhibiting dorsal stream processing) will have an impact on ventral stream processing. As we only use skilled readers in this experiment we can assume that both processing streams are functional under normal reading conditions. By impairing the dorsal stream we can investigate whether the magnocellular-dorsal stream normally contributes to lexical processing or whether it only contributes to sub-lexical processing.

In order to investigate this hypothesis, we use a task that demonstrates lexicality effects. The word superiority effect (WSE) was first demonstrated by Cattell (1886). He found that when words were tachistoscopically presented the viewer was able to recall a greater number of letters that had been present in a word context compared to in a random letter string. The Reicher-Wheeler task (Reicher, 1969; Wheeler, 1970) was developed in order to attempt to determine the factors that underlie this finding. In this task, participants are shown an isolated letter, a jumbled letter string, or a single word. This is immediately followed by a mask. The participants are then presented with two letters and have to make a forced-choice decision as to which of the letters had been present in the original stimuli. This eliminates the possibility of guesswork. An important aspect of this task is that both of the letters in the forced-choice scenario would have formed a real word if they had been present in the word context. For example, both the letters “D” and “K” could form a word in the context of “wor_”.

In the original experiment, Reicher (1969) found that participants were more able to correctly identify a letter when it had been presented as part of a word compared to when the letter had been presented in isolation. This finding appears to indicate activity of the ventral or lexical processing stream. If the participants were using sub-lexical processing then they would not be able to recognise words before they recognised individual letters. The participants in Reicher's study also found in easier to recognise a letter when the letter had been presented in a real word context compared to in a non-word context. The WSE is greater for high frequency words compared to low frequency words (Krueger, 1992). This indicates that the participants are using a lexical strategy to process the words as only the ventral route is expected to show a word frequency effect (see experiment 5.1). It appears that top-down processing is central to this effect. Recognition of the word facilitates recognition of the individual letters.

Related to the word superiority effect is the pseudo-word superiority effect (PSE) (Baron & Thurston, 1973; Carr, Davidson, & Hawkins, 1978; Estes & Brunn, 1987; Grainger & Jacobs, 2005; Grainger et al., 2003; Grainger & Jacobs, 1994; McClelland & Johnston, 1977; McClelland, 1976; Paap et al., 1982; Reicher, 1969; Ziegler et al., 1997). It is easier to identify a single letter in pronounceable non-words compared to unpronounceable non-words. Grainger and Jacobs (2005) found that letter recognition in pseudowords was enhanced compared to if the context was a row of x's if the pseudoword had one real word neighbour. This was only true if the neighbour word contained the target letter in the correct position: If the wrong alternative letter was in the neighbour word, letter recognition was impaired. More than one real word neighbour did not lead to any further enhancement of letter recognition. This suggests an important role for orthographic processing in the WSE and the PSE. The facilitation of letter recognition in non-words that have real word neighbours suggests that these pseudowords receive a degree of lexical activation (though to a lesser degree than real words). Supporting this idea, ERPs to real word and pseudowords show a more similar pattern of cortical activation compared to non-words (Ziegler et al. 1997).

Regardless of what the actual mechanism responsible for the WSE and the PSE is, it is clear that some top-down, or lexical route processing is occurring. It has been established that all readers when learning to process words rely initially on sub-lexical processing and that they only develop whole-word lexical processing when reading skill is improved (Borowsky et al., 2006; Pugh et al., 1996, 2000; Sandak et al., 2004). Dyslexics fail to adopt this faster lexical processing route (Zoccolotti et al., 2005). The question addressed by the present experiment is – what is the effect on word recognition for a reader who has successfully developed the lexical reading route when the sub-lexical route is inhibited? Can the lexical processing route function optimally without the contribution of the sub-lexical route?

In order to test this we present the stimuli on a red background to inhibit the functioning of the magnocellular visual pathway. This pathway is proposed to provide the main source of input to the dorsal processing stream (Maunsell, Nealey, & De Priest, 1990). We use a task that highlights the involvement of lexical processing: the Reicher-Wheeler task. The word superiority effect (WSE) demonstrates the role of context in word recognition. Readers are able to recognise the presence of a letter faster when the letter is presented in the context of a word than when the letter is presented in isolation (Grainger et al., 2003; Hildebrandt et al., 1995; Jordan & Patching, 2004; Krueger & Stadtlander, 1991; Krueger & Shapiro, 1979; Reicher, 1969). It is also easier to recognise a letter as having been present when the letter was presented in the context of a real word than when it was presented in the context of a non-word (Grainger et al., 2003; Hildebrandt et al., 1995; Reicher, 1969). This implies that top-down processing facilitates letter recognition in the word context condition. We tested whether the word superiority effect would persist when the sub-lexical processing stream was inhibited. Can a sub-optimal dorsal processing stream influence the operation of the lexical ventral processing stream?

Based on previous research (e.g., Jordan & Patching, 2004) we predict that when the words are presented on a white background allowing both visual pathways to function optimally there will be a word superiority effect: Letters will be easier to identify when they have been presented in the context of a real word compared to when they have been presented in the context of a non-word. Because we know that the use of a red background inhibits magnocellular functioning (e.g., Chapman et al., 2004) we also predict that if inhibition of dorsal stream functioning influences ventral stream functioning then there will be an attenuation of the word superiority effect. If ventral stream processing is disrupted, the participants will be unable to code the words as whole lexical items and so the top-down facilitation of letters from the lexical level will not occur and there will be no difference in ease of identification between letters that had been present in words and letters that had been present in non-words.

6.1.1 Method

Design

This experiment investigated the effect of losing stimuli contrast on the Word Superiority Effect. We looked at the effect of two variables: Context and Background Colour which were fully crossed leading to a 2 (Context) x 2 (Background Colour) design. There were two levels of the variable “Context”: “Word” in which the context that the letter may or may not have appeared in was a real word and “Non-word” in which the context that the letter may or may not have appeared in was a non-word. The variable of “Context” was fully crossed with the variable “Background colour” which had two levels: “White” in which stimuli items were presented in normal high contrast, black and white stimuli, and “Red” in which stimuli items were presented in on a red background. Each of the 20 participants was exposed to all four conditions.

Apparatus

To present the stimuli, a RM innovator Pentium 4 computer connected to an Iiyama Vision Master Pro 413 monitor with a 17-inch screen (refresh rate 74.999 Hz) was used. A Psychology software Tools Inc serial response box (model 200A) recorded participants’ responses.

Materials

Using a counterbalanced design, participants were shown 80 centrally presented four-letter strings. Forty of these were real words and the other forty were non-words. Half of the "word" stimuli contained the target letter and the other half did not. Half of the non-word stimuli contained the target letter and the other half did not. The stimuli items that did contain the target letter were the experimental items and the items that did not contain the target letter were the filler items. These stimuli were crossed with the two levels of the variable "Background colour": white background and red background. The background colour that each word list appeared in was counterbalanced across participants to ensure that any effects found for a particular background colour were not due to the words themselves. All of the stimuli were presented in Courier New font 16.

Real Word Stimuli Word frequency was not a factor in this experiment so frequency was controlled for and counterbalanced across word lists. All 40 of the four-letter real words selected for this experiment were within the frequency range of 100 to 200 occurrences per million. The words were an equal number of nouns, verbs and adjectives. When a letter was presented that was not in the original word, the new letter was chosen so that if it were inserted in the word, it would form an orthographically and phonologically legal word.

Non-word Stimuli In total, there were forty non-word stimuli items presented. All of the non-words were taken from the ARC non-word database (Rastle, Harrington, & Coltheart, 2002). The non-words were all phonologically legal. All had orthographically existing onsets, orthographically existing bodies and only legal bigrams. When a letter was presented that was not in the original non-word, the new letter was chosen so that if it were inserted in the word, it would form an orthographically and phonologically legal non-word.

Presentation Positions

All of the target letters were displayed in the same space where the third letter of the letter string had been. The test letter always appeared where the third letter of the word or non-word had been. This was to avoid making letter position into an extra variable. Future experiments may look at this factor. The third letter position was chosen because the two inner letters in a four letter word are subject to the maximum amount of lateral masking. The third letter position was chosen rather than the second because the second letter tended to mostly be one of the five vowels. This did not allow for much variability within the choice of letters.

Background Colours

The words were presented in two different colour conditions: On a white background or on a red background. We presented the stimuli in blocks so that all of the stimuli presented against a white background were viewed in one block and all the stimuli presented against the red background were in a separate block. We presented all stimuli of the same colour in one block so that participant's eye had time to adjust to the new contrast level during the practice trials for that block and so that their eyes did not need to adjust at the beginning of each trial. In the condition with the white background, the text was black and the background was white, giving the highest possible contrast between background and letters. In the condition with the red background, the background was red (hue = 0, saturation = 255, luminance = 128, R = 255, B = 0, G = 0) and the text was grey (hue = 170, saturation = 0, luminance = 128, R = 128, B = 128, G = 128).

The order of presentation of these blocks was randomised across participants to control for any order effects. All of the participants completed the task in the same room, under the same lighting conditions. The only illumination in the room was from an overhead strip light (luminance level approximately 600 Lux).

Participants

There were 20 participants in total. All of the participants were right handed and were native English speakers. All were undergraduates at the University of Edinburgh. All had normal or corrected-to-normal vision. None of the participants had any history of reading or visual problems.

Procedure

The participants were instructed to fixate on a gap between two vertical lines in the centre of the screen. This fixation point was present on the screen for 2000ms. A letter string then appeared for 50ms. The letter stings always appeared on the central fixation point within foveal range. After the stimulus had been on the screen for 50ms, a mask consisting of “OXOX” appeared on the screen covering the area where the stimulus item had been. The mask was present on the screen for 100ms. This was followed by a target letter that was present until the participant had made their response. As soon as the participant made their response, the fixation point for the next trial appeared. Participants had to indicate whether the target letter that they had just viewed had been part of the letter string (word or non-word) that had appeared before it. Using the index finger of each hand, the participants had to press one of two buttons to indicate whether the letter had been present or not. The hand that each participant used to respond to a “Yes” decision or a “No” decision was counterbalanced across participants. Reaction times and error rates were recorded. There were eight practice trials to begin to make sure that the participant had correctly understood the procedure and to enable their eyes to adjust to the different colour backgrounds.

6.1.2 Results

The data were analysed using analysis of variance (ANOVA). There was one repeated-measures within-participants and between-items factor: Context (Real words and Non-words) and one within-participants and within-items factor: Background Colour (White background and Red background). Reaction time data measured in milliseconds were analysed using a 2 (Context) X 2 (Background Colour) repeated measures ANOVA. Error rates were analysed using a 2 (Context) X 2 (Background Colour) repeated measures ANOVA. Items that participants made errors on were excluded from the reaction time analysis as were items that had a reaction time that was more than 2.5 standard deviations above or below the mean for that participant for that particular type of item. These values were replaced by the mean reaction time score for that participant for that particular type of item. A total of 496 items were replaced in the reaction time analysis giving a replacement rate of 62%. This high replacement rate was due to a high number of errors made on the task possibly as a result of the fast presentation time (50ms).

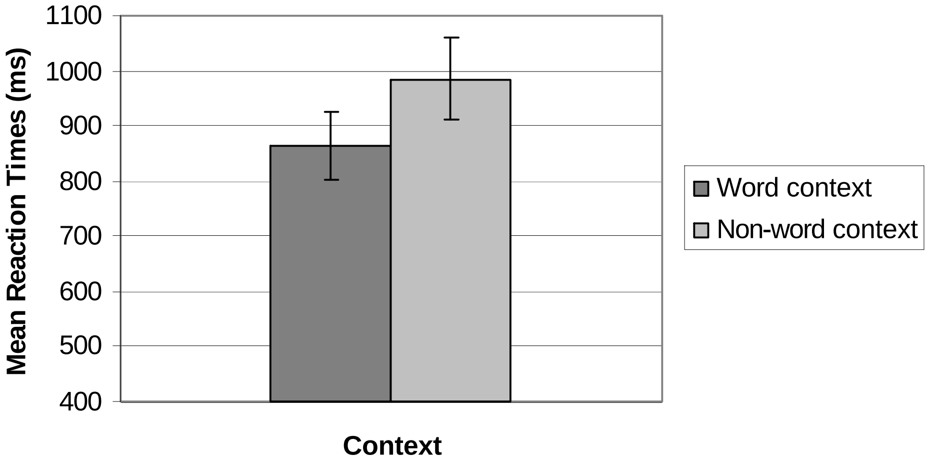
Reaction Times

Table 13: Mean reaction time scores in milliseconds (ms) for participants to correctly recognise that an individual letter was present in either a real word context or a non-word context when viewed with either a white background or a red background

	Background Colour	
Context	White	Red
Word Context	848.5	879.6
Non-word Context	967.9	1002.2

We successfully replicated the word superiority effect by showing that participants were faster to recognise that an individual letter had been presented in the context of a real word (864.1 ms) compared to when the letter had been presented in the context of a non-word (985.1 ms). There was an effect of Context, significant both by-participants and by-items (F_1 (1, 19) = 8.77, *MSE* = 33405.05, $p< 0.01$; F_2 (1, 9) = 23.73, *MSE* = 6349.80, $p= 0.001$) (see Figure 30).

Figure 30: Mean reaction times measured in Milliseconds (ms) for participants to correctly judge that a single letter was present in either a real word context or in a non-word context.



The word superiority effect was not attenuated as predicted by the presence of a red background. The interaction between Context and Background colour was non-significant, both by-participants and by-items (both *Fs* < 1). We did not find an overall effect of background colour. Background colour was non-significant both by-participants and by-items (both *Fs* < 1) such that overall there was no significant difference in reaction times to items presented with a white background compared to items presented with a red background.

Error Rates

The total percentage of errors made was 62%. Table 14 shows the average number of errors made by participants in each condition.

Table 14: Percentage of errors made by participants when recognising the presence of individual letters in either a real word context or in a non-word context when viewed with either a white background or a red background

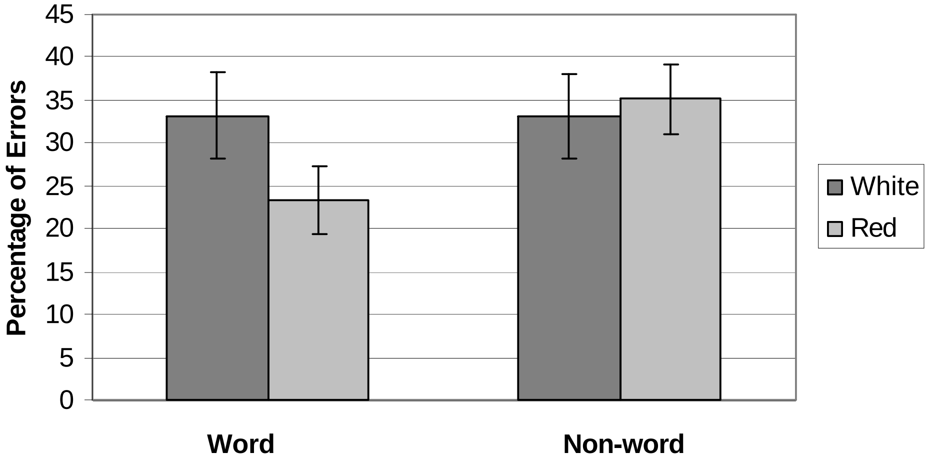
	Background Colour	
Context	White	Red
Word Context	33.2	23.3
Non-word Context	33.1	35.2

We did not find a significant difference between the number of errors made on detecting the presence of a letter in the real word context compared to in the non-word context. Context was non-significant both by-participants and by-items (both Fs < 1).

There was no overall effect on error rates of viewing the stimuli against a red background. Background colour was non-significant both by-participants and by-items (both Fs < 1) such that there was no significant difference between the amount of errors made on recognising the presence of an individual letter in a stimulus item when the item was viewed with a white background compared to when it was viewed with a red background.

The interaction between Context and Background colour was significant by-participants but non-significant by-items (F_1 (1, 19) = 8.14, *MSE* = 0.88, *p*= 0.010; F_2 (1, 9) = 3.45, *MSE* = 4.18, *p* = 0.096) such that the colour of the background that the stimuli was presented against had no effect on the number of errors made when detecting the presence of an individual letter within the context of a non-word. However, when detecting an individual letter within the context of a real word there were significantly fewer errors made when the background was red (23.3 %) compared to when the background was white (33.2 %). With the white background, there was no difference in the number of errors made in the real word context (33.2 %) compared to the non-word context (33.1 %) (see Figure 31).

Figure 31: Percentage of errors made by participants when recognising words and non-words presented either against a white background or a red background



6.1.3 Discussion

This experiment investigated whether disrupting the activity of the magnocellular visual pathway and therefore disrupting dorsal stream processing would significantly impact on the processing of the ventral stream. Previous research has shown that it is easier to recognise that a single letter had been previously presented in the context of a real word compared to when the letter was presented in the context of a non-word immediately prior to a forced-choice decision (Grainger et al., 2003; Hildebrandt et al., 1995; Reicher, 1969). This is the word superiority effect. The word superiority effect must be a product of ventral stream processing as only the ventral stream is able to recognise words as whole units. For the word superiority effect to occur, the word must be recognised before the constituent letters. In the present experiment stimuli were presented either against a white background or against a red background. The red background is designed to selectively inhibit the activity of the dorsal processing stream in an attempt to establish whether a deficit in sub-lexical processing impacts on lexical processing.

