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**THE USE OF ISOLUMINANT STIMULI TO IDENTIFY THE ROLE OF THE
MAGNOCELLULAR PATHWAY IN WRITTEN WORD RECOGNITION**

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Abstract

Previous research has indicated that information carried by the Magnocellular (M) pathway may be used in written word recognition and reading, although these findings are far from conclusive. The precise nature of this potential role of the M pathway in word recognition is also unclear, with some researchers suggesting that it is to convey word-level shape information whilst other researchers have indicated that the M pathway's role may relate to attentional selection. Eight experiments are reported that used isoluminant stimuli to investigate the validity of these claims. Experiment 1 examined the use of Heterochromatic Flicker Photometry to create isoluminant stimuli and in particular, the effect of stimulus type on the luminance ratios obtained. Experiments 2-4 investigated the recognition of words, pseudowords and illegal nonwords under isoluminant and non-isoluminant conditions in a Reicher-Wheeler task. Experiment 5 was a further Reicher-Wheeler task experiment in which case type (lowercase, UPPERCASE, and MiXeDcAsE), stimulus type and target luminance were varied. The recognition of isoluminant and non-isoluminant letter and nonletter strings were compared in Experiments 6 and 7. Experiment 8 used a similar design to previous experiments to investigate whether the recognition of isolated letters might also use M pathway information. These experiments revealed that with lowercase words, accuracy in the Reicher-Wheeler task is reduced at isoluminance in comparison to perception under non-isoluminant conditions, indicating that M pathway information is used in the recognition of these stimuli. Furthermore, this reduction in accuracy at isoluminance was shown to extend to pseudowords and illegal nonwords, to words and nonwords presented in upper and mixed case, and to isolated letters. However, with nonletter strings, no reduction in

accuracy at isoluminance was obtained in the Reicher-Wheeler task. The implications of these findings for the various theoretical explanations of the M pathway's role in written word recognition are discussed.

Chapter 1

Introduction

1. Written word recognition

The way in which humans recognise written words has been an area of debate in psychology ever since the pioneering research carried out by Cattell (1886). By presenting letter strings for short durations and making participants report as much as possible, Cattell discovered that briefly presented words are identified more accurately than random letter strings, a phenomenon now known as the Word Superiority Effect (or Lexical Status Effect). Since then, research into written word recognition has uncovered further phenomena, such as the Word-Letter Effect (Johnston & McClelland, 1973; see also Jordan & Bevan, 1994, 1996), which is the finding that with brief presentations, participants are more accurate at identifying letters presented in words than letters presented in isolation. The identification of such phenomena has greatly aided the development and testing of theories designed to explain the processes involved in written word recognition by suggesting which physical characteristics of words are encoded by the reader.

2. Holistic models of written word recognition

In recent years a number of different theories of word recognition have emerged. These can be broadly divided into analytical and holistic models. Analytical models assume that word-level codes are formed from their component letter units (e.g. the Interactive Activation model: McClelland & Rumelhart, 1981; the Activation-Verification model: Paap, Newsome, McDonald & Schvaneveldt, 1982; the Process model: Besner & Johnston, 1989). In contrast to these, holistic models emphasise word-level as well as analytical processing.

The idea that words might be processed holistically has been around for a long time (Pillsbury, 1897), although in recent years most models of word recognition have been analytical, taking individual letters or letter features as the basic components of analysis. However, there are several current models that emphasise word level processing (e.g. the Unitization Model: Healy, Oliver & McNamara, 1987; the Parallel Input Serial Analysis (PISA) model: Allen & Madden, 1990; Allen & Emerson, 1991; the Holistically Biased Hybrid model: Allen Wallace & Weber, 1995). For the purpose of this thesis, it is the Holistically Biased Hybrid model that is of particular interest as it is based around the physiology of the visual system.