Following previous research (Grainger et al., 2003; Hildebrandt et al., 1995; Reicher, 1969) we predicted that under normal, high-contrast conditions where stimuli were presented on a white background there should have been a word superiority effect. Reaction times to isolated letters in a forced choice task should be faster to letters that had been presented in the context of a real word compared to letters that had been presented in the context of a phonologically, and orthographically legal non-word. Our data supports this prediction. Participants were faster to respond to letters that had been presented in the context of a word compared to letters that had been presented in the context of a non-word. Looking at the error rates, there were no significant differences in the number of errors made to letters that had been presented in a real word context compared to letters that had been presented in a non-word context. This means that the results cannot be explained by a speed-accuracy trade-off. Participants were as accurate at responding to letters in words as they were to respond to letters in non-words. However, the reaction time data shows that participants were significantly faster to identify a letter that had been presented in the context of a real word.

Our second hypothesis was that when the words were presented on a red background the word superiority effect would be attenuated. The results of the present experiment did not support this hypothesis. Based on previous research, the red background was designed to inhibit the activity of the magnocellular pathway (Bedwell, Brown, & Miller, 2003; Breitmeyer & Breier, 1994; Breitmeyer & Williams, 1990; Brown & Koch, 2000; Chapman et al., 2004; Edwards et al., 1996; Pammer & Lovegrove, 2001). We proposed that the use of a red background would inhibit the activity of the magnocellular pathway and, as a consequence, the dorsal processing stream would be inhibited. We had predicted that this would have a negative impact on the ventral processing stream and that this would reduce the word superiority effect. There was no overall effect of using the red background. There was no difference in either reaction times or error rates for items in the high-contrast, black and white condition compared to items in the red background condition. If the red background did inhibit the activity of the magnocellular visual pathway then this did not affect the speed or the accuracy with which the participants responded to the items.

There was no effect of presenting stimuli on a red background on either context level. There were no significant differences in either reaction times or error rates for recognising letters that had been in either a word context or a non-word context either with a white background or with a red background. We had predicted that participants would show the normal word superiority effect when words were presented on a white background with faster reaction times and lower error rates to letters that had been presented in the context of a real word compared to letters that had been presented in the context of a non-word. We predicted that the pattern of results would be different when the words were presented on a red background. We predicted that, with a red background, there would be no difference in either reaction times or error rates to letters that had been presented in the context of a real word compared to letters that had been presented in the context of a non-word. The results show that there was no interaction between the variables of context and background colour so this hypothesis is not supported by the present experiment.

One possible explanation for this null result is that although the activity of the magnocellular pathway may have been inhibited by the red background, it might not have significantly affected the task as all of the stimuli in the present experiment were presented at a central fixation point. When items are presented centrally they are only received by the foveal region of the retina. The foveal samples the central 1 – 2° of the visual field around the fixation point. The predominant type of retinal ganglion cell that arises from this region of the retina is the parvocellular retinal ganglion cell. The parvocellular pathway is the other of the two main visual pathways that are responsible for detecting visual stimuli. The magnocellular retinal ganglion cell is the predominant type of cell arising from the parafoveal region of the retina. It is possible that to obtain an effect on stimuli perception of selectively inhibiting the activity of the magnocellular visual pathway the stimuli should be presented to the parafoveal area of the visual field. If the parafoveal area of the visual field relies mostly on the magnocellular pathway for stimuli perception then inhibition of the magnocellular pathway should be most evident when items are presented to this area of the visual field.

To test this idea, the next experiment will again use a red background with the same parameters as in the present experiment in an attempt to examine the effect of inhibiting the magnocellular visual pathway on perception of stimuli in both centrally presented conditions and in parafoveally presented conditions. The next experiment will be a lexical decision experiment in which participants are required to make a decision as to whether a letter string is a real word or a non-word. If the magnocellular pathway is important for facilitating lexical processing then it can be expected that participants' performance on real words should be influenced by the red background whereas participants' performance on non-words should remain relatively unchanged regardless of background colour. As the magnocellular pathway is the predominant pathway arising from the parafoveal region of the retina, it is predicted that the word – non-word effect will be significantly more influenced by changes in background colour when the items are presented parafoveally compared to when they are presented foveally at a central fixation point.

6.2 The Effect of magnocellular inhibition on the Recognition of Words and Non-words in foveal and parafoveal vision

In the previous experiment we demonstrated the presence of the word superiority effect and successfully replicated the findings of previous research on this topic (Grainger et al., 2003; Hildebrandt et al., 1995; Reicher, 1969). However, when we attempted to block this effect by selectively inhibiting the magnocellular visual pathway we failed to find any significant differences between the white background conditions designed to replicate previous word superiority effect findings and the red background conditions designed to impede this effect by inhibiting the magnocellular pathway.

One possible explanation for the negative result in the previous experiment is that the effect of using isoluminant stimuli to block the magnocellular pathway might not lead to observable effects in foveal vision. In the previous experiment all of the items were presented on a central fixation point, meaning that they were only received and processed by the foveal region of the retina. The most common retinal ganglion cell type to arise from the retina in the foveal area is the parvocellular retinal ganglion cell which is specialised for detecting fine-grain and colour information in the visual field. The magnocellular retinal ganglion cell is the most common type of cell to arise from the parafoveal area of the retina. The parafoveal area of the retina samples outside of the central 2° of the visual field to a distance of approximately 15° of visual angle.

It is possible that in the previous experiment, because all of the stimuli items were presented on a central fixation point, even if the activity of the magnocellular pathway were inhibited this effect would not have been apparent in the task. Although there are magnocellular retinal ganglion cells arising from the central area of the retina, the main cell type is parvocellular (Dacey, 1994; Perry et al., 1984a; Polyak, 1941). Inhibiting the magnocellular pathway may disrupt parafoveal perception of stimuli more than foveal perception as magnocellular retinal ganglion cells are the predominant type of cell in the parafoveal/ peripheral regions of the retina whereas parvocellular retinal ganglion cells are the predominant type of cell in the fovea. Therefore, it is possible that foveal perception of stimuli may be adequately achieved through only the parvocellular pathway. In the present experiment, we propose that in order to affect the perception of stimuli by selectively inhibiting the activity of the magnocellular visual pathway the stimuli should be presented to the parafoveal area of the visual field. If the parafoveal area of the visual field is sampled mostly by the magnocellular pathway then the effect on stimuli perception of magnocellular inhibition should be most evident when items are presented to this area of the visual field.

In Experiment 6.1 we successfully replicated the word superiority effect showing that in a forced-choice task where the participant had to identify which of two letters had been presented the decision was faster when the letter had been presented in the context of a word compared to in the context of a non-word. However, we failed to find any effect of magnocellular/ dorsal stream inhibition on the word-superiority effect. In a similar study, Jordan and Patching (2004) demonstrated that the advantage of words over individual letters only applied to stimuli that were presented centrally. They found that single letters were faster than words when viewed in either the left visual field or in the right visual field. They suggested that these results imply that words in lateralised displays are processed differently to words that are directly fixated. Their results suggest that words that are viewed foveally are accessed differently to words viewed by the parafovea. The word-letter advantage in the centre of the visual field (foveal area) implies that the stimuli are being recognised by the lexical route. The reverse pattern in the left and right visual field displays (in the parafovea) implies that sub-lexical processing is responsible for parafoveal access of words.

As we have previously seen, skilled readers use both the ventral (lexical) and dorsal (sub-lexical) processing streams (Borowsky et al., 2006; Pugh et al., 1996, 2000; Sandak et al., 2004). It has been proposed that the ventral route is used to access familiar words that are stored in lexical memory (e.g., Pugh et al., 2000). Whole word orthographic representations are mapped onto complete phonological representations. Both magnocellular and parvocellular pathways input to the ventral stream (Ferrera, Nealey, & Maunsell, 1994; Nealey & Maunsell, 1994). The dorsal stream is used to process words when there is no lexical representation of the word encoded in memory. This is the route that is used when learning to read: the ventral route only develops as reading skill increases (Pugh et al., 1996, 2000; Sandak et al., 2004). Individual letters are mapped onto individual phonemes. Non-words have to be processed by the dorsal, sub-lexical route (Rastle & Coltheart, 1998) as they are novel stimuli and there cannot be any representation in lexical memory. Also, there is a much greater effect of word length for non-words suggesting a greater involvement of sub-lexical processing in non-words compared to words (Juphard et al., 2004; Weekes, 1997). Familiar words, both regularly spelled and exception, can be processed by the ventral, lexical route. It is believed that only the magnocellular pathway inputs to the dorsal stream (Maunsell, Nealey, & De Priest, 1990) though there may also be a small amount of parvocellular input (Maunsell et al., 1990). Processing by the dorsal route is more laborious and slower than processing by the ventral route (Paap & Noel, 1991). When using lexical processing, words are recognised more easily than letters. When using sub-lexical processing, words are processed incrementally and so there will be no word-letter advantage (Hildebrandt et al., 1995).

In the present experiment, we investigate the effect of magnocellular/ dorsal stream inhibition on lexical (ventral stream) processing and sub-lexical (dorsal stream) processing in the foveal and the parafoveal areas of the visual field. We compare the recognition times and error rates of responses to regular words (which can be processed either lexically or sub-lexically) and non-words (which can only be processed sub-lexically) in both central presentations and in right visual field (parafoveal) presentations. We chose to use only orthographically legal non-words in the non-word stimuli lists to ensure that the task was of sufficient difficulty to engage the participants' attention. The experiment is divided into two equal length parts; in one part the stimuli are presented against a white background and in the other part, the stimuli are presented against a red background. Although the magnocellular pathway is the predominant type of input to arise from the parafovea, there are also some parvocellular retinal ganglion cells in the parafovea (Dacey, 1984; Perry et al., 1984a; Polyak, 1941) so we used the red background to selectively inhibit the magnocellular pathway. As the dorsal stream is predominately magnocellular, inhibiting only the magnocellular pathway will allow us to determine the contribution of the sub-lexical processing of the dorsal stream to both foveal and parafoveal word recognition. A red background has been shown to inhibit the activity of the magnocellular pathway (see previous experiment for details) (e.g., Breitmeyer & Breier, 1994; Brown & Koch, 2000).

The present experiment uses a red background (with the same parameters that were specified in the previous experiment (see Section 6.1.1) to examine the effect of inhibiting the magnocellular visual pathway on the perception of stimuli by the dorsal processing stream in both the foveal and the parafoveal regions of the retina. This experiment is a lexical decision experiment in which participants are required to decide whether a letter string is a real word or a non-word.

As we are using a highly-skilled reading group, we predict, based on the findings of Borowsky and others (Borowsky et al., 2006; Pugh et al., 2000; Sandak et al., 2004) that the participants will be able to employ ventral stream processing to recognise real words faster than the non-words. The non-words can have no representation in lexical memory and so will be reliant on the slower sub-lexical, dorsal stream processing. Therefore, we predict that real words will be recognised faster than non-words.

Our second prediction, based on the finding of Jordan and Patching (2004) that the advantage of words over single letters is only present in directly fixated items, is that ventral stream, lexical processing is only operational in foveated items. Therefore, we predict that stimuli presented to the fovea will be recognised faster than stimuli presented to the parafovea.

Our third prediction, based on the fact that the magnocellular pathway is the predominant pathway to arise from the parafoveal area of the retina (Dacey, 1994; Perry et al., 1984a; Polyak, 1941) is that inhibition of the magnocellular pathway (by presenting the stimuli against a red background) will have the greatest impact on stimuli presented to the parafoveal area of the retina compared to stimuli presented to the foveal area of the retina. We predict that the red background will slow down lexical decisions and give rise to a greater number of errors for items presented parafoveally. The red background should have little impact on items presented foveally as the output from the fovea is mostly parvocellular (Dacey, 1994; Perry et al., 1984a; Polyak, 1941).

As real words can be processed by the ventral stream they should be recognised faster than non-words that rely on the dorsal stream (e.g., Borowsky et al., 2006) when the stimuli are presented centrally. Our fourth prediction is that if only dorsal stream processing operates in the parafovea as suggested by the findings of Jordan and Patching (2004) then there should be no difference between regular words and non-words in the parafoveal presentation position as both stimuli types will be relying on sub-lexical dorsal stream processing. Therefore, we expect an interaction between visual field presentation and item type (word or non-word).

Finally, we predict that the red background will produce a difference in reaction times and error rates for real words between the foveal and parafoveal presentation positions. If the real words depend on dorsal stream processing when they appear parafoveally, inhibiting magnocellular function and therefore dorsal stream processing will disrupt real word recognition in the parafovea. Real word recognition in the fovea will not be disrupted by the red background. As the non-words are always identified through sub-lexical processing through the dorsal stream, inhibition of the dorsal stream through using the red background will not affect parafoveally presented non-words more than foveally presented non-words.

6.2.1 Method

Design

This experiment used a lexical decision task to investigate how losing magnocellular pathway input affects responses to real words and orthographically legal non-words. We looked at the effect of three variables: Target Type, Visual Field, and Background Colour which were fully crossed leading to a 2 (Target Type) x 2 (Visual Field) x 2 (Background Colour) design. There were two levels of the variable “Target Type”: “Words” which are real words of regular spelling and of a frequency range of below 20 occurrences per million, and “Non-words” which are orthographically legal non-words. The variable of “Target Type” was crossed with the variable “Visual Field” which had two levels: “Fovea” in which stimuli items were presented to the centre of the visual field, and “Parafovea” in which stimulus items were presented to the right visual field parafovea. The variable of “Background colour” had two levels: “White” in which items were presented on a white background and “Red” in which items were presented on a red background. We measured reaction times and error rates. Each of the 24 participants was exposed to all twelve conditions.

Apparatus

To present the stimuli, a RM innovator Pentium 4 computer connected to an Iiyama Vision Master Pro 413 monitor with a 17-inch screen (refresh rate 74.999 Hz) was used. A Psychology software Tools Inc serial response box (model 200A) recorded participants’ responses.

Materials

The stimuli items were either real words or orthographically legal non-words of either four or five letters. Participants were shown 160 letter strings. Eighty of these were orthographically legal non-words and the other 80 were real words. Half of these items were experimental items and the other half were filler items. All of the stimuli were presented in Courier New font 16.

Non-word stimuli In the non-word stimuli set all of the items had orthographically legal onsets, orthographically legal bodies, only legal bigrams, and the same amount of syllables.

Real Word Stimuli In the real word stimuli set all of the items had regular spelling and were of a frequency range below 20 occurrences per million (word group frequency *mean* = 11.725, *mean deviation* = 1.969, *range* = 7). The words consisted of an equal number of nouns, verbs and adjectives.

Background Colours

The words were presented in two different background colour conditions: white background and red background. The presentation or the stimuli was counterbalanced across background presentation colour. In the condition with the white background, the text was black and the background was white, giving the highest possible contrast between background and letters. In the condition with the red background, the background was red (hue = 0, saturation = 255, luminance = 128) and the text was grey (hue = 170, saturation = 0, luminance = 128, R = 128, G = 128, B = 128). The order of presentation of these blocks was randomised across participants to control for any order effects. All of the participants completed the task in the same lab under the same lighting conditions. The only source of light in the room was an overhead strip light (approximate luminance level was 600 Lux).

Presentation Positions

Using a counterbalanced design, the letter strings were either presented on a central fixation point (foveal area of the visual field) or in the right visual field (parafoveal area of the visual field). We chose to present the items only to the right visual field parafovea and not the left visual field parafovea as the reading direction in English is from left to right and so the parafoveal preview originates in the right visual field. These stimuli were crossed with the two levels of the variable “background colour”: white or red background. Letter strings were either presented to the fovea which means that they were presented within the central 2° around the fixation point or they were presented to the right visual field parafovea which means that the first letter of the word was presented at 2.5° from the fixation point to ensure that the entire letter string fell only within the range of the parafovea. Participants sat at a distance of approximately 60 cm from the screen.

Participants

There were 24 participants in total. All of the participants were right handed. All were undergraduates at the University of Edinburgh. All had normal or corrected-to-normal vision. None of the participants had any history of reading or visual problems.

Handedness: Participants were given a modified version of Annett's handedness questionnaire (1967, 1970) to ensure that they were all right-handed.

Procedure

The task was to look at the letter strings that appeared on the screen and to make a decision as to whether the letters formed a real word or a non-word. The participants were instructed to fixate on a gap between two vertical lines at the centre of the screen. This fixation point was present on the screen for 2000ms. The fixation point disappeared after 2000ms and a letter string then appeared for 250ms. The letter stings could appear either in the right visual field parafovea or on the central fixation point within foveal range. After the stimulus had been on the screen for 250ms, a mask consisting of "XXXXX" appeared on the screen covering the area where the stimulus item had been. The mask remained on the screen until the participant had made a response. As soon as the participant made their response, the fixation point for the next trial appeared. Using the index finger of each hand, the participants had to press one of two buttons to indicate whether the stimulus was a word or a non-word. The hand that each participant used to respond to a particular type of stimuli (word or non-word) was counterbalanced across participants. Reaction times and error rates were recorded. Participants were given 10 practice trials to make sure that they had correctly understood the procedure and to give them time to adjust to the changes in background colour.

6.2.2 Results

The data were analysed using analysis of variance (ANOVA). There were two repeated-measures within-participants and within-items factors: Visual Field (foveal and parafoveal presentations) and Background Colour (white or red background) and one within-participants and between-items factor: Target Type (Real words and orthographically legal non-words). Reaction time data measured in milliseconds were analysed using a 2 (Target Type) X 2 (Visual Field) X 2 (Background Colour) repeated measures ANOVA. Error rates were analysed using a 2 (Target Type) X 2 (Visual Field) X 2 (Background Colour) repeated measures ANOVA. Items on which participants made errors were excluded from the reaction time analysis as were items that had a reaction time that was more than 2.5 standard deviations away from the mean for that participant for that particular type of item. These values were replaced by the mean reaction time score for that participant for that item type. A total of 414 data points were replaced giving a replacement rate of 10.8%.

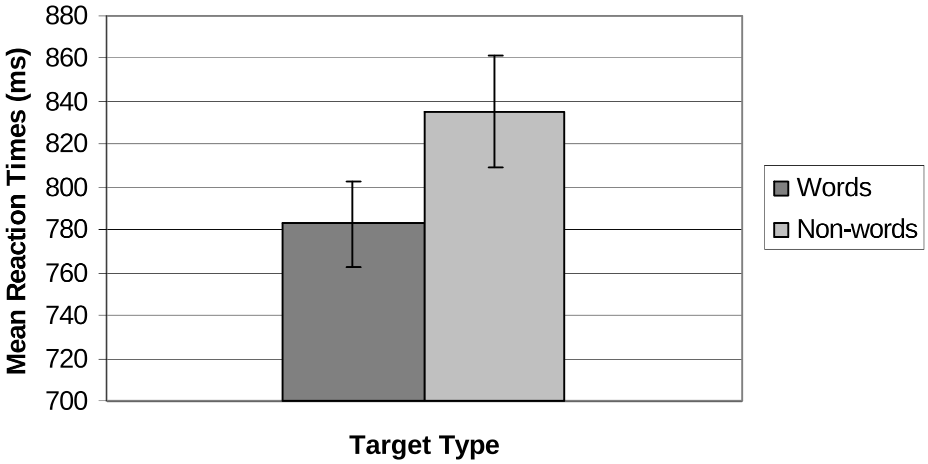
Reaction Times

Table 15: Participants' mean reaction time scores in milliseconds (ms) for real words and orthographically legal non-words, in both the foveal presentations and the parafoveal presentations, viewed against a white background and against a red background

	Background Colour Visual Field Presentation Position			
	White		Red	
Target Type	Foveal	Parafovea	Foveal	Parafovea
Words	701.8	793.7	753.5	881.6
Non-words	768.3	833.5	806.4	934.2

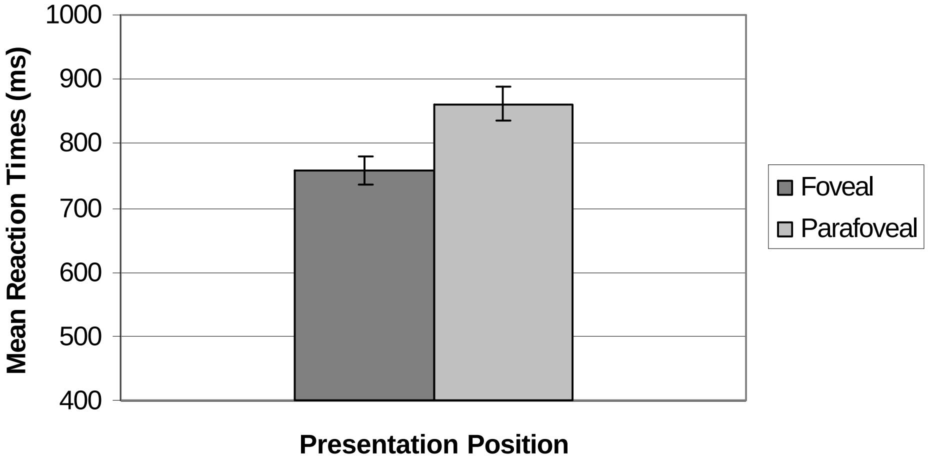
Our first prediction was that real words would be recognised faster than non-words as only real words can have lexical representations in lexical memory and so only real words can be processed by the ventral stream. Our findings support this hypothesis. Real words (782.7 ms) were recognised significantly faster than non-words (835.5 ms). Target Type was significant both by-participants and by-items (F_1 (1, 23) = 15.88, *MSE* = 8488.99, $p< 0.001$; F_2 (1, 9) = 45.14, *MSE* = 2317.65, $p< 0.001$) (see Figure 32).

Figure 32: Participants' mean reaction times measured in milliseconds (ms) to real words and non-words



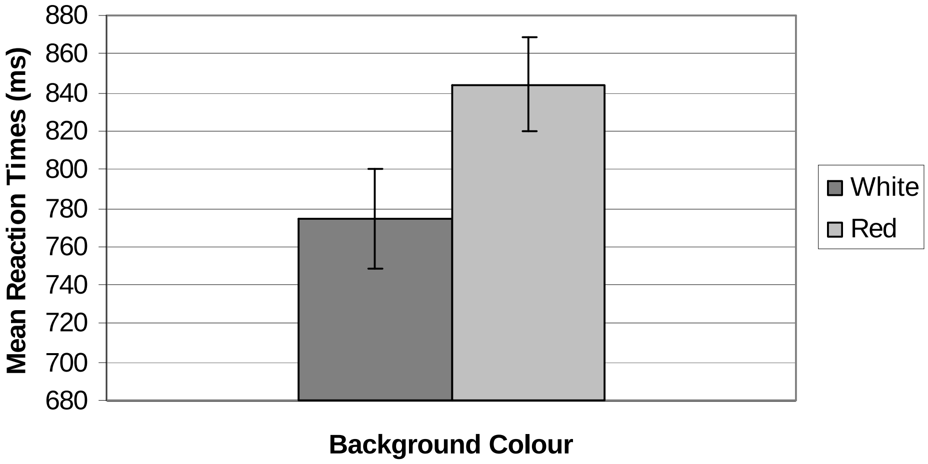
Secondly, we predicted that items that were presented to the area of the visual field that is received by the foveal area of the retina would be recognised faster than items presented to the area of the visual field that is received by the parafoveal area of the retina. Again, our results bear out this prediction. Items that were presented centrally (757.5 ms) were recognised significantly faster than items that were presented in the right visual field (860.8 ms). Visual field presentation position was significant both by-participants and by-items (F_1 (1, 23) = 36.45, *MSE* = 14036.19, $p< 0.001$; F_2 (1, 9) = 1078.26, *MSE* = 460.32, $p< 0.001$) (see Figure 33).

Figure 33: Participants' mean reaction times measured in milliseconds (ms) to items presented in the right visual field parafoveal area of the visual field compared to items presented at a central (foveal) presentation point



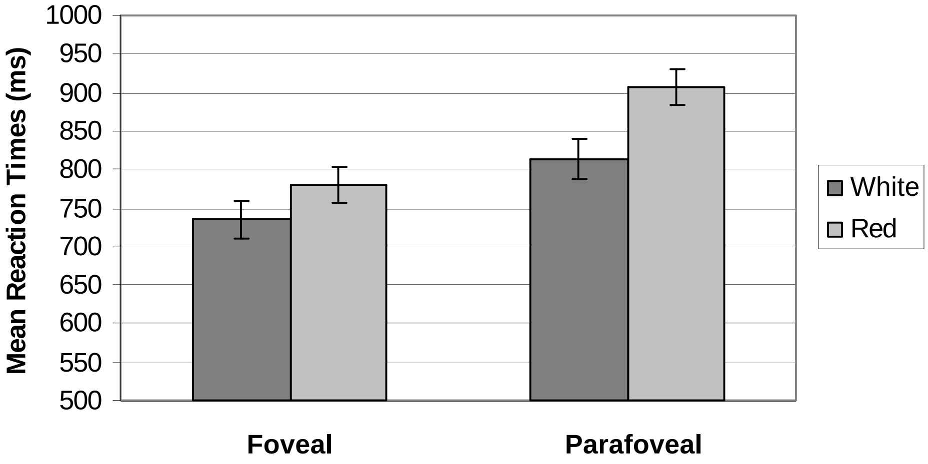
Our third prediction was that the red background (and therefore magnocellular inhibition) would have a greater impact on items presented parafoveally with there being little or no effect on items presented foveally. This is the pattern of results that we found. We found an overall effect of background colour with items that were presented against a white background (774.3 ms) being recognised faster compared to items presented against a red background (843.9 ms). Background Colour was significant by-participants and by-items (F_1 (1, 23) = 8.86, *MSE* = 26222.96, $p<$ 0.01; F_2 (1, 9) = 582.42, *MSE* = 413.72, $p<$ 0.001) (see Figure 34).

Figure 34: Participants' mean reaction times measured in milliseconds (ms) to items presented against a white background compare to against a red background



However, we also found that items presented to the parafoveal area of the visual field were more affected by the red background than items presented to the foveal area of the visual field providing support for our third prediction. The interaction between Visual Field and background colour was significant, both by-participants and by-items (F_1 (1, 23) = 6.69, *MSE*= 4369.06, $p < 0.02$; F_2 (1, 9) = 22.08, *MSE* = 497.41, $p < 0.001$). The background colour had less impact on items presented at the central presentation position. There were no significant differences in reaction times to items presented at the central fixation point with a white background compared to items presented with a red background. However, in the parafoveal presentation condition, items were recognised significantly slower when presented with a red background (907.9 ms) compared to when they were presented with a white background (813.6 ms) (see Figure 35).

Figure 35: Participants' mean reaction times measured in milliseconds to items presented at the central fixation point and the right visual field parafoveal presentation position with either a white background or a red background



Our fourth prediction was that real words would be recognised faster in foveal vision compared to in parafoveal vision but that there would be no difference between the two presentation positions for non-words. Our results do not support this hypothesis. We failed to find any significant differences between non-words and real words between the two visual field presentation positions. The interaction between Target Type and Visual Field was not significant, either by-participants or by-items (both *Fs* < 1) such that both words and non-words were recognised faster in foveal vision than in parafoveal vision.

Our final prediction was that the red background would disrupt the recognition of real words when they were presented parafoveally but not when they were presented foveally. If foveally viewed words are processed as lexical units and parafoveally viewed words are processed sub-lexically as proposed by Jordan and Patching (2004) then we expected the processing of real words only to be affected by magnocellular/ dorsal stream inhibition when they were presented parafoveally. Non-word processing should be equally affected by the red background in both foveal and parafoveal presentation positions as non-words must always rely on sub-lexical processing. However, our results do not support this hypothesis. We did not find any differences in the effect of background colour on real words compared to non-words. The interaction between Target Type and background colour was not significant, either by-participants or by-items (both *Fs* < 1) such that there was no significant difference in the effects of background colour (white or red) on reaction times to real words and orthographically-legal non-words. The three-way interaction between Target Type, Visual Field and Background Colour was non-significant, both by-participants and by-items (both *Fs* < 1) showing no significant differences between words and non-words in either the parafoveal presentation condition or in the central presentation condition, either viewed with a white background or viewed with a red background. All other effects and interactions were non-significant.

Error Rates

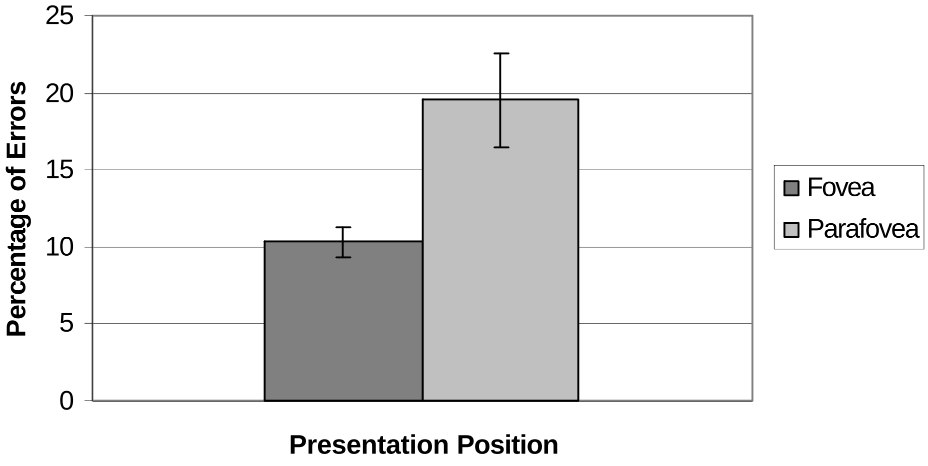
Table 16: Percentage of errors made by participants for real words and non-words in foveal and parafoveal presentation positions, viewed either against a white background or against a red background.

	Background Colour Visual Field Presentation Position			
	White		Red	
Target Type	Foveal	Parafovea	Foveal	Parafovea
Real words	10.4	15.0	10.0	30.8
Non-words	12.1	15.8	9.6	16.3

Although real words were recognised faster than non-words (supporting our first hypothesis) there was no difference in the number of errors made on real words compared to non-words. There was no evidence for a speed-accuracy trade off. Target Type was non-significant both by-participants and by-items (both *Fs* < 1).

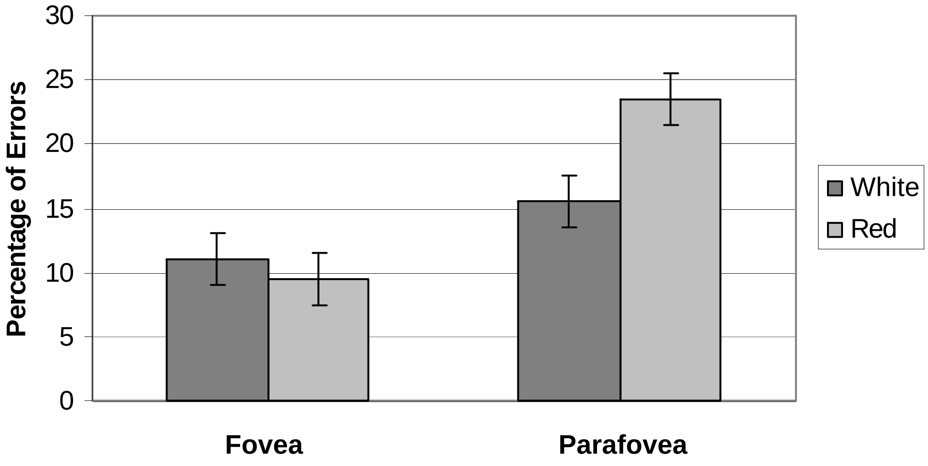
However, we did find that there were significantly more errors made on items presented in the parafoveal area (19.5 %) of the visual field compared to items presented in the foveal area of the visual field (10.3 %) (F_1 (1, 23) = 8.77, *MSE* = 4.39, $p < 0.01$; F_2 (1, 9) = 24.38, *MSE* = 1.89, $p < 0.001$) (see Figure 36). Not only were items recognised faster when they were presented foveally compared to when they were presented parafoveally (supporting our second hypothesis), they were also recognised more accurately in foveal vision.

Figure 36: Percentage of errors made by participants when responding to items presented at the foveal presentation point and at the parafoveal presentation point



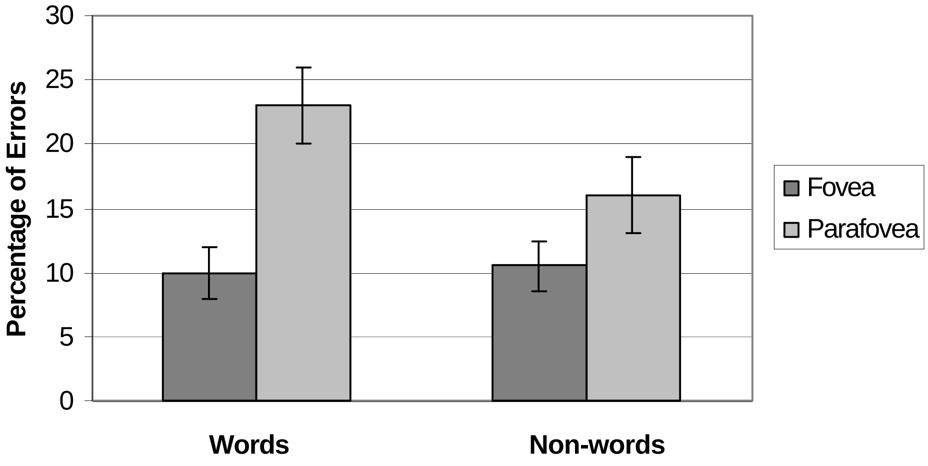
As well as finding that the red background slowed the reaction times to parafoveally presented items more than foveally presented items (supporting our third hypothesis), we also found that the red background affected the accuracy of recognition in the parafovea more than in the fovea. The red background had no effect on the accuracy of recognition of items presented at a central presentation point. The interaction between Visual Field and Background Colour was significant, both by-participants and by-items (F_1 (1, 23) = 4.79, *MSE*= 2.30, $p < 0.05$; F_2 (1, 9) = 11.16, *MSE* = 1.19, $p = 0.01$) such that there were no significant differences between the white background and red background conditions for items presented at the central fixation point. However, there were significantly more errors made on items presented at the parafoveal presentation position under red background conditions (23.5 %) compared to under white background conditions (15.5 %) (see Figure 37).