The Holistically Biased Hybrid model is a “horse race” framework, inspired by the earlier models of Healy et al. (1987) and Allen and Madden (1990). Following on from models as far back as that of Coltheart, Davelaar, Jonasson and Besner (1977), the Holistically Biased Hybrid model claims that there are two main pathways: phonological, where written words are converted into a speech based code prior to recognition, and orthographic, where there is direct visual access to the lexicon. These two pathways are necessary due to the irregular nature of language. The orthographic pathway has word-level, syllable-level and letter-level channels, and the phonological pathway has syllable and letter-level channels. All of these channels process information independently and in parallel. For the majority of experimentation into this model, it is assumed that the orthographic pathway is used most of the time, and just the letter-level and word-level channels are examined for simplicity. It is proposed that the word-level channel uses the spatial frequency patterns of whole words as its basic unit of analysis, whereas the letter-level channel uses the spatial frequency patterns of individual letters.

According to Allen et al. (1995), when reading text, it is the word-level channel that normally wins the “horse race” to the lexicon. This is because the letter-level channel cannot directly access the mental lexicon. In order to generate a word level code from letter level information, a process similar to Fourier synthesis called superposition needs to occur. As this process needs to use the “smart” central processor, it is a more time consuming approach to lexical access than using the word-level channel, which is essentially “dumb” (Allen & Madden, 1990). It is therefore proposed that the letter-level channel is used only in unusual circumstances, when activation via the word-level channel is insufficient for lexical access. For example, when the input is degraded through the use of brief exposure durations, the low familiarity of the spatial frequency pattern of nonwords means that the levels of activation in the word-level channel are not enough to output a code. This means that judgements about such strings can only be made by creating a pseudoword-level code through the superposition process. Similarly, when letter strings (both words and nonwords) are presented in mixed case, the familiarity of the associated spatial frequency pattern is extremely low and thus the recognition process needs to rely upon information from the letter-level channel. Allen et al. (1995) further propose that the word-level channel is sensitive to word frequency, with higher frequency words enjoying an encoding advantage, something which is not present in the letter-level channel.

3. Evidence for holistic processing in written word recognition

The idea that we use word-level shape information in word recognition is a controversial one, and although a number of studies have supported this idea (e.g. Boden & Giaschi, 2000; Fisher, 1975; Haber, Haber & Furlin, 1983; Jordan & Scott-

Brown, 1999; McClelland, 1976; Monk & Hulme, 1983; Wheeler, 1970), there are several others that have failed to find any evidence of use of word shape (e.g. Besner, 1989; Paap, Newsome & Noel, 1984).

Most studies investigating word shape have used a definition describing shape in terms of the patterns of “ascenders” (e.g. b, d, l), “descenders” (e.g. g, p, q), and “neutral letters” (e.g. a, c, e). For example, the word leak would have the shape ANNA. However, there are several problems with this kind of approach to providing evidence for holistic processing (Jordan & Scott-Brown, 1999). First, according to this definition, the following letter strings have the same shape:

ccclllcc

mmmdddmmm

Both of these have the same pattern of ascenders and neutral letters, but they clearly cannot be defined as having the same shape, thus the definition is an oversimplification. Second, the definition is not compatible with models like the Holistically Biased Hybrid model (Allen et al. 1995), which, as stated above, claims that the basic units of analysis in written word recognition are the spatial frequency patterns of whole words. Evidence that we at least acquire spatial frequency information from text during reading comes from a study in which participants were required to read a screen filled with lowercase text. Contrast sensitivity functions were measured before and after reading. It was found that participants adapted to the principal spatial frequency of the text, resulting in reduced contrast sensitivity at that spatial frequency (Greenhouse, Bailey, Howarth & Berman, 1992). Finally, by defining word shape in terms of ascenders, etc., there is the implication that in order to identify the shape of the word there must first be some analysis of the individual

letters. Therefore the use of such information would still be essentially an analytical approach to word recognition. By instead defining word shape as the pattern of low spatial frequency information that spans the whole word, the need for any kind of individual letter analysis is avoided.