Figure 37: Percentage of errors made by participants on items that were presented at a central presentation point or at the right visual field parafoveal presentation point, viewed against either a white background or against a red background



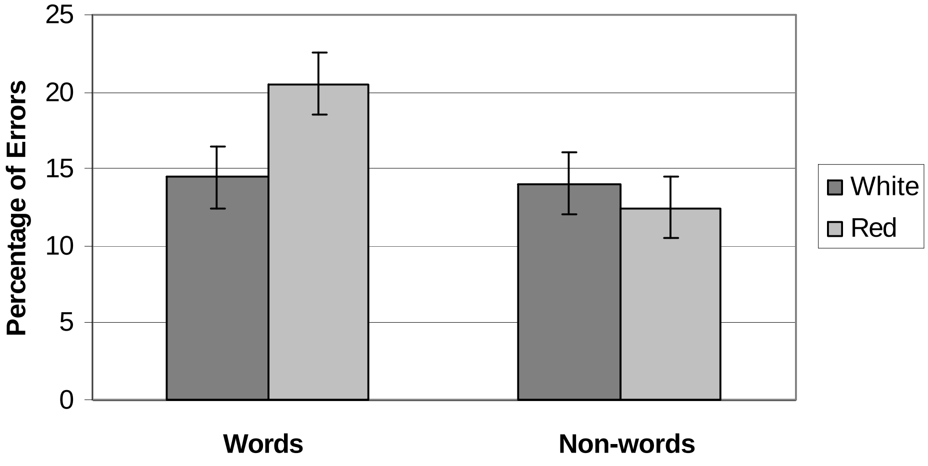
Our fourth prediction had been that real words would be recognised faster in the foveal presentation position than in the parafoveal presentation position but that there would be no difference between foveal and parafoveal presentation positions for non-words. Our reaction time results did not bear out this prediction. However, when we look at the number of errors made we can see a trend for real words to be recognised more accurately in the foveal presentations than in the parafoveal presentations suggesting that there had been a speed-accuracy trade off. There was a trend for there to be a greater effect of parafoveal presentation on real words compared to non-words (F_1 (1, 23) = 1.64, *MSE* = 4.12, $p > 0.1$; F_2 (1, 9) = 6.65, *MSE* = 1.22, $p < 0.02$). There were a greater number of errors made on real words when they were presented parafoveally (23.0 %) compared to foveally (10.0 %). There was a lesser effect on the number of errors made between viewing non-words in the foveal presentation position (10.5 %) compared to the parafoveal presentation position (16 %). (see Figure 38).

Figure 38: Percentage of errors made by participants on words and non-words that were presented either at a central fixation point or at the right visual field parafoveal presentation point



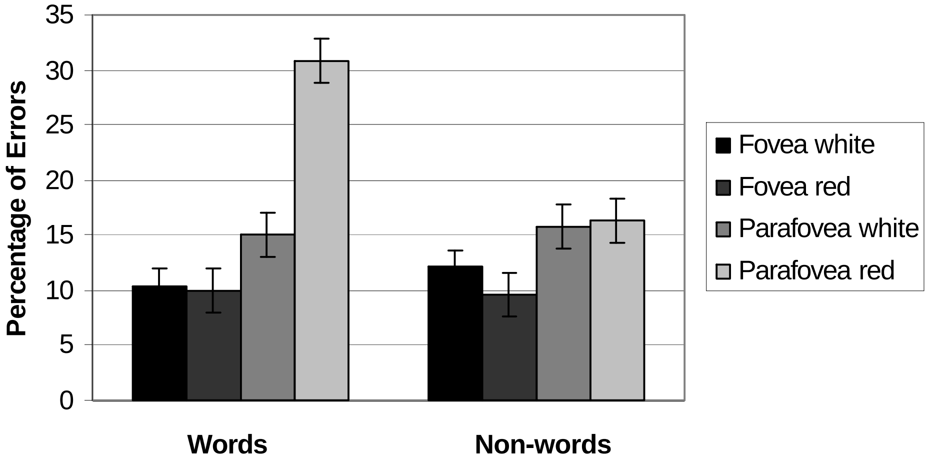
Our final prediction was that the red background would affect real word recognition in the parafovea but not in the fovea and that there would be no affect of the red background between foveal and parafoveal presentations for non-words. Our reaction time data did not support this but again the error data suggests that there was a speed-accuracy trade off. We found that real words were more affected than non-words by being presented against a red background (F_1 (1, 23) = 5.59, MSE = 1.64, $p < 0.03$; F_2 (1, 9) = 10.36, MSE = 1.06, $p < 0.01$) such that for real words there were significantly more errors made in the red background condition (20.5 %) compared to in the white background condition (14.5 %). For non-words however, there was no significant difference between the error rates in the white background condition compared to in the red background condition (see Figure 39).

Figure 39: Percentage of errors made by participants on real words and non-words presented either against a white background or against a red background



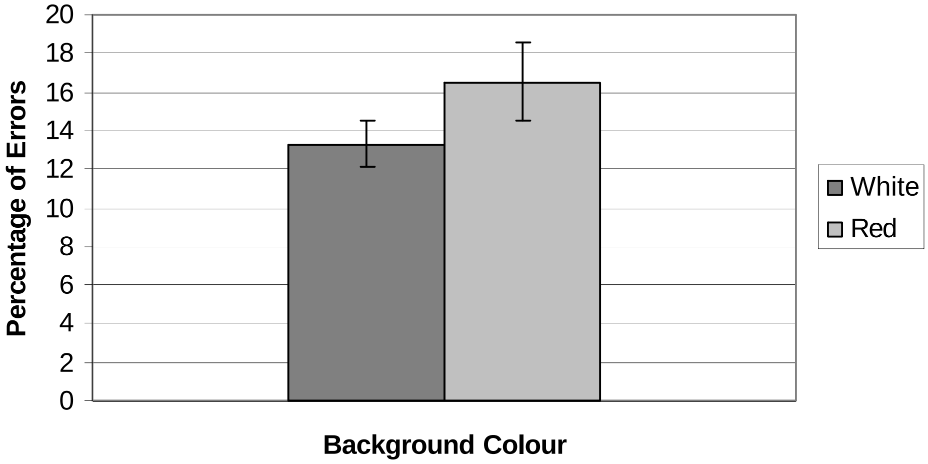
There was a trend for the accuracy of recognition of real words to be more affected by the red background when the words were presented parafoveally. The three-way interaction between Target Type, Visual Field and Background Colour was not significant by-participants but was significant by-items (F_1 (1, 23) = 2.17, *MSE*= 2.46, $p > 0.1$; F_2 (1, 9) = 4.79, *MSE* = 1.33, $p < 0.05$). The failure to reach significance by-participants means that we cannot be confident that there was an effect (see Figure 40).

Figure 40: Percentage of errors made by participants on words and non-words, presented at either the central presentation point or in the right visual field parafovea, against either a white background or against a red background



We also found an effect of background colour but this was not significant for all participants (F_1 (1, 23) = 2.20, *MSE* = 5.33, $p < 0.1$; F_2 (1, 9) = 8.19, *MSE* = 0.78, $p < 0.01$) such that there was a trend for the red background to elicit more errors compared to the white background (see Figure 41). All other effects and interactions were non-significant.

Figure 41: Percentage of errors made by participants on items presented with a white background compared to items presented with a red background



6.2.3 Discussion

The present experiment investigated the effect of inhibiting the magnocellular visual pathway on the perception of stimuli by the dorsal and ventral processing streams in both the foveal and the parafoveal regions of the retina. We tested this by looking at the differences in participants' ability to recognise both regularly-spelled real words (ventral or dorsal processing stream) and non-words (only dorsal processing stream) under conditions that allowed both processing streams to be active (white background) compared to conditions specifically designed to inhibit the activity of the magnocellular pathway (red background). Based on previous research (Borowsky et al., 2006; Pugh et al., 2000; Sandak et al., 2004) we predicted that regularly spelled words (which can be processed by the ventral stream) would be recognised faster than non-words (which have to be processed by the slower dorsal stream). The results of the present experiment support this hypothesis. Real words were recognised faster than non-words supporting the idea that skilled readers can use ventral stream processing to recognise real words but have to rely on the slower dorsal stream to recognise non-words. Real words can be recognised as whole units: non-words have to be incrementally assembled and are therefore slower to be recognised.

Based on the result of Jordan and Patching (2004) that indicated that the word-letter advantage only exists when viewing items in the centre of the visual field (and therefore ventral stream processing only operates in the area of the visual field that is viewed by the fovea), we predicted that items viewed in the fovea would be recognised faster, and more accurately than items viewed in the parafovea. Our results partially support this hypothesis. Overall, items presented to the fovea were recognised faster and more accurately than items presented to the parafovea. However, we did not find an interaction between item type (word and non-word) and visual field presentation position. If ventral stream processing could only occur on items that were presented foveally then we would have predicted that real words would have been recognised faster in the fovea compared to the parafovea. When the real words were presented parafoveally they should have been processed sub-lexically by the dorsal stream and therefore been slower. There should have been no effect on non-words between foveal and parafoveal presentation positions. However, this interaction was non-significant suggesting that there was no difference in the processing of regular words between the foveal and parafoveal presentation conditions. This suggests that either regular words were being processed by the ventral stream when they appeared both foveally and parafoveally (and therefore contradicting Jordan & Patching's (2004) findings that only sub-lexical processing occurs parafoveally) or that regular words were being processed by the dorsal stream in both presentation positions. This may have been a possibility. All of the words in this experiment were low frequency. As a result of this there will have been less exposure to these words and so it could be claimed that there is a weaker lexical representation of these words in lexical memory. This may encourage reliance on the dorsal stream as regular words can be processed by either stream.

As predicted, the parafoveal area of the visual field was found to be more severely affected by the inhibition of the magnocellular pathway compared to the foveal area. We predicted that because the magnocellular pathway is the predominant type of pathway to arise from the parafoveal area of the retina (Dacey, 1994; Perry et al., 1984a; Polyak, 1941) that selectively blocking the magnocellular pathway would lead to a decrease in performance in the parafoveal, compared to the foveal, area of the visual field. The results support this hypothesis. The red background lead to slower reaction times and higher errors rates compared to the white background but only for items that were presented parafoveally. There was no effect of background colour on items that were presented foveally. This result demonstrates that the parafoveal area of the visual field is more affected than the foveal area of the visual field by the inhibition of the magnocellular pathway. This supports the idea that the magnocellular pathway is the essential to parafoveal viewing but not so essential to foveal viewing.

Finally, we predicted that the red background would produce a difference in reaction times and error rates for real words between the foveal and parafoveal presentation positions. If the real words were dependant on the dorsal stream when they appeared parafoveally, inhibiting magnocellular function and therefore dorsal stream processing should have disrupted real word recognition but only in the parafovea. As the non-words are always identified sub-lexically through the dorsal stream, inhibition of the dorsal stream was not predicted to affect parafoveally presented non-words more than foveally presented non-words. The reaction time data do not support this hypothesis. The red background did not inhibit real word recognition in the parafovea. However, the error rate data partially support this hypothesis. There was a tendency for real words to produce more errors in the parafovea when the items were presented against a red background.

Overall, we did find support for the idea that skilled readers are able to use lexically-based ventral stream processing to access real words but that they have to rely on slower, sub-lexical processing by the dorsal stream to identify non-words as proposed by previous research (Borowsky et al., 2006; Pugh et al., 2000; Sandak et al., 2004). However, we only found partial support for the idea that lexically-based processing can only occur in centrally (and therefore, foveally) presented words as suggested by Jordan and Patching (2004). If this had been the case then we would have expected real words to have been recognised faster in foveal presentations compared to parafoveal presentations but no difference for non-words between foveal and parafoveal presentation positions. This was not the case. We did not get a significant interaction. However, we did find that there was a tendency for real words to produce more errors when they were presented parafoveally compared to foveally but no difference for the amount of errors made on non-words between the foveal and parafoveal presentation positions. Based on this result, we propose an alternative account of the distribution of the dorsal and ventral processing streams across foveal and parafoveal visual field areas. We describe this account in detail in the final chapter after we have presented the findings of the last experiment. In the final experiment, we look at the effect of inhibiting dorsal stream functioning on regularly-spelled words (which can be processed by either the dorsal or ventral streams), and exception words (which are thought to rely exclusively on the ventral processing stream) in both the fovea and the parafovea.

6.3 The Effect of magnocellular inhibition on the Recognition of regular words and exception words in foveal and parafoveal vision

In the previous experiment (6.2) we investigated the effects of inhibiting dorsal stream functioning (by disrupting the magnocellular pathway) on the recognition of regularly spelled words and non-words. Both of these types of stimuli can be processed sub-lexically by the dorsal stream but only the regular words can be processed lexically by the ventral stream (Borowsky et al., 2006; Pugh et al., 2000; Sandak et al., 2004). Based on this research we had predicted that real words (which can be processed as lexical units by the ventral stream) would be recognised faster than non-words (which have to rely on sub-lexical, dorsal stream processing). In experiment 6.2 we found that real words were processed faster than non-words supporting the idea that real words can be recognised by the lexical route but non-words have to be incrementally assembled by the sub-lexical route and so are processed slower. The findings of experiment 6.1 also provide support for the hypothesis that skilled readers can process real words as whole units. We successfully replicated the word superiority effect (Grainger et al., 2003; Hildebrandt et al., 1995; Reicher, 1969) showing that, at least in centrally presented stimuli, words are recognised faster than their component letters. We also demonstrated that the dorsal stream does not appear to have a major contribution to the processing of centrally-presented words in this type of task when the participants are readers with a high level of skill.

Jordan and Patching (2004) showed that the word-letter advantage only occurs in the centre of the visual field. In left and right visual field presentations they found a letter-word superiority effect. Related to this finding, we found in experiment 6.2 that items were recognised faster in the fovea than in the parafovea. Taken together, these two findings suggest that ventral stream processing occurs in the fovea and dorsal stream processing occurs in the parafovea. However, if this was the case we would have expected regular words (processed by the ventral stream) to be recognised faster than non-words (processed by the dorsal stream) and for there to be no difference in speed of processing between regular and non-words when they were presented parafoveally and therefore would both be dependent on dorsal stream processing. This is not what we found. We found no interaction between word type and visual field presentation position. However, we did find that there was a tendency for participants to be more accurate at recognising real words when they were presented foveally compared to when they were presented parafoveally. There was no effect of visual field presentation on the number of errors made on non-words.

However, if the conclusions of Jordan and Patching are correct and parafoveally viewed words are limited to sub-lexical processing by the dorsal stream this would explain why magnocellular inhibition had no impact on the word superiority effect in experiment 6.1 as all the stimuli in that experiment were presented centrally. Based on previous findings (Breitmeyer & Breier, 1994; Brown & Koch, 2000; Chapman et al., 2004), we inhibited the magnocellular pathway by presenting stimuli on a red background. This should inhibit dorsal stream processing as input to the dorsal stream is believed to be predominately magnocellular (Maunsell, Nealey, & De Priest, 1990). The previous experiment (6.2) investigated the effect of magnocellular-dorsal stream inhibition on the recognition of regular words and non-words. Non-words have to be processed sub-lexically (Rastle & Coltheart, 1998) whereas regular words can be processed by either route (Borowsky et al., 2006; Pugh et al., 1996, 2000; Sandak et al., 2004). As the magnocellular pathway is the predominant visual pathway to arise from the parafovea (Dacey, 1994; Perry et al., 1984a; Polyak, 1941), magnocellular inhibition should be more evident in parafoveal presentation conditions. In experiment 6.2 we found that magnocellular inhibition only slowed responses to items that were presented to the parafovea and also led to more errors being made in the parafoveal presentation positions. There was no effect of magnocellular inhibition on items that were presented centrally to the foveal area of the visual field.

However, the dorsal-ventral, fovea-parafovea link is less clear. Overall, we had an effect of magnocellular inhibition: responses to items against a red background were slower and less accurate, suggesting heavy dorsal stream involvement. We had predicted that dorsal stream inhibition would lead to a greater difference in responses to regular words and non-words when they were presented against a red background (when the magnocellular pathway was inhibited) compared to when they were presented against a white background (with the magnocellular, and therefore, dorsal stream functioning optimally). Although the dorsal stream would have been inhibited, the ventral stream should still have been functioning optimally and so there should have been no difference in speed of processing between real words when they were presented against the white background compared to when they were presented against the red background. However, as the red background inhibits the dorsal pathway non-word processing should have been inhibited and we would have expected there to be a greater difference in speed of processing between words and non-words when they were presented against the red background. Although we did not find this interaction when we looked at reaction times, we did find that more errors were made on real words when they were presented against a red background compared to against a white background.

All of the words used in experiment 6.2 were low frequency. It has been proposed that the lexical route to word recognition only develops after a certain level of reading skill has been attained and words have been established in lexical memory (Pugh et al., 2000; Sandak et al., 2004). When learning to read, words have to be processed incrementally by the dorsal route until they become familiar enough to be recognised as whole units. There is a great deal of evidence to suggest that high frequency words are processed more easily than low frequency words suggesting that there may be variance in the degree of ventral stream involvement depending on how familiar the words are. For example, low frequency words show greater effects of word length than high frequency words (Content & Peereman, 1992) and commonly, high frequency words do not show any effect of word length (Weekes, 1997). The much greater effect of word length on non-words (Weekes, 1997) also suggests that the magnitude of the length effect is related to the amount of sub-lexical processing that is involved. The stronger the representation is in lexical memory, the less sub-lexical processing is required. Therefore, non-words that can have no memory trace (as they have never been encountered before) will require maximal sub-lexical processing and high frequency real words will require the least. Based on this argument, low frequency regular words may rely more heavily on dorsal stream processing than on ventral stream processing. Exception words cannot be processed by the sub-lexical dorsal route as they do not have regular spelling-to-sound mappings. They must always be processed lexically by the ventral route. This may explain why poor readers and dyslexics have difficulties when reading exception words as beginner readers and dyslexics do not have an adequately developed ventral route (De Luca et al., 2002; Spinelli et al., 2005; Ziegler et al., 2003; Zoccolotti et al., 2005).

The results of experiment 6.2 showed that there was no effect of magnocellular inhibition on either speed or accuracy of processing for items that were presented foveally. However, magnocellular-dorsal stream inhibition slowed responses to, and elicited a greater number of errors on items that were presented parafoveally. This suggests varying degrees of sub-lexical processing. As there were no differences in response times between words and non-words (although there were a greater number of errors made on real words with magnocellular inhibition) it appeared that some of the readers were largely dependent on dorsal stream processing. There is a possibility that this may have been a product of the task: only regular words and non-words were shown to the participants. Both of these items types can be processed by the dorsal stream. Also, low frequency regular words may not have a very strong representation in lexical memory and so may rely more heavily on the dorsal route. To investigate this idea further, in the present experiment we compare regular words and exception words. We will use only low frequency words again to minimise the impact of the strength of the lexical representation in memory. We ask the question: if the degree of exposure to the word is controlled for, will there be differences between words that have to be processed by the lexical ventral route and words that can be processed by the dorsal route? If there is a weaker lexical representation (as the words are low frequency) will there be a greater reliance on the dorsal processing route when this route is available?

We present regularly spelled words and exception words to both the foveal and the parafoveal areas of the visual field either against a white background (with both dorsal and ventral routes functioning optimally) or against a red background (with the dorsal route inhibited). All of the words (both regular and exception) that are used in this experiment were low frequency. We present an equal number of non-words as filler items and participants have to make a decision as to whether the letter strings are real words or non-words. As in the previous two experiments, we use a red background to impair magnocellular function (see experiment 6.1 for details on methodology). Given that low frequency words show greater word length effects than high frequency words (Content & Peereman, 1992) and that high frequency words often show no effects of word length (Weekes, 1997) this suggests that there is a greater inclination to rely on the dorsal processing stream to recognise less familiar words.

Firstly, we predict that there will be no difference in either reaction times or error rates between regular and exception words when they are presented foveally but that there will be a greater number of errors made on exception words compared to regular words when they are presented parafoveally. This prediction is based on the study of Jordan and Patching (2004) which suggests that all centrally presented words are processed by the ventral stream. As all of the words are low frequency we predict that they will have similar strengths of lexical representation in lexical memory. Therefore, we predict that there will be no differences between responses to the two word types when they are presented centrally. Jordan and Patching’s study also suggests that parafoveally viewed words are processed by the dorsal stream. Therefore, our second prediction is that if parafoveally viewed words can only be processed sub-lexically then there will be a greater number of errors made on exception words that are presented parafoveally as these words cannot be correctly recognised by incremental sub-lexical processing as they do not have regular grapheme-to-phoneme mapping. There will be no difference in the number of errors made on regular words between the foveal and parafoveal presentation positions as these words can be processed by both the dorsal and ventral streams (Borowsky et al., 2006; Pugh et al., 1996, 2000; Sandak et al., 2004).

Our third prediction is that regularly spelled words will be recognised faster when they are presented to foveal vision compared to when they are presented to parafoveal vision. If, as Jordan and Patching conclude, foveated words are processed by the ventral stream and parafoveally viewed words are processed by the dorsal stream then we predict that when regular words are viewed foveally they will be recognised using the faster ventral stream but when they are viewed parafoveally they will be recognised by the slower dorsal stream. There will be no difference in reaction times to exception words between the foveal and parafoveal presentation positions.

As a red background inhibits magnocellular functioning (Breitmeyer & Breier, 1994; Brown & Koch, 2000; Chapman et al., 2004) and the dorsal stream is allegedly composed of mostly magnocellular input (Maunsell, Nealey, & De Priest, 1990) then if Jordan and Patching were correct in assuming that processing in parafoveal vision is sub-lexical (dorsal stream) then we would predict that the processing of regular words would be impaired most when they are presented parafoveally against a red background. Our fourth prediction is that regular words will be processed slower and will elicit more errors when they are presented parafoveally against a red background compared to when they are presented parafoveally against a white background. Exception words will not be affected by magnocellular - dorsal stream inhibition as exception word processing is thought to rely exclusively on the ventral stream. Therefore, there should be a similar pattern of results for exception words in foveal and parafoveal vision when viewed against a white background or a red background.

6.3.1 Method

Design

This experiment used a lexical decision task to investigate the effect of a red background on the recognition of regularly spelled words and exception words that were presented in the both the foveal, and the parafoveal area of the visual field. We looked at the effect of three variables: Regularity, Visual Field, and Background Colour which were fully crossed leading to a 2 (Regularity) x 2 (Visual Field) x 2 (Background Colour) design. There were two levels of the variable "Regularity": "Regular" which were regularly spelled words and "Exception" which were words with irregular spelling. The variable of "Visual Field" had two levels: "Fovea" in which stimuli items were presented to the centre (foveal area) of the visual field, and "Parafovea" in which stimuli items were presented to the right visual field parafovea. The variable of "Background Colour" had two levels: "White" in which items were presented against a white background and "Red" in which items were presented on a red background. Each of the 24 participants was exposed to all eight conditions.

Apparatus

To present the stimuli, we used a RM innovator Pentium 4 computer connected to an Iiyama Vision Master Pro 413 monitor with a 17-inch screen (refresh rate 74.999 Hz). A Psychology software Tools Inc serial response box (model 200A) was used to record participants' responses.

Materials

Using a counterbalanced design, participants were shown 160 letter strings that consisted of four or five letters. We had to use words of different lengths to ensure that there were enough available exception words in the appropriate frequency range. Word length was counterbalanced across the word lists. Eighty of these items were real word experimental items. The other 80 items were non-word filler items. The stimuli were presented either at the central presentation point (foveal presentation) or in the right visual field (parafoveal presentation). These stimuli were crossed with the two levels of Background Colour: White background and red background. All of the stimuli were presented in Courier New font 16.

Real Word Stimuli The words that were used as experimental items were controlled for frequency as frequency was not a factor in this experiment. Of the 80 real word experimental items, 40 had regular spelling and 40 had irregular spelling. Within each list, there were an equal number of nouns, verbs and adjectives to counterbalance for any effect of word class. Each participant saw a total of 160 items across the four conditions. Eighty of these were real words and the other 80 were non-word filler items. The words used in the experiment were taken from the British National Corpus (BNC). Words were excluded if they were plurals, were inflected or were proper nouns. All of the low frequency words were below 20 occurrences per million. The two word groups were matched for mean frequency and range of frequencies (regular word group *mean* = 11.725, *mean deviation* = 1.969, *range* = 7; exception word group *mean* = 10.98, *mean deviation* = 1.318, *range* = 10). The definition of word regularity was taken from the SEDL website (Southwest Educational Development Laboratory). Words had to meet two criteria before they were considered to be exception words. Firstly, they had to have a different pronunciation from other words that shared the same spelling. Secondly, the pronunciation of the exception word had to be the least common pronunciation of that letter cluster.

Non-word Stimuli In total, there were eighty non-word stimuli items presented. Forty of these were four letters long and the other 40 were five letters long. All of the non-words were taken from the ARC non-word database (Rastle, Harrington, & Coltheart, 2002). The non-words were all phonologically legal. All had orthographically existing onsets, orthographically existing bodies and only legal bigrams. All had monomorphemic syllables and had a similar number of phonological neighbours (range: 10 – 15).

Background Colours

The words were presented in two different conditions: against a white background and against a red background. In the condition with the white background, the text was black and the background was white. In the condition with the red background, the background was red (hue = 0, saturation = 255, luminance = 128; R = 255, G = 0, B = 0) and the text was neutral grey (hue = 170, saturation = 0, luminance = 128; R =

128, G = 128, B = 128). The experiment was split into two blocks. In one block, participants saw the stimuli against a white background and in the other block participants saw the stimuli against a red background. The order of presentation of these blocks was randomised across participants to control for any order effects. All participants completed the task in the same laboratory under the same lighting conditions. The only source of illumination in the room was an overhead strip light (luminance was approximately 600 Lux).

Presentation Positions

All of the stimuli were presented in lower-case Courier New font making each letter uniformly 3mm wide. Letter strings were either presented to the fovea meaning that they were presented within the central 2° around the fixation point or they were presented to the right visual field parafovea meaning that the first letter of the word was presented at 2.5° from the fixation point to ensure that the entire letter string fell only within the range of the parafovea. Participants sat at a distance of 60 cm from the screen to ensure that the visual angle remained constant.

Participants

There were 24 participants in total. All of the participants were right handed. All were undergraduates at the University of Edinburgh. All had normal or corrected-to-normal vision. None of the participants had any history of reading or visual problems.

Handedness: Participants were given a modified version of Annett's (1967, 1970) handedness questionnaire to ensure that they were right-handed.

Procedure

The participants were instructed to fixate on a gap between two vertical lines in the centre of the screen. The fixation point was present on the screen for 2000ms. This was followed by a letter string which was presented for 250ms. This short presentation duration minimises the chance that the participant will make an eye-movement towards the parafoveal stimuli. The letter stings could appear either in the right visual field parafovea or on the central fixation point within foveal range. After the stimulus had been on the screen for 250ms, a mask consisting of "**XXXXX**" appeared on the screen covering the area where the stimulus item had been. The mask remained on the screen until the participant had made a response. As soon as the participant made their response, the fixation point for the next trial appeared. Participants had to indicate whether the stimulus that they had just viewed was a real word or a non-word. Using the index finger of each hand, the participants had to press one of two buttons to indicate whether the stimulus was a word or a non-word. The hand that each participant used to respond to a particular type of stimuli (word or non-word) was counterbalanced across participants. Reaction times and error rates were recorded. There were 10 practice trials to begin to make sure that the participant had correctly understood the procedure.

6.3.2 Results

The data were analysed using analysis of variance (ANOVA). There were two repeated-measures within-participants and within-items factors: Visual Field (foveal and parafoveal presentations) and Background Colour (white or red background) and one within-participants and between-items factor: Regularity (regularly spelled words and exception words). Reaction time data measured in milliseconds were analysed using a 2 (Regularity) X 2 (Visual Field) X 2 (Background Colour) repeated measures ANOVA. Error rates were analysed using a 2 (Regularity) X 2 (Visual Field) X 2 (Background Colour) repeated measures ANOVA. Items that participants made errors on (8.18 %) were excluded from the reaction time analysis as were items that had a reaction time that was more than 2.5 standard deviations away from the mean for that participant for that particular type of item. These values were replaced by the mean reaction time score for that participant for that item type. A total of 190 items were replaced giving a replacement rate of 9.89%.

Reaction Times

Table 17: Participants' mean reaction time scores in milliseconds (ms) for regularly spelled, and exception words, in both the foveal presentations and the parafoveal presentations, viewed either against a white background or a red background

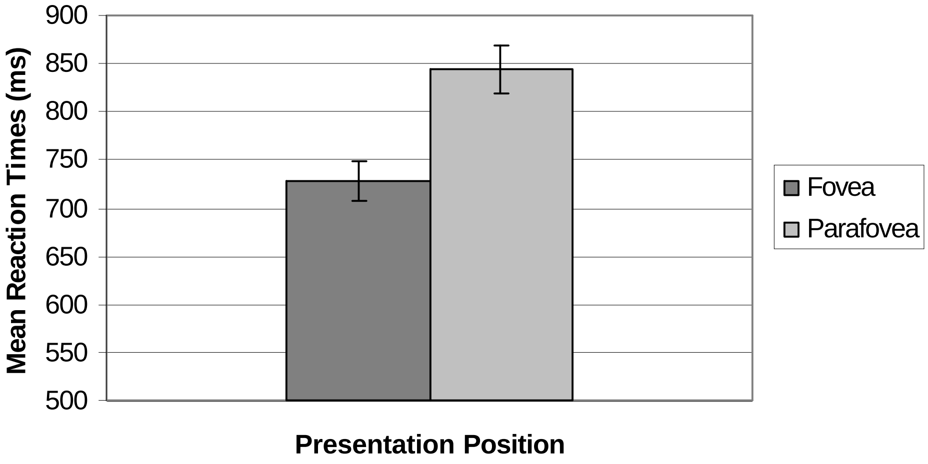
	Background Colour Visual Field Presentation Position			
	White		Red	
Regularity	Foveal	Parafovea	Foveal	Parafovea
Regular words	690.5	797.1	776.6	903.8
Exception words	691.4	794.8	752.9	879.5

Our first hypothesis was that there would be no significant difference, in either reaction times or errors rates between regular or exception words when they were presented foveally. This is what we found. Neither the reaction times to regularly spelled words nor the reaction times to exception words were affected by visual field presentation position. The interaction between Regularity and Visual Field was not significant, either by-participants or by-items (both *Fs* < 1). Viewing the stimuli in either the parafoveal area of the retina or on a central fixation point did not make any difference in the reaction times to regularly spelled words compared to exception words. However, we also predicted (hypothesis three) that regular words would be recognised faster in foveal presentations compared to in parafoveal presentations and that there would be no difference in reaction times to exception words between foveal presentations and parafoveal presentations. The non-significant interaction between word type and visual field means that we did not find support for our second hypothesis.

Our fourth hypothesis was that the recognition of regular words would be slower and would elicit more errors when they were presented in the parafoveal area of the visual field against a red background. Our data did not support this hypothesis. The three-way interaction between Regularity, Visual Field and Background Colour was non-significant, both by-participants and by-items (both *Fs* < 1) such that varying the background colour of the stimuli from white to red did not differentially affect regularly spelled words and exception words in either the right visual field parafovea or at a central fixation point.

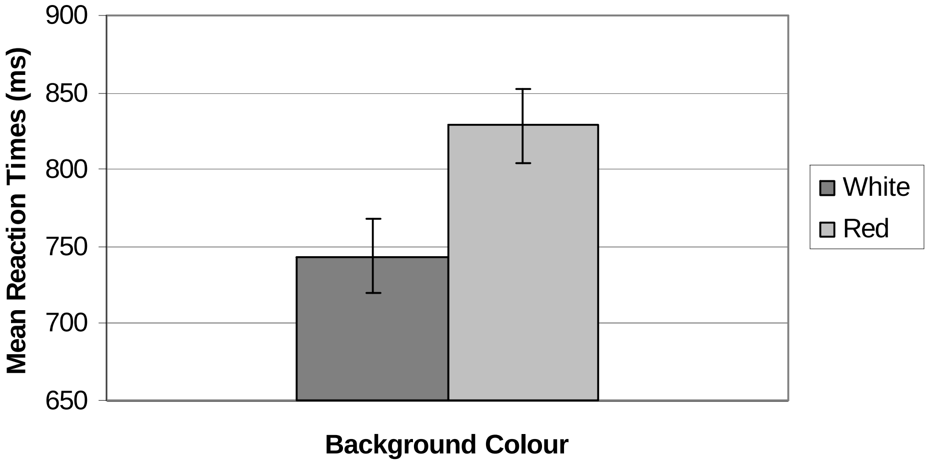
We did find a significant effect of visual field presentation position (F_1 (1, 23) = 35.44, *MSE* = 18224.66, $p < 0.001$; F_2 (1, 9) = 691.41, *MSE* = 411.52, $p < 0.001$) such that words that were presented in the foveal area of the visual field (727.9 ms) were recognised significantly faster than words that were presented in the parafoveal area of the visual field (848.3 ms) (see Figure 42).

Figure 42: Participants' mean reaction times measured in milliseconds (ms) to words presented in the foveal presentation position and in the parafoveal presentation position.