It is possible to spatially filter stimuli so that they contain only low spatial frequency shape information, either through mathematical algorithms or through placing a ground glass filter in front of the screen. Legge, Pelli, Rubin & Schleske (1985) measured reading rates for text scrolled across the screen with a range of different filters. They found that reading rate was unaffected by bandwidth at above 2 cycles/character. At bandwidths below this level, reading rate fell with decreasing bandwidth. This suggests that reading is unimpaired when higher spatial frequency information is removed from the input through blurring. It is only below a critical bandwidth of 2 cycles/character, when relatively low spatial frequency (word shape) information is also removed that reading speed is affected, indicating that such low spatial frequency shape information can be utilised for the purposes of reading.

Research has shown that readers are able to identify words that have been spatially filtered so that only coarse-scale information remains, even if these are presented at brief exposure durations. Jordan and Scott-Brown (1999) spatially filtered lowercase words to leave only low spatial frequency word shape information. Stimuli were presented onscreen for 50 ms, and participants responded in a two forced-choice (Reicher-Wheeler) procedure. The two choices had the same pattern of ascenders, descenders and neutral letters when presented in lowercase, although the choices were shown in uppercase to prevent simple shape matching. If people were unable to gain any information from the filtered stimuli then performance in this task

would be approximately 50%. However, performance was close to 90%, indicating that readers are able to utilise coarse scale visual cues in order to obtain word information from such low spatial frequency images. Jordan & Scott-Brown (1999) provided further evidence of a role for word shape in word recognition through a priming study. Participants were required to respond to briefly presented lowercase target letter strings which were preceded by equally brief low spatial frequency lowercase primes, which were either congruous or incongruous with the target string. It was found that despite the presentation times for primes being so brief, typically 12msec, there was a performance advantage for congruent over incongruent primes for words, indicating that word shape information had been used during recognition. Furthermore, there was no such advantage for nonwords. This fits neatly in with the Holistically Biased Hybrid model of word recognition, which would predict that any performance disadvantage for incongruent primes for nonwords should be smaller than the performance disadvantage for words as the spatial frequency pattern of such strings is unfamiliar, leading to letter-level processing.

One of the key strengths of the Holistically Biased Hybrid model is that it is able to account for findings that cannot be explained by other theories such as the Interactive Activation Model (McClelland & Rumelhart, 1981). For example, Allen et al. (1995) carried out a lexical decision task study which found that the mixed-case disadvantage was greater for nonwords than for words at longer exposure durations. However, for brief exposure durations, the mixed-case disadvantage was larger for words. This finding is predicted by the Holistically Biased Hybrid model, as for longer exposure durations, the word-level channel can be used for lexical access for words and nonwords presented in lowercase. However, when letter strings are

presented in mixed-case, the letter-level channel is used, leading to slower responses. Furthermore, the disadvantage would be greatest for the nonwords, as the letter-level pathway is able to process the familiar letter sequences of words faster than nonwords. For brief exposure durations, nonwords are processed by the letter-level channel whether presented in mixed-case or lowercase. Therefore the slowing in responses due to case mixing should be greatest for words. The Interactive Activation Model is unable to predict a result such as a larger mixed-case disadvantage for words at brief exposure duration, since it would require levels of feedback from the word-level nodes to be greater for nonwords than for words.

4. The mapping of the word level channel onto the Magnocellular pathway

In addition to its explanatory power, the Holistically Biased Hybrid model is also of particular interest due to the fact that it is based around the physiology of the visual system. In their description of the model, Allen et al. (1995) suggest that the word-level channel maps onto the Magnocellular visual pathway whilst the letter-level channel maps onto the Parvocellular pathway.

The distinction between the Magnocellular and Parvocellular (M and P) pathways is a popular one due to the potential to explain a wide range of phenomena on the basis of the anatomical and physiological differences between the two pathways. Approximately 80% of all retinal ganglion cells project to the P pathway, whilst 10% project to the M pathway (Silveira & Perry, 1991). If lesions are carried out to both pathways, little vision is left remaining (Schiller, Logothetis & Charles, 1990). The two pathways run in parallel from the retina to the lateral geniculate nucleus (LGN) whilst remaining anatomically separate (Conley & Fitzpatrick, 1989; Michael, 1988). The M ganglion cells provide input to layers 1 and 2, whilst P

ganglion cells provide input to layers 3-6. The projections from the M and P layers of the LGN to V1 are also segregated (Fitzpatrick, Lund & Blasdel, 1985). Beyond V1, the M and P pathways spread throughout a number of different areas (see DeYoe & Van Essen, 1988 for a review). The M pathway has both direct and indirect connections (via V2) to the medial temporal area (MT), from where the major outputs are to the superior temporal and medial superior temporal areas. The superior temporal area projects heavily into the posterior parietal cortex. The P pathway continues to V4 and onto the inferior temporal cortex. As the pathways extend beyond V1 there is some degree of separation, though it is far from complete (Merigan & Maunsell, 1993). However, the lack of complete segregation does not mean that parallel processing does not occur beyond V1, simply that it may be organised in a different way than “pure M” versus “pure P” (Born, 2001).

The M and P pathways differ in their responses across a range of dimensions including colour sensitivity, motion sensitivity, contrast sensitivity, spatial sensitivity and conduction velocity (e.g. Lehmkuhle, 1993; Livingstone & Hubel, 1988; Van Essen, Anderson & Fellman, 1992). Of these dimensions, the final two are of particular relevance to the mapping of the word-level and letter-level channels onto the M and P pathways. Research has shown that at any given retinal eccentricity, the average size of the centre of a receptive field is larger for M cells than for P cells. Furthermore, the inhibitory receptive field surrounds are stronger for P cells (Marroco, 1976; Schiller & Malpeli, 1978). From this it would be expected that the M pathway is more sensitive to lower spatial frequencies at any given eccentricity, and this view is supported by a number of studies (e.g. Derrington & Lennie, 1984; Legge 1978). In a review of studies Lehmkuhle (1993) found that M cells are about

10 times more sensitive to spatial frequencies below 1 cyc/deg. The difference in conduction velocity between the two pathways occurs due to M cells having thicker axons than P cells, meaning that the neural impulses travel more rapidly to the brain (Kaplan & Shapley, 1982; Marroco, 1976).

Based on this evidence, it would appear that the word and letter-level channels could map neatly onto these pathways. According to the Holistically Biased model, word-level information is carried by the M pathway, which is more sensitive to lower spatial frequencies, and thus better equipped to carry coarse-scale shape information and due to its faster conduction velocity has an advantage in the race to the lexicon. The P pathway, although having slightly slower conduction rates, is more sensitive to high spatial frequencies and is therefore well equipped to carry the fine detail required of the letter-level channel.

One potential problem with this mapping is that some physiological evidence suggests that there is considerable overlap in the spatial frequencies to which M and P pathways are most sensitive (Merigan & Maunsell, 1993). However, a lesion study by Merigan, Byrne & Maunsell (1991) clearly indicated that M pathway neurons are more sensitive at low spatial frequencies, although only at high temporal frequencies. Ibotenic acid lesions were placed on the Magnocellular layers of the LGN in monkeys. Contrast sensitivity was then measured for the detection of drifting gratings of 1 cyc/deg. At low temporal frequencies (1Hz), loss in sensitivity was minimal. At 5Hz, sensitivity was reduced following the lesion, and this reduction was even greater at 20Hz, indicating that at these higher temporal frequencies, pre-lesion sensitivity can be attributed to the M pathway. With gratings of higher spatial frequency, the loss in sensitivity was found to be negligible at all temporal frequencies, indicating

that it is mainly the Parvocellular system that contributes to contrast thresholds at these spatial frequencies. This is supported by work involving P pathway lesions (Merrigan, Katz & Maunsell, 1991). Given that in normal reading, fixation durations average about 200-250ms (e.g. Rayner & McConkie, 1976), corresponding to a temporal frequency of approximately 4-5Hz, these findings indicate that it is possible that the M pathway is used to provide low spatial frequency information, assuming that the comparison between monkeys and humans is valid.