We also found that overall, words that were presented against a white background (743.5 ms) were recognised faster than those presented against a red background (828.2 ms). This effect was significant both by-participants and by-items (F_1 (1, 23) = 13.11, *MSE* = 26284.75, $p < 0.001$; F_2 (1, 9) = 75.73, *MSE* = 1817.84, $p < 0.001$) (see Figure 43).

Figure 43: Participants' mean reaction times measured in milliseconds (ms) to words presented against a white background compared to against a red background



However, the background colour of the stimuli did not affect regularly spelled words and exception words differently. The interaction between regularity and background colour was non-significant, both by-participants and by-items (both *Fs* < 1). Inhibiting the magnocellular pathway by changing the colour of the background to red had no effect on the reaction times to either of the visual field presentation positions. The interaction between visual field and background colour was non-significant, both by-participants and by-items (both *Fs* < 1). Overall, we found no significant difference between reaction times to regularly spelled words and to exception words. Regularity was non-significant both by-participants and by-items (both *Fs* < 1).

Error Rates

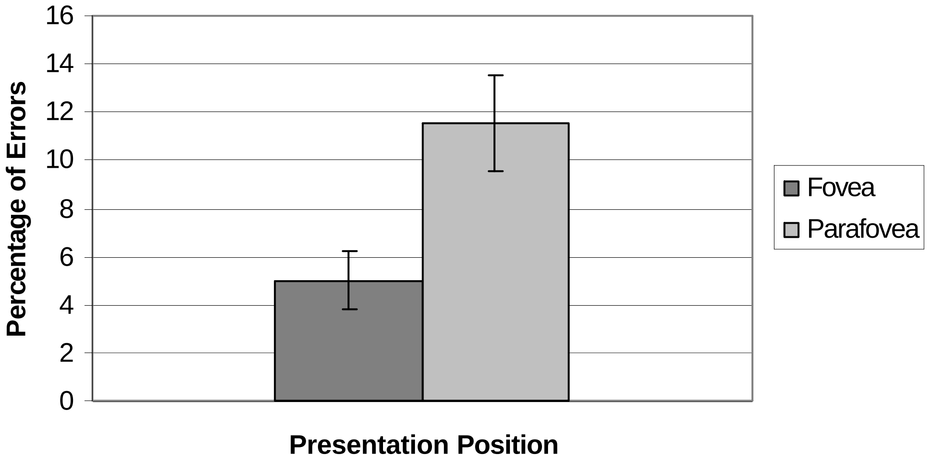
Table 18: Percentage of errors made by participants on regular words and exception words in foveal and parafoveal presentation positions, viewed against either a white background or against a red background. The total percentage of errors made was 8.18%

	Background Colour Visual Field Presentation Position			
	White		Red	
Regularity	Foveal	Parafovea	Foveal	Parafovea
Regular words	4.2	7.5	3.8	15.1
Exception words	6.2	7.5	6.3	15.3

Our second hypothesis predicted differences only in the error rates for exception words between foveal and parafoveal conditions. Although we predicted that there would be no difference in reaction times between regular words and exception words when they were presented foveally, we also predicted that there would be a greater number of errors made on exception words compared to regular words when they were presented parafoveally. However, our error data do not support this hypothesis. The interaction between Regularity and Visual Field was non-significant, both by-participants and by-items (both *Fs* < 1). There was no difference in the number of errors made between regular spelled words and exception words between the right visual field parafoveal presentation positions and the central, foveal presentation position.

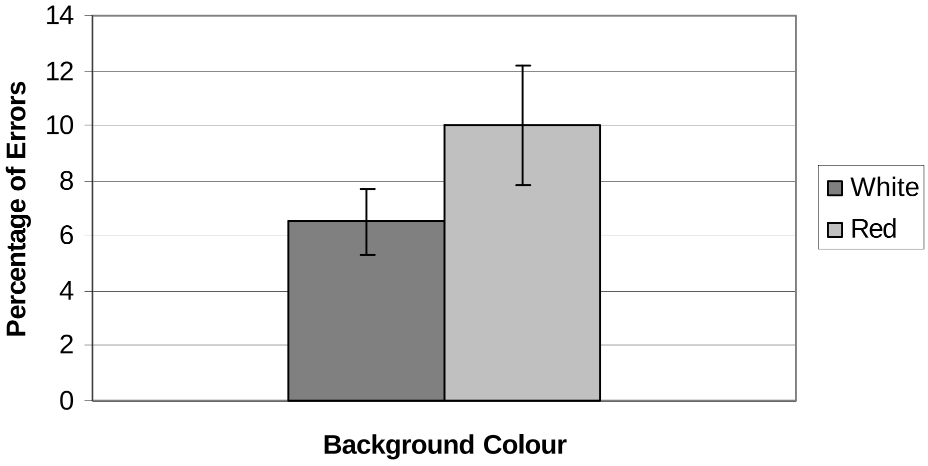
However, we did find that as well as being faster, words that were presented to the centre of the visual field were also recognised more accurately compared to words that were presented parafoveally. There were a greater number of errors made on words that were presented in the parafoveal area of the visual field (11.5 %) compared to words that were presented in the foveal area of the visual field (5.0 %). Visual Field was significant both by-participants and by-items (F_1 (1, 23) = 5.92, MSE = 3.07, $p < 0.05$; F_2 (1, 9) = 34.47, MSE = 1.26, $p < 0.001$) (see Figure 44).

Figure 44: Percentage of errors made by participants on words that were presented in the foveal presentation position compared to words that were presented in the parafoveal presentation position



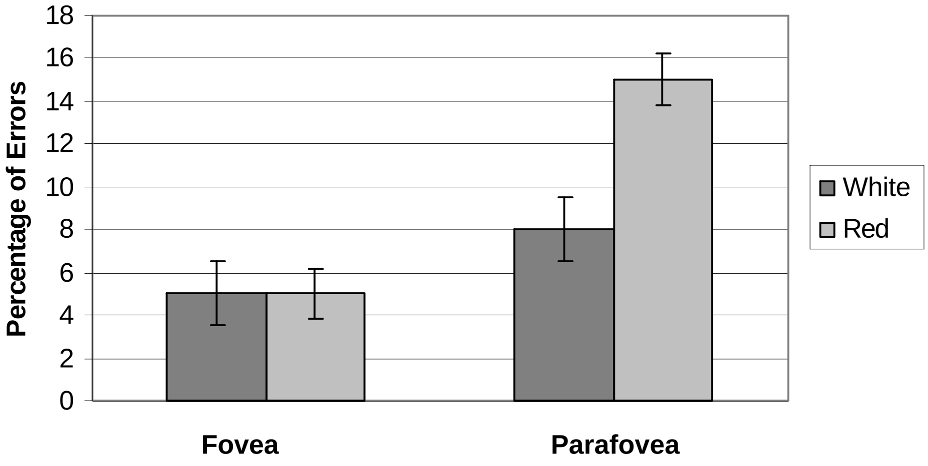
We also found that words that were presented against a red background (10.0 %) elicited significantly more errors than items presented against a white background (6.5 %). Background Colour was significant by-participants and by-items (F_1 (1, 23) = 6.31, MSE = 1.01, $p < 0.05$; F_2 (1, 9) = 15.21, MSE = 1.01, $p < 0.01$) (see Figure 45). Not only did magnocellular inhibition slow the recognition of words but it also made recognition less accurate.

Figure 45: Percentage of errors made by participants on items presented against a white background compared to against a red background



We also found a significant interaction between background colour and visual field presentation position that showed that the red background affected accuracy of recognition in the parafovea more than in the fovea. Presenting the stimuli against a red background produced more errors in the parafoveal viewing condition. The interaction between Visual Field and Background Colour was significant, both by-participants and by-items (F_1 (1, 23) = 6.69, *MSE*= 0.05, $p < 0.05$; F_2 (1, 9) = 5.01, *MSE* = 3.42, $p = 0.05$). There was no difference in the number of errors made on items presented at the central presentation point and items presented in the right visual field parafoveal position when the stimuli were presented with a white background. When the stimuli were presented against a red background, there were significantly more errors made on items presented in the right visual field parafoveal presentation position (15.0 %) than on items presented at the central fixation point (5.0 %) (See Figure 46). All effects of word regularity and interactions with regularity were non-significant.

Figure 46: Percentage of errors made by participants in the central presentations compared to in the right visual field presentations against either a white background or against a red background



6.3.3 Discussion

This experiment investigated whether inhibiting the activity of the magnocellular pathway would have an adverse effect on sub-lexical processing in the parafoveal area of the visual field. We tested this by looking at the differences in participants' performance on a lexical decision task under conditions designed to either inhibit the functioning of the sub-lexical (dorsal) route or under conditions that allowed both the sub-lexical and the lexical (ventral) routes to function optimally. The stimuli were varied by regularity in an attempt to show that low-frequency regular words rely more heavily on the dorsal rather than the ventral route and would be more affected by loss of the magnocellular pathway than exception words which can only be recognised by the ventral route. Words were presented to either the fovea or the parafovea with the expectation that recognition of items in the parafovea would be more difficult under conditions where magnocellular input is inhibited as the magnocellular pathway is the predominant pathway arising from the parafoveal area of the retina.

Based on previous findings (Borowsky et al., 2006; Jordan & Patching, 2004; Pugh et al., 1996; Sandak et al., 2004) we predicted that both types of words (regular and exception) would be recognised faster when they were presented to the foveal area of the retina compared to when they were presented to the parafoveal area. The results of the present experiment support this hypothesis. Words were recognised faster and more accurately when they were presented centrally (to the foveal area of the retina) compared to when they were presented in the right visual field (to the parafoveal area of the retina). We predicted items would be faster and more accurately recognised in the fovea compared to the parafovea because according to Jordan and Patching (2004) ventral stream processing only occurs in the processing of words that are directly fixated. Words that are viewed in lateralised positions are processed sub-lexically as demonstrated by their finding of the letter-word superiority effect in left and right visual field presentations. This finding supports the assertion of Jordan and Patching.

We had also predicted that there would be no difference in recognition times between regular and exception words when they were viewed in the central area of the visual field but that there would be more errors made on exception words than on regular words when they were viewed parafoveally. As both word types were of an equal, low-frequency range they would have similar amounts of exposure and a similar strength of lexical representation in memory. The extent of ventral route processing depends on how strongly the representation of the word is in lexical memory (Pugh et al., 2000; Sandak et al., 2004). Based on Jordan and Patching (2004) there should have been no difference in reaction times to regular words and exception words when they were presented foveally as both word types would be processed by the ventral stream. This is what we found. However, based on the conclusions of Jordan and Patching conclusions we would have predicted that there would have been more errors made on exception words that were presented parafoveally as only sub-lexical processing would have been available and exception words do not have regular grapheme-to-phoneme correspondence and so could not be accurately processed in this way. Our findings do not support this hypothesis: there were no differences in the number of errors made on exception words between the foveal and parafoveal conditions.

Related to this, we predicted that if the ventral stream is only active in foveal vision and that parafoveal vision relies on the processing by the dorsal stream that the processing of parafoveally presented regular words would be impaired under conditions that impair magnocellular functioning. Regular words can use either ventral or dorsal processing and according to Jordan and Patching (2004) only dorsal stream processing occurs in parafoveal vision so we predicted that dorsal stream inhibition would lead to slower reaction times to, and a greater number of errors made on regular words compared to when they are presented under conditions that are designed to optimally activate both the ventral and dorsal pathways. Our findings do not support this hypothesis. Although we found an overall effect of presenting the words on a red background showing that magnocellular inhibition slowed responses and led to a greater amount of errors, and that magnocellular inhibition led to more errors in word recognition when the words were presented to the parafovea compared to the fovea, we did not find that regular words were more affected than exception words. Magnocellular inhibition did not affect the recognition of words that were presented to the foveal area of the retina. There was no difference between the white background condition and the red background condition for either reaction times or error rates for items presented to the centre of the visual field. We had chosen to use only low frequency words as the extent of ventral stream involvement depends on how strongly the items are encoded in lexical memory. We reasoned that low frequency words, as they have had less exposure, would have a less strong memory trace and so would be more likely to rely on dorsal stream processing. Overall, we did not find support for Jordan and Patching's proposal that centrally presented words are processed lexically and laterally presented words are processed sub-lexically.

In conclusion, this experiment was designed to investigate whether inhibiting the activity of the magnocellular pathway would selectively disrupt processing of regular words that were presented in the parafoveal area of the visual field. We predicted, based on the study of Jordan and Patching (2004) that if ventral stream processing can only occur in foveal vision, exception words will elicit a greater number of errors when they are presented parafoveally compared to when they are presented foveally. We did not find this to be the case. We also predicted that if only dorsal stream processing occurs in parafoveal vision that regular words would be slower, but just as accurate in parafoveal versus foveal vision and that regular words presented in parafoveal vision would be slower and elicit a greater number of errors under conditions that inhibit magnocellular processing compared to under conditions where both processing streams are functional. The findings of this study do not support this hypothesis. We did find that magnocellular inhibition disrupted parafoveal processing more than foveal processing (indeed processing of words by the fovea appears to be entirely unaffected by magnocellular inhibition) but we did not find any affects of word regularity.

6.4 Implications for reading

In these three experiments we have shown that inhibiting the functioning of the magnocellular visual pathway affects parafoveal perception of lexical stimuli and appears to have little or no effect on the perception of foveally presented stimuli. In Experiment 6.1 we successfully replicated the word superiority effect (Grainger et al., 2003; Hildebrandt et al., 1995; Jordan & Patching, 2004; Reicher, 1969) and also showed that this effect is not affected by inhibition of the magnocellular visual pathway. This result supports the conclusions of Jordan and Patching (2004) that lexical processing occurs only on centrally fixated words and that words that appear in either the left visual field or in the right visual field are processed sub-lexically. They had found that word-letter superiority only occurred when the stimuli were presented at a central fixation point. When they presented the stimuli in either the left or right visual fields, they found a letter-word superiority effect instead. They concluded that fixated words were processed in a different way to laterally presented words. Although the result of Experiment 6.1 supports this idea, the results of the subsequent two experiments do not.

When words are processed by the ventral stream they are processed as whole units. Whole phonological representations are mapped onto whole-word orthographic representations (Borowsky et al., 2006; Pugh et al., 2000; Sandak et al., 2004). It is only through this type of processing that the word superiority effect can exist. For whole words to be recognised faster than the component letters, the word must be recognised first. Sub-lexical processing occurs through the dorsal processing stream (e.g., Pugh et al., 2000). This is the type of processing that would allow a letter-word superiority effect. As words are recognised incrementally, the letters in the word must be recognised faster than the whole word. Only when all (or a sufficient amount) of the letters are identified can the whole word be recognised. Based on this, we investigated the findings of Jordan and Patching. The findings of the three experiments in this chapter partially support the idea that foveated words are processed by the ventral stream and words that are viewed parafoveally are processed by the dorsal stream. In Experiments 6.2 and 6.3 we found that words that were viewed in central, foveal vision were recognised faster and more accurately than words that were viewed in the parafovea. This finding supports the idea of foveal-ventral and parafoveal-dorsal processing as the ventral processing stream is faster than the dorsal stream so we would predict that foveal processing would be faster than parafoveal processing.

Also supporting the foveal-ventral and parafoveal-dorsal hypothesis is the findings in Experiments 6.2 and 6.3 that magnocellular inhibition (and therefore dorsal stream inhibition) affected stimuli presented to the parafoveal areas of the visual field more than the foveal areas. However, in Experiment 6.3 we predicted that if only dorsal stream processing is available to parafoveal vision, then viewing exception words in parafoveal vision should lead to a greater number of errors than when they are viewed in foveal vision. Our findings did not support this prediction. There were no differences in the amount of errors made between foveal and parafoveal presentations of exception words. This finding suggests that a degree of ventral stream processing must have been available in parafoveal vision. Another finding which casts doubt on the segregation of ventral and dorsal processing between foveal and parafoveal vision is the finding that there was no interaction between word type and visual field presentation in Experiment 6.3. We predicted that regular words would be recognised faster in foveal (ventral) than in parafoveal (dorsal) presentation positions as the dorsal route is slower than the ventral route. We predicted that the recognition times of exception words would not be affected in this way. We did not find this. Instead, we found that the recognition of all words was slower in parafoveal presentations. This finding suggests ventral processing involvement in both word types when they appear in parafoveal vision. In conclusion, the results of these three experiments do not support the conclusions of Jordan and Patching (2004).

6.5 Chapter Summary

In this chapter we have shown that inhibiting the magnocellular visual pathway (and therefore dorsal steam processing) does not appear to affect words that are presented to central (and therefore, foveal) vision. It has been argued that lexical access occurs only when words are directly fixated and that when words are viewed in the parafoveal area of the visual field they are processed sub-lexically (Jordan & Patching, 2004). The results of the three experiments reported here do not fully support these claims. Although we found evidence to suggest that inhibiting the magnocellular pathway disrupts parafoveal perception of words more than foveal perception of words, we also found evidence to suggest that ventral stream processing can occur in the parafovea as well as in the fovea. We propose an alternative explanation of the distribution of ventral and dorsal stream processing in which we link the employment of the ventral stream to visual attention. This theory will be explained in the final chapter where the results of all eight experiments are brought together.

Chapter 7

Discussion and Conclusions

7.0 Chapter Overview

In this chapter we will summarize the findings of our experiments and we will also discuss what these findings imply about reading in general. In Section 7.1 we summarize our experimental findings and conclusions and we present an alternative theory on the distribution of ventral and dorsal stream processing. We also discuss the involvement of ventral and dorsal processing deficits in dyslexia. In section 7.2 we discuss the limitations of the experimental approaches that we used and in section 7.3 we make suggestions for future research in this area.

7.1 Summary of Experiments, Conclusions and Implications

7.1.1 Summary of results and conclusions

The effect of monocular occlusion on the distribution of visual attention

It has been shown that there is a greater effect of word length when words are presented in the left visual field compared to when they are presented in the right visual field (e.g., Ellis 2004; Faust et al., 1993). Ellis and others argue that the difference in the word length effects between the left and right visual fields reflects different methods of lexical access between the two brain hemispheres. Nazir (2000), on the other hand argues that there are not two different methods of lexical access for words presented in the left and right visual fields and instead the differences between the visual field length effects are a product of lexical knowledge and perceptual learning. Nazir argues that length effects are less for familiar words and this, coupled with perceptual learning which makes words more easily identified in the visual field positions in which they have been most commonly viewed, is what contributes to lesser effects of word length on items viewed centrally or in the right visual field. The results of our first two experiments do not fully support either of these hypotheses. In experiment one (section 4.1) we showed that words were more accurately recognised when they were presented to the centre of the visual field compared to when they were presented in either the left or right visual fields. This finding provides support for Nazir's theory. However, we found that words were recognised more accurately when they were presented in the left visual field compared to when they were presented in the right visual field. This finding does not support Nazir's theory. If lexical knowledge and perceptual learning could account for the differences between the length effects in the left and right visual fields then we would have expected the right visual field presentations of words to be more accurate and faster as it is more common to fixate a word close to the beginning than close to the end of the word. This would mean that the words are viewed more frequently in the right visual field than in the left visual field.

The results of the second experiment also fail to fully support the theories of either Ellis or Nazir. In the second experiment (section 4.2) we found an effect of word length in the left visual field with four letter words being recognised faster than seven letter words when the words were viewed binocularly. However, this length effect was non-significant when the right eye was occluded. There was a trend for four letter words to elicit a greater number of errors when the right eye was occluded suggesting almost a reversal of the length effect that we found under binocular viewing conditions. This experiment does not provide support for either Ellis (2004) or Nazir (2000). If the word length effect in the left visual field could have been attributed to different methods of lexical access between the two brain hemispheres then it should not have been attenuated by occluding the right eye. Even with the right eye covered, the left visual field is still processed by the right hemisphere and the right visual field is still processed by the left hemisphere. Therefore, hemispheric asymmetries should have persisted even with the right eye occluded and we should still have found a length effect in the left visual field of the same magnitude as when both eyes were used for viewing. The results of the second experiment also do not support the assertions of Nazir. If the word length effect in the left visual field had been a product of lexical knowledge combined with perceptual learning then there should have still been a length effect in the left visual field even with the right eye covered.

We propose an alternative account of the variation in word length effects throughout the visual field that is related to the distribution of visual attention. Roth et al. (2002) had shown that occluding one of the eyes during a line-bisection task appeared to affect the attentional systems of the two brain hemispheres. Occluding either the left or the right eye led to a decrease in the activity of the attentional systems of the brain hemisphere contralateral to the occluded eye and an increase in the attentional systems of the brain hemisphere ipsilateral to the occluded eye. Milner et al. (1992) had shown that perceptions of line length could be altered by influencing the focus of the viewer's attention. They showed that the section of line that receives direct attention appears to be longer than section of line (of equal length) that does not receive direct attention. Based on this, we propose that the word length effects depend on the allocation of visual attention throughout the visual field. The greatest word length effect will be in the area of the visual field that does not receive direct attention. The area of the visual field that the reader is directly focusing on will produce the least noticeable length effects. McConkie and Rayner (1975) demonstrated that the perceptual span (the area of the visual field from which meaningful information can be extracted) is asymmetrical extending approximately 3-4 characters to the left of fixation and approximately 14-15 characters to the right of fixation. Binder et al. (1999) proposed that this asymmetry is caused by a rightward bias that develops through the habit of reading from left to right (for languages that are read in this direction). Therefore, attention is automatically directed towards the right of fixation unless a regressive saccade is planned (Henderson & Ferreira, 1990). We propose that this predisposition to focus attention to the right of fixation is what leads to the lesser effects of word length in the right visual field. As attention is focused on this area, there is a greater perceptual span and longer words are as clearly visible as shorter words. When we occluded the right eye we suppressed the attentional systems of the left hemisphere and increased activation of the attentional systems of the right hemisphere. This appeared to reduce the attentional resources that were directed on the right visual field while increasing the attentional resources that were allocated to the left visual field which, in turn, reduced the difference in reaction times between four and seven letter words.

Dorsal and ventral stream processing in highly skilled readers and in dyslexics

In chapter five we discussed the relationship between reading skill and word length effects. It has been demonstrated that word length effects are reduced as reading skill improves (Aghababian & Nazir, 2000). When learning to read, all readers show large effects of word length regardless of where in the visual field the words are viewed. These word length effects are reduced as reading skill improves but they remain for dyslexic readers (De Luca et al., 2002; Spinelli et al., 2005; Ziegler et al., 2003; Zoccolotti et al., 2005). It is thought that beginner readers and dyslexics use a sub-lexical strategy to identify words and that a faster, lexical strategy only develops as reading skill improves (Aghababian & Nazir, 2000; Zoccolotti et al., 2005). When using the sub-lexical route, word recognition is achieved through incremental mapping of letters onto individual phonemes. In contrast, when the lexical route is used, words are recognised as whole units and whole word orthographic representations are mapped onto whole word phonological representations. The lexical route can only be employed when there has been previous exposure to the word and a representation of the word is stored in lexical memory. This means that non-words cannot be processed by the lexical route as they have never been encountered before and can have no representation in lexical memory. Non-words can only be processed incrementally using the sub-lexical route (Rastle & Coltheart, 1998). Exception words cannot be processed sub-lexically as these words do not have regular grapheme-to-phoneme mapping and so the correct pronunciation cannot be deduced from the orthography of the word.

The differences between lexical and sub-lexical processing have been accounted for by neurological models of word processing (Borowsky et al., 2006; Posner & Raichle, 1994; Pugh et al., 1996, 2000; Sandak et al., 2004). In these models, sub-lexical processing is completed by the dorsal processing stream and lexical processing is accomplished by the ventral processing stream. Both of these processing streams are situated in the left brain hemisphere and both arise from the occipital lobe (where feature analysis begins). However, on leaving the occipital lobe, these streams project to different brain areas. The ventral stream projects from the occipital lobe to the temporal lobe whereas the dorsal stream projects from the occipital lobe to the parietal lobe and onto the frontal lobe. As the ventral stream processes words as lexical units and recognises words by retrieving whole word lexical representations from lexical memory, this processing stream cannot read non-words but can recognise both regularly spelled words and exception words. There will be lesser length effects when words are processed by this stream as words are recognised as whole units. On the other hand, the dorsal stream processes words incrementally by mapping letter units onto individual phonemes. As a consequence of this, the dorsal stream cannot process exception words but can process regularly spelled words and non-words. There will be large effects of word length when words are processed by this stream. Skilled readers use both processing streams to read (Borowsky et al., 2006; Pugh et al., 1996, 2000; Sandak et al., 2004). Beginner readers initially rely on the dorsal stream but come to utilise both streams as reading skill develops. Dyslexic readers fail to develop the faster, more efficient ventral processing stream (De Luca et al., 2002; Spinelli et al., 2005; Ziegler et al., 2003; Zoccolotti et al., 2005). Both the magnocellular and parvocellular visual pathways input to the ventral stream (Ferrera, Nealey, & Maunsell, 1994; Nealey & Maunsell, 1994). Input to the dorsal stream is thought to be almost exclusively magnocellular (Maunsell, Nealey, & De Priest, 1990).

In order to test the hypothesis that skilled readers can utilise both the dorsal and ventral processing streams but that dyslexic readers rely exclusively on the dorsal stream, we compared the two groups on the recognition of regular and exception words. Regular words can be processed by either the dorsal or ventral stream but exception words can only be processed by the ventral stream. We predicted that the dyslexic readers would be impaired on the recognition of exception words if they were relying exclusively on dorsal stream processing. In experiment three (section 5.1) we found that skilled readers were faster at making lexical decisions compared to the dyslexic group supporting the idea that the skilled readers were able to use the faster ventral stream to recognise the words whereas the dyslexics were limited to using the slower dorsal stream. We also found a tendency for the skilled readers to be affected by the frequency of the words (suggesting that the words were being recognised as whole units) whereas there was no effect of word frequency for the dyslexic readers suggesting that they were incrementally processing the words. We found a tendency for the dyslexic readers, but not the skilled readers, to be affected by word regularity. The reaction time data showed that this effect was in the opposite direction to what we predicted. The dyslexic readers were actually faster at recognising exception words compared to regular words. However, the error data showed that there was a speed-accuracy trade off and that exception words produced a greater amount of errors compared to regularly spelled words.

The skilled readers in experiment three were not affected by the regularity of the words. Sereno and Rayner (2000) had shown that skilled readers are only affected by word regularity when the word had previously been viewed in the parafoveal preview. They found that there was no difference between high frequency exception words and high frequency regular words but low frequency regular words were recognised faster than low frequency exception words. This suggests that low frequency regular words receive a greater amount of facilitation from parafoveal preview compared to low frequency exception words.

Chace, Rayner and Well (2005) demonstrated that only skilled readers were able to extract phonological information from parafoveal preview. Poorer readers could not. A phonologically similar preview word provides a greater amount of facilitation than an orthographically similar preview word. Homophone previews of the target word provide facilitation even when the preview word is orthographically dissimilar to the target word (Miellet & Sparrow, 2004; Pollatsek et al., 1992). Unsworth and Pexman (2003) showed that in a lexical decision task, less skilled readers were less able to extract phonological information from words and they were less able to perform efficient grapheme-to-phoneme matching. Dyslexic readers have been found to show different patterns of eye-movements compared to skilled readers. Dyslexics tend to make shorter saccades and have longer fixations (e.g., Ram-Tsur et al., 2006). We propose that this is because they are less able to extract phonological information from parafoveal preview. If they are unable to extract as much information from parafoveal preview as skilled readers then they will require longer fixations when the word is fixated by the fovea to extract the same amount of information. It has been shown that when foveal processing is difficult there is less preview benefit gained (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens et al., 1999; Vitu et al., 1999; White, Rayner, & Liversedge, 2005). Therefore, if dyslexics find word recognition difficult then foveal processing load will be higher than that for skilled readers and the dyslexics will not obtain as much preview benefit as skilled readers because there will be less processing resources to devote to processing the parafoveally viewed stimulus.

We proposed that the ventral stream processing deficit of dyslexics may be exacerbated by difficulties in perceiving stimuli that are presented to the parafoveal area of the retina. It has been claimed that a portion of dyslexic readers have a deficit in the magnocellular visual pathway (e.g., Stein & Walsh, 1997). We predicted that if this were true, dyslexics (or at least those who had a magnocellular deficit) would be impaired at detecting stimuli that appeared in parafoveal vision as the magnocellular retinal ganglion cell is the most common type of cell to sample the parafoveal area of the retina (Dacey, 1994; Perry et al., 1984a; Polyak, 1941).

Experiment four (section 5.2) compared the abilities of both dyslexic and skilled readers in recognising regular and exception words that appeared in either foveal or parafoveal vision. Again, we found that the skilled readers were faster and more accurate at recognising words compared to the dyslexic readers. This supports the idea that the skilled readers are using the faster ventral stream whereas the dyslexics were limited to slower dorsal stream processing. As in the previous experiment, the dyslexics tended to be affected by word regularity (suggesting dorsal stream processing) but the skilled readers were not (suggesting ventral stream processing). We also found that words were recognised faster when they were viewed foveally compared to when they were viewed parafoveally. We propose that this indicates that the skilled readers rely on ventral stream processing for words that are directly fixated but that words that are viewed parafoveally are processed by the slower dorsal stream.

Rayner, Liversedge and White (2006) demonstrated that when the eye is fixated on a word in a sentence, information is also being encoded about the word directly to the right of the fixated word. A fixated word only has to be viewed for 50-60ms to encode a sufficient amount of information about the word for it to be recognised (Liversedge et al., 2004; Rayner et al., 2003; Rayner et al., 1989). However, if the word directly to the right of the fixated word is masked or disappears after 60ms then reading is disrupted. This suggests that there may be two processes occurring at the same time: Ventral processing on the fixated word and slower dorsal processing on the parafoveally viewed word. If dyslexic readers do not have an intact ventral processing stream then they will be forced to process the fixated word using the dorsal stream and so will not have sufficient processing resources to allocate to processing the parafoveally viewed word.

The fifth experiment (section 5.3) tested dyslexics and skilled readers on a more direct test of the ability to extract phonological information from words viewed parafoveally. We presented word pairs in either foveal or parafoveal vision and the participant had to decide if the two words in the pair rhymed or not. Again we found that skilled readers were able to complete this task faster, and more accurately than the dyslexic readers. The skilled readers were able to detect phonologically similarity between the two words even when one of these words was an exception word and so the rhyme judgement could not be based on orthographic comparisons alone. They were equally as able to judge this type of word pair and they were the word pairs that both looked and sounded alike. On the other hand, the dyslexic readers were impaired at detecting phonological similarity when the phonology of the two words was not predictable from the orthography of the words. This deficit was particularly evident when the words were viewed in parafoveal vision supporting the idea that dyslexics have difficulty in extracting phonological information from words when they are viewed in the parafovea.

The impact of magnocellular inhibition on dorsal and ventral stream processing

In order to test the impact of magnocellular inhibition on both dorsal stream processing and parafoveal perception of words we presented the stimuli against a red background in experiments six (section 6.1), seven (section 6.2) and eight (section 6.3). We chose to inhibit the magnocellular pathway in this way as it was easier to control for other factors that might also influence word recognition. If we had attempted to select a group of dyslexics who had a magnocellular impairment then we would have had to control for the variability in the other dyslexic symptoms. By using the red background to selectively inhibit the magnocellular retinal ganglion cells of skilled readers we know that any differences in the participant's word recognition abilities under these conditions when compared to normal, high-contrast conditions are due to magnocellular inhibition.

In experiment six (section 6.1) we showed that ventral stream processing was not affected by the inhibition of a previously functional magnocellular pathway. By inhibiting magnocellular functioning we proposed that dorsal stream functioning would be impaired as the dorsal stream is thought to be composed of almost exclusively magnocellular input (Maunsell, Nealey, and De Priest, 1990). We used a Word Superiority Effect (Reicher, 1969; Wheeler, 1970) task in this experiment because in order for a word to be recognised faster than its component letters, the word must be recognised as a whole unit before the individual letters are recognised. This must be due to ventral stream processing as this processing stream is the only route that is capable of recognising words in this way. If processing was carried out by the dorsal stream then we would have predicted a letter-word superiority effect as this route decodes words incrementally, letter-by-letter. We successfully replicated the word superiority effect when the stimuli were presented in high contrast conditions. However, there was no impact on the word superiority effect when we inhibited the magnocellular pathway. The findings of this experiment support the idea that the word superiority effect is a product of ventral stream processing and that ventral stream processing is not affected by the inhibition of a previously functional magnocellular pathway.

Related to this study, Jordan and Patching (2004) demonstrated that the word superiority effect only exists when items are directly fixated by the fovea. When they tested for this effect in lateralised displays they found that there was a letter-word superiority effect. Based on this finding, and the findings of experiment six, we proposed that ventral stream processing only occurs for items in foveal vision and that parafoveally viewed words were processed by the dorsal stream. Based on this assumption, we predicted that inhibition of the magnocellular pathway (by presenting the stimuli against a red background) would have a greater impact on stimuli that were viewed parafoveally and would have little or no impact on stimuli that are viewed foveally. The inhibition of the magnocellular pathway would impact on parafoveal word perception in two ways: Firstly, as magnocellular retinal ganglion cells are the most common type of cell in the parafoveal area of the retina (e.g., Dacey, 1994), inhibition of the magnocellular pathway would disrupt the actual perception of words viewed parafoveally. Secondly, as the input to the dorsal processing stream is believed to be predominately magnocellular (Maunsell, Nealey, and De Priest, 1990), and if only dorsal stream (and not ventral stream) processing occurs in parafoveal vision then this would exacerbate the problem with parafoveal perception of words.