The Holistically Biased Hybrid theory is not the only model of word recognition to claim that the M pathway is used to transmit word shape information. Chase (1996) proposes a similar model in which word recognition relies on the integration of information from the M and P pathways. In the initial stages of visual processing, low spatial frequency shape information is provided by the faster M pathway. The P pathway then provides further high spatial frequency information at a later stage of processing. According to this model, the word recognition process begins immediately with the low spatial frequency information. If sufficient information is available then words can be identified rapidly on the basis of the M pathway alone. However, when recognition is not possible, the system needs to wait for the additional information provided by the P pathway, which is then integrated with the representation already formed.

5. Alternative roles for the M pathway in reading

5.1 Saccadic suppression

The idea, proposed by both Allen et al. (1995) and Chase (1996), that word-level shape information is provided by the M pathway as part of the word recognition process is far from being the only suggested role for the M pathway in reading. One

of the earliest ideas relates to the finding that reading is characterised by a number of brief fixations separated by small saccades. These rapid eye movements typically span 8-9 characters (2 degrees of visual angle) and are on average 25-30msec in duration (Rayner & McConkie, 1976). According to Breitmeyer (1980, 1993; see also Singer & Bedworth, 1973), the transient (Magnocellular) visual subsystem is activated at the start of the saccade and suppresses the sustained (Parvocellular) system. This prevents neural activity elicited in one fixation from persisting into the next fixation and therefore producing forward masking. Unlike the theories described earlier in this chapter, this model proposes only an indirect role for the M pathway in reading and word recognition, with text being processed solely by the Parvocellular system.

This model has also been used to explain the occurrence of developmental dyslexia. It has been postulated by a number of researchers (Breitmeyer, 1993; Livingstone, Rosen, Drislane & Galaburda, 1991; Lovegrove, Martin & Slaghuis, 1986; Lovegrove & Williams, 1993) that dyslexia is caused by an M pathway deficit, which weakens saccadic suppression. Such an explanation of dyslexia is consistent with the finding that when people with dyslexia read sentences presented one word at a time, thereby keeping saccades to a minimum, reading levels are greatly increased (Hill & Lovegrove, 1993). Furthermore, the theory can also account for secondary symptoms found in people with developmental dyslexia. Martin (1974) claims that saccadic suppression has a variety of other functions, including the prevention of the perception of retinal image smear during saccades, the loss of visual direction constancy, and instability of the visual world. These symptoms were all found in

approximately 60-70% of a group of developmental dyslexics tested by Stein, Riddell & Fowler (1989).

5.2 Attentional selection

More recent research has however indicated that it is extremely unlikely that the role of the M pathway in reading is to suppress P pathway activity during saccades. A large number of researchers (Anand & Bridgeman, 1995; Bridgeman & Macknik, 1995; Burr, Morrone & Ross, 1994; Burr & Morrone, 1996; Shiori & Cavanagh, 1989; Uchikawa & Sato, 1995) have found that it is Magnocellular rather than Parvocellular sensitivity that is inhibited during saccadic suppression. This has caused researchers to search for alternative hypotheses regarding the role of the M pathway in reading and word recognition and its link with developmental dyslexia. As mentioned above, the M pathway has a strong projection to the posterior parietal cortex, a structure dealing with the allocation of attention (Maunsell, 1992; Mishkin, Ungerleider & Macko, 1983; Ungerleider & Haxby, 1994). It is therefore perhaps not unsurprising that the majority of theories have involved the allocation of attention. Researchers have identified at least three different processes in word recognition and reading that could rely upon attentional processes involving the M pathway: the covert identification of letters, the ordering of letters and the programming of saccades.

5.2.1 Attentional selection: Identification and ordering of letters

According to the spotlight model of attention (Posner, 1980), stimuli that fall within an attended location (the “spotlight”) are processed more rapidly and more accurately than those that fall outside this area. Our attention can be focussed on a particular point by two methods; either by voluntarily focussing on that location or

through an involuntary response to the abrupt onset of a stimulus (Jonides & Yantis, 1988). Of these, the later is more dominant, and will always override voluntary attention (Hikosaka, Miyachi & Shimojo, 1993). It has been postulated by a number of researchers that this attentional spotlight is guided by information provided by the M pathway (Steinman, Steinman & Lehmkuhle, 1997; Vidyasagar, 1999; Vidyasagar & Pammer, 1999).

The proposal that the attentional spotlight might be guided by the M pathway is supported by research by Steinman et al. (1997) designed to examine the optimal cue properties for evoking visual attention. A series of experiments was carried out in which the spatial, chromatic and luminance contrast properties of cues were manipulated. The findings indicated that the cues designed to stimulate the M pathway always overrule P pathway biased cues, even when these are presented first. However, it should be noted that there is evidence to suggest that attentional capture is not mediated solely by the Magnocellular system. A number of studies have shown that the appearance of a cue designed to evoke minimal responsiveness in the M pathway can still capture attention (Gellatly, Cole & Blurton, 1999; Lambert, Wells & Kean, 2003; Yantis & Hillstrom, 1994).

Vidyasagar (1999) claims that the most important aspect of learning to read may be the training of this attentional spotlight to move sequentially over the letters and words in a line of text. Any M pathway impairment would lead to difficulties in developing this ability and could therefore lead to a severe impairment in reading development. Without a smooth flow of attentional focus, children may be particularly hindered in the identification of individual letters or words as well as in the ordering of letters within words. Evidence that the M pathway is involved in letter

position encoding is provided by a study by Cornelissen, Hansen, Gilchrist, Cormack, Essex and Frankish (1998). Participants were tested on a coherent motion detection task and were split into two groups of 'good' and 'poor' motion detectors. These groups were matched on age, IQ and reading ability. The groups undertook a lexical decision task in which the nonwords used were anagrams. Good performance on this task required an ability to encode letter positions accurately. The results showed lower error rates for 'good' coherent motion detectors than for 'poor' ones. Similar findings were produced using a primed reaction time task. As coherent motion detection is thought to rely on the Magnocellular system (e.g. Cornelissen, Hansen, Bradley & Stein, 1996), these findings indicate that information processed by the M pathway may be used to facilitate the ordering of letters within words. Further support comes from a study by Cornelissen, Hansen, Hutton, Evangelinou and Stein (1998) which examined single word reading in children. Regression analysis indicated that recognition errors were best predicted by performance on a coherent motion task, even when variables such as age, IQ and reading ability were controlled for.

5.2.2 Attentional selection: Programming of saccades

The posterior parietal cortex has strong connections with the frontal eye fields and the intermediate layers of the superior colliculus, both of which are important for saccadic eye movements (Mowafy, Lappin, Anderson & Mauk, 1990). It has therefore been postulated that deficiencies in the M pathway may interfere in the planning of saccades. Steinman, Steinman and Garzia (1998) found that in people with dyslexia, the area of attentional focus is narrower and there is an area of inhibition of visual attention surrounding the attentional focus. It is argued that these

deficits could impair the planning of saccades. This in turn could have the effect of slowing the processing of peripheral words and increasing the number of abnormal fixations. This view has been supported by a number of studies showing that people with dyslexia make more erratic eye movements than controls (Pavlidis, 1981, 1985; Zangwill & Blakemore, 1972). Furthermore, research by Hendricks and Puts (2000) provide clear evidence of a role for the M pathway in the programming of saccades. A study was carried out in which participants were required to carry out a speeded task that required them to make accurate saccades. It was found that when targets were presented under conditions designed to reduce the responsiveness of the M pathway, response times were increased compared to presentations under normal conditions. This explanation is also consistent with the finding by Hill and Lovegrove (1993) described above, that reading levels for those with dyslexia are increased when sentences are presented one word at a time.