We found some evidence to support this hypothesis. Words were recognised faster than non-words. Non-words can only be processed sub-lexically (Rastle & Coltheart, 1998) and so must be reliant on the dorsal stream but real words can be processed by either the dorsal or the ventral stream (e.g., Borowsky et al., 2006). This finding demonstrates some degree of ventral stream involvement. Secondly, items presented centrally were recognised faster than those presented in the right visual field parafoveal area. This supports the idea that foveated words are processed by the faster ventral stream but parafoveally viewed words rely on the slower dorsal stream. We also found that the red background lead to slower and less accurate responses to parafoveally viewed words but had no effect on foveally viewed words. This finding supports the idea that magnocellular inhibition affects the parafoveally perceived areas of the visual field more than the foveated area of the visual field. However, we only found partial support for the idea that only dorsal stream functioning occurs in parafoveal vision. We predicted that regularly spelled words (which can be processed by either the dorsal or ventral stream) would be faster when they were presented foveally (and so would be processed by the ventral stream) compared to when they were presented to the parafovea (and so would be reliant on dorsal stream processing). Our findings support this hypothesis. However, we also predicted that presenting the regular words against a red background would disrupt the recognition of these words more in the parafoveally viewed area of the visual field than in the foveated area of the visual field. Magnocellular inhibition (by imposing a red background) should lead to dorsal stream inhibition and this should be evident when words are viewed parafoveally but not when they are viewed foveally if only dorsal stream processing occurs in the parafovea. Our results do not fully support this idea. Inhibiting the magnocellular pathway did not significantly slow responses to regular words that were viewed parafoveally (although there was a tendency for regular word recognition in the parafovea to be less accurate under conditions of magnocellular inhibition).

Experiment eight (section 6.3) repeated the experimental procedure of experiment seven except that in experiment eight we compared regular word recognition to exception word recognition. As previously stated, regular words can be processed by either stream however, exception words can only be correctly processed by the ventral stream. Exception words do not have regular grapheme-to-phoneme mapping and so cannot be incrementally assembled. We predicted that if ventral stream processing only occurs in foveal vision and that dorsal stream processing only occurs in parafoveal vision then there would be no difference between regular (dorsal and ventral) and exception (ventral only) words when they were viewed in foveal vision. However, when they were viewed in parafoveal vision we predicted that regular words would be slower (as they are processed by the dorsal stream) but that there would be more errors made on exception words (as they cannot be processed by the dorsal stream and the dorsal stream is the only route that is operational in parafoveal vision according to Jordan & Patching, (2004)). Our results did not support these predictions. We did not find any interaction of visual field with word type so we cannot conclude that only dorsal stream processing occurs in parafoveal vision. As there were no differences between exception words that were viewed foveally and exception words that were viewed parafoveally then we cannot conclude that there is no ventral stream processing involved in recognising parafoveally viewed words.

Another indication that ventral processing was occurring in parafoveal preview was the failure of magnocellular (and dorsal stream) inhibition to disrupt the processing of parafoveally viewed regular words. If only dorsal stream processing was occurring in parafoveal vision then regular words recognition should have been disrupted by magnocellular inhibition and this was not the case. We did find that foveal processing of words was faster and more accurate compared to parafoveal processing of words. We also found that magnocellular inhibition slowed word recognition in general and also led to more word recognition errors being made in parafoveally viewed words compared to foveally viewed words. However, magnocellular inhibition did not affect regular and exception words differently.

In conclusion, we did not find evidence to support the idea that ventral stream processing only occurs in foveal vision and that parafoveal word recognition relies only on the dorsal stream as was suggested by the results of Jordan and Patching (2004). However, we did find that magnocellular inhibition affected word recognition in the parafoveally viewed areas of the visual field but had little effect on word recognition in foveal vision. In the next section (7.1.2) we present an alternative account of the distribution of ventral and dorsal stream processing that is linked with visual attention. In section 7.1.3 we discuss the relationship between dorsal and ventral stream processing and dyslexia.

7.1.2 An alternative account of the distribution of ventral and dorsal stream processing across foveal and parafoveal vision

Jordan and Patching (2004) demonstrated that there is a word superiority effect when the stimulus is directly fixated. Words were recognised faster than their constituent parts. They also demonstrated that letters were recognised faster than whole words when the stimuli were presented in either the left or the right visual fields. They concluded that these findings reflect different methods of word processing between centrally and laterally presented words. As the word superiority effect depends on the word being recognised faster than the individual letters we took this to indicate that this effect relies on processing by the ventral stream as only the ventral stream can identify words as whole units. The letter superiority effect demonstrated by Jordan and Patching for stimuli that were presented in the parafoveal area of the visual field suggests that individual letters were being recognised faster than whole words. We took this to indicate that parafoveally viewed words were processed by the dorsal stream.

We found some evidence to support the idea of a foveal-ventral and parafoveal-dorsal processing split. In experiment six we demonstrated that the word superiority effect persisted in central vision even when the dorsal stream was inhibited. This suggests that foveal processing was entirely due to the ventral stream. Inhibiting the dorsal stream had no effect on the processing of lexical stimuli in central vision. We also found that lexical items were consistently recognised faster when they were directly fixated compared to when they were viewed parafoveally. Directly fixated items were processed faster when they were presented to foveal vision compared to when they were presented in the left visual field parafoveal area (experiments 1 and 4) and also when they were presented in the right visual field parafoveal area (experiments 1, 4, 5, 7 and 8). We also found that magnocellular inhibition disrupted parafoveal recognition of words and had little or no effect on foveal recognition of words (experiments 7 and 8). It is believed that dorsal route input is almost exclusively magnocellular (Maunsell, Nealey, & De Priest, 1990; Mishkin, Ungerlieder, & Macko, 1983) so we concluded from this that magnocellular inhibition would inhibit the activity of the dorsal stream. As this disruption was most obvious in parafoveal vision, and that dorsal stream inhibition did not appear to affect foveal processing of words at all, we concluded that only dorsal stream processing occurs in parafoveal vision and only ventral stream processing occurs in foveal vision.

However, we also found evidence to suggest that there is not a clear distinction between foveal-ventral processing and parafoveal-dorsal processing. In experiment one we found that changing the focus of visual attention from the right visual field to the left visual field led to a reduction in the word length effect that we found in the left visual field under conditions that facilitated the focusing of attention on the right visual field. Word length effects are thought to reflect dorsal stream processing. Beginner readers show large effects of word length and these decrease in magnitude as reading skill develops and the ventral processing stream begins to develop (Aghababian & Nazir, 2000; Borowsky et al., 2006; Pugh et al., 1996, 2000; Sandak et al., 2004). The word length effect that we found in the left visual field (experiment 2) under conditions that would favour the focusing of visual attention on the right visual field suggests that words that appeared in the left visual field were being processed by the dorsal stream. However, when we occluded the right eye (and therefore reduced left hemisphere attentional dominance and increased right hemisphere attentional dominance (Roth et al., 2002) we found that there was not a significant length effect in the left visual field. This suggests that as the right hemisphere now had attentional dominance in the task (and therefore attention was now focused on the left visual field) that this was the reason for the absence of the word length effect.

Further evidence against a clear segregation of foveal-ventral processing and parafoveal-dorsal processing comes from the finding that although magnocellular (and therefore, dorsal stream) inhibition affected words presented to the parafoveally viewed area of the visual field and not words presented to the foveally viewed area of the visual field, there was no difference in speed of recognition of regular words between foveal and parafoveal presentation positions (experiments 4, 6 and 8). As regular words can be processed by either stream, we predicted that they would be recognised faster in foveal vision (where they would be processed by the ventral stream) and slower in parafoveal vision (where they would be processed by the dorsal stream). Although we found that stimuli processing was faster overall when the items were presented to foveal vision compared to when they were presented to parafoveal vision, the processing of regular words was not slowed to a greater extend than the processing of exception words. In fact, the finding that exception words could be accurately recognised in parafoveal vision (experiment 8) suggests that these words were being processed by the ventral stream. We also found (in experiments 7 and 8) that the processing of regular words in parafoveal vision was not disrupted by dorsal stream inhibition. Regular words were recognised just as quickly in parafoveal vision when they were viewed under conditions of dorsal stream inhibition compared to when they were viewed under conditions where both processing streams were functioning optimally. Although there was a tendency for regular word recognition to be less accurate under conditions of dorsal stream inhibition, this was non-significant. Instead it appears that ventral stream processing can occur in parafoveal vision as well as in foveal vision.

Instead of a straight segregation between ventral-foveal and dorsal-parafoveal processing, we propose an alternative account involving the distribution of visual attention. We propose that ventral stream processing occurs on the word that is receiving direct visual attention and that all other words that are visible, but not attended, are processed by the dorsal stream. Experiment two demonstrated that when visual attention was focused on the left visual field there was an absence of word length effects compared to when attention was focused on the right visual field. It has been demonstrated that although fixations last for 200-250ms (Liversedge & Findlay, 2000; Rayner, 1998; Starr & Rayner, 2001), the fixated word needs only to be present for 50-60ms for it to be encoded (Rayner et al., 1989; Ishida & Ikeda, 1989; Liversedge et al., 2004; Rayner et al., 2003). However, when the word directly to the right of the fixated word is masked or disappears (at the beginning of the fixation or after 60ms of fixation) then reading rate is slowed. This suggests that the word directly to the right of the fixated word is being processed at the same time as the fixated word is being processed. This implies that there are two processes occurring at the same time. We propose that in the initial 50-60ms of a fixation visual attention is focused on the fixated word. This enables the fixated word to be processed by the faster ventral stream. As this process is occurring, information about the word directly to the right of the fixated word is being processed by the dorsal stream. After 50-60ms, visual attention switches from the fixated word to the next word and processing continues. If there are two routes being used (the ventral route on the word that attention is focused on, and the dorsal route on the next word in the sentence) and the ventral route is functioning optimally (ventral route involvement is related to reading skill) then the reader will be able to extract a greater amount of information from the word that is viewed parafoveally. If the ventral route is functioning optimally then processing of the fixated word can be achieved through this route alone leaving the dorsal route free for processing the parafoveally viewed word. This idea is supported by the finding that only highly skilled readers appear to be able to extract phonological information from a parafoveally viewed word (e.g., Chace et al., 2005). As ventral stream involvement increases (with reading skill) a greater amount of information can be extracted from parafoveal preview. We will discuss what happens when the ventral stream is impaired in section 7.1.3.

7.1.3 Dyslexia and the dorsal and ventral processing streams

We have previously discussed how the degree of ventral stream involvement appears to be related to reading skill. We proposed that a failure to develop a functional ventral stream may be an underlying cause of the reading problems experienced by dyslexic readers. We found some support for this idea. For example, in experiments 3 and 4 (sections 5.1 and 5.2) we found that the dyslexic participants tended to show an effect of word regularity whereas the non-impaired reading group did not. This indicates a ventral processing stream problem. Exception words can only be processed by the ventral route as they do not have regular grapheme-to-phoneme mapping and so cannot be processed in increments by the dorsal stream. We also found (in experiments 3, 4 and 5) that the dyslexics were consistently slower than the non-impaired group at making lexical decisions or recognising words. This finding supports the idea that the non-impaired participants were able to utilise the faster ventral processing stream but that the dyslexic readers were forced to rely on the slower dorsal processing stream.

We concluded from this that the lack of an adequate ventral processing stream would lead to a disruption when reading sentences (although we did not test this idea in the present thesis, we plan to conduct further research in this area). It has previously been shown that processing occurs on the word directly to the right of the fixated word at the same time as processing occurs on the fixated word (Rayner, Liversedge and White, 2006). In the same study, it was shown that disrupting the fixated word only affected reading rate when the word was disrupted in the initial 60ms of viewing. However, when the word directly to the right of the fixated word disappeared or was masked, reading rate was disrupted even if the manipulation was made after 60ms. This suggests that there are two processes occurring simultaneously. We proposed that the ventral stream is being used for processing of the fixated word and that the dorsal stream is being used for processing the word directly to the right of the fixated word. If the ventral stream is not functional (as we propose is the case in dyslexia) then only dorsal stream processing is available for processing both the fixated word and the word directly to the right. As a consequence of this we propose that dyslexic readers will not have the same amount of resources to allocate to processing the non-fixated word as the dorsal stream is occupied in processing the fixated word. This would lead to the dyslexics getting less preview benefit than skilled readers.

Supporting this idea, dyslexics tend to make shorter saccades and longer fixations (e.g., Ram-Tsur et al., 2006) suggesting that they do not receive the same amount of preview facilitation as non-impaired readers. It has been shown that skilled readers are more able to extract phonological information from parafoveal preview and that less skilled readers only appear to get orthographic facilitation (Chace, Rayner, & Well, 2006). Phonological similarity of a preview word to a target word has been shown to provide a greater amount of facilitation than an orthographically similar preview word (Miellet & Sparrow, 2004; Pollatsek et al., 1992). We suggest therefore that orthographic processing of the preview word precedes phonological processing of the preview word and that less skilled readers only reach the orthographic processing stage in parafoveal preview and so obtain less overall preview benefit.

We examined the impact of magnocellular suppression on word recognition in experiments six, seven and eight. As input to the dorsal stream is proposed to be almost exclusively magnocellular (Maunsell, Nealey & De Priest, 1994) we concluded that suppressing the magnocellular pathway would inhibit dorsal stream functioning. We found that magnocellular suppression affected word recognition when the words were viewed in parafoveal vision but that it did not affect word recognition when the words were presented in foveal vision. There appeared to be no effect of magnocellular suppression on non-words regardless of were in the visual field they were viewed. This finding supports the assumption that the magnocellular pathway is the dominant source of output from the parafoveal area of the retina to the brain and that it plays an active role in visual word recognition. We propose that a magnocellular deficit in a sub-set of dyslexics (e.g., Stein & Walsh, 1997) exacerbates the ventral route problems for these readers.

7.2 Limitations of our Approach

One of the interesting findings of the work in this thesis was that the degree of ventral stream involvement appeared to vary with reading skill. There were suggestions in some of the experiments in chapter 5 that a portion of the dyslexic participants were able to utilise the ventral processing stream under certain circumstances. It is possible that the dyslexic readers that we used in these studies did have some access to ventral stream processing but that the degree of ventral stream involvement was less than that of the skilled readers. We feel that in future research the level of reading skill should be more rigorously controlled for. In addition to this, we suggest that experiments of this nature should be conducted on primary school age children as all of the dyslexic participants in our studies were educated to undergraduate level. The dyslexia pre-tests showed that the reading age of the participants was only one-two years behind their average chronological age (although they showed a greater level of impairment in spelling). Testing dyslexic children before they have had opportunities to adopt coping mechanisms to help counteract their word recognition difficulties may help separate the issues of reading skill and ventral stream involvement.

There was also the issue of whether presenting the stimuli against a red background in experiments six, seven and eight really did inhibit the functioning of the magnocellular pathway and did not just general decrease the visibility of the stimuli. However, we did find that non-words were not affected by the red background (experiment 7) and so we concluded that the parafoveal deficit exhibited when the stimuli were presented against a red background was not simply due to visual acuity.

One of the main difficulties with lateralised research is that it is difficult to ensure that the participants are constantly maintaining fixation on the centre of the visual field. We controlled for this in experiment five by using an eye-tracker so that we could ensure that the participants were fixating on the centre of the screen before we initiated each trail. However, at the time of conducting experiments six, seven and eight, we only had access to a DPI eye-tracker and we could not present the stimuli against a coloured background using the available software. In future experiments we suggest that a more flexible eye-tracker is used that has software that allows for such manipulations of the stimuli.

It is also difficult to make any firm assertions about parafoveal preview in sentence reading when we only tested the recognition of isolated words in these experiments. The data in this thesis only provides information about the perception and recognition of single words when they are viewed in the area of the visual field that is perceived by the parafovea. We can only speculate about the implications for parafoveal preview in sentence reading. In future work we hope to extend our findings to the recognition of words in the context of a sentence.

7.3 Suggestions for Future Research

In future research we plan to extend the findings of the experiments in this thesis to studies in which we look at words in the context of sentences. As previously stated, we can only speculate about the impact of magnocellular inhibition on parafoveal preview in sentence reading based on what we found about the parafoveal perception of words viewed in isolation. In future studies we plan to conduct experiments in which we inhibit the magnocellular visual pathway during sentence reading using the same technique that we employed in this thesis. We can then examine the impact of magnocellular inhibition on parafoveal preview benefit with varying types of stimuli. For instance, we can test whether participants will have reduced preview benefit and be limited to orthographic facilitation when the magnocellular pathway is inhibited. We can vary the preview words regularity or frequency.

In these future experiments we also plan to control more strictly for the participants reading skill level. We found a great deal of variation in the reading levels of the dyslexic participants in the present studies. We did not control for the level of reading skill of the control group participants. In future we feel that it is important to do so. It would also be interesting to compare primary school age children on sentence reading with magnocellular inhibition. If, as suggested by previous research (e.g., Aghababian & Nazir, 2000), all young children (dyslexic or not) rely on dorsal stream processing then we would expect to find less difference in the impact of magnocellular inhibition between young dyslexic and control readers and non-dyslexic adult readers. This will provide support for the idea that inhibiting the magnocellular pathway does inhibit dorsal stream processing and that all readers when learning to read initially rely on dorsal stream processing.

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