6. Evidence for a role for M pathway in reading and word recognition

6.1 Evidence for using low spatial frequencies in reading

One key source of evidence of a role for the M pathway in word recognition and reading is studies providing support for the view that lower spatial frequencies are the most important in reading. Legge et al. (1985) discovered that maximum reading rates occur when the size of characters is between 0.3 and 2.0 degrees of visual angle. Given that it was also found that the optimal spatial frequency bandwidth for reading is 2 cycles per character, this result suggests that the optimal spatial frequency range for reading is the relatively low range of approximately 1-6 cyc/deg. Furthermore, due to the methodology employed in this study, the optimal spatial frequency range may actually be lower than that implied by the results. In order to measure maximum

reading rates, text was scrolled across the screen at increasing speed. This is substantially different to normal reading, in which the eyes are scanned across the text, because it prevents the reader from using information from the periphery and also causes the text to become blurred, an effect that increases with velocity. The blurring of the text effectively removes further high spatial frequency information from the stimulus, suggesting that actual bandwidths were lower than those reported, leading to a reduced optimal spatial frequency range.

A study by Jordan and Patching (2003) used an adaptation technique, in which participants adapted to vertical gratings of various spatial frequencies and were then shown briefly presented letter strings. Perception of these strings was tested using a two-alternative forced choice (2-AFC) task. They found that for briefly presented words, performance was reduced relative to the control condition for all adaptation conditions. However, the performance deficit was greatest when participants adapted to gratings of 1 or 2 cyc/deg. In a follow up study in which exposure duration was modified in order to obtain equivalent performance across all adaptation conditions, it was the low spatial frequency (1 or 2 cyc/deg) adaptation conditions in which exposure durations were the longest. These findings indicate that whilst a range of spatial frequency information is important for written word recognition, lower spatial frequencies are in fact the most crucial. This conclusion is supported by the study by Jordan and Scott-Brown (1999) described above, as well as by an experiment by Boden and Giaschi (2000) in which briefly presented low spatial frequency filtered words were shown to be particularly effective primes in a word recognition task.

An experiment carried out by Chase (1996) provides evidence that low spatial frequency information is particularly important for words rather than nonwords. A 2-

AFC paradigm was used in which high frequency words and random letter strings were presented tachistoscopically. These were either spatially filtered so that just high spatial frequency information remained or presented normally with the full range of spatial frequencies available. It was found that whilst a normal word superiority effect was obtained for the full spatial frequency stimuli, with the high spatial frequency stimuli there was no difference in performance between the word and nonword conditions. This suggests that low spatial frequency information plays a particularly important role in facilitating the recognition of familiar words.

6.2 Studies involving dyslexics

A large proportion of the work investigating the role of the M pathway in reading and word recognition has taken the form of studies examining readers with developmental dyslexia. If conclusive evidence were found to suggest that readers with dyslexia suffer from a Magnocellular deficit, then this would help support claims that the M pathway plays a role in reading. A review of studies measuring contrast sensitivity in people with dyslexia was carried out by Skottun (2000). If contrast sensitivity is reduced at low spatial frequencies for dyslexics, this would indicate reduced M pathway functioning. However, out of the 22 studies examined, only three found hints of reduced contrast sensitivity for spatial frequencies below 1.5 cyc/deg (Borsting, Ridder, Dudeck, Kelley, Matsui & Motoyama, 1996; Cornelissen, Richardson, Mason, Fowler & Stein, 1995; Martin & Lovegrove, 1988) and these deficits were not statistically significant. Four of the studies showed reduced contrast sensitivity in dyslexic readers at low to mid spatial frequencies (below 8 cyc/deg), providing partial support for a role for the M pathway, whilst seven found no deficit at any spatial frequency. However, 11 of the studies provided positive evidence against

the Magnocellular deficit theory, showing either deficits solely at high spatial frequencies or deficits which were most pronounced at high frequencies.

Several studies have shown that visual search times and reading speeds of people with dyslexia are improved by blurring the text (e.g. Williams, Brannan & Lartigue, 1987; Williams & Lecluyse, 1990). Williams, May, Solman and Zhou (1995) argue that these findings were due to the reduction in contrast which accompanied the blur. They found that visual search performance was increased for dyslexic participants when contrast was lowered. According to Williams et al., this performance enhancement occurs because low contrast stimuli maximally activate the M pathway and therefore improve its deficient response. However, again not all studies have produced such results. Hogben, Pratt, Dedman and Clark (1996) failed to find any improvements in reading in dyslexics due to blurring the image, and a study by O'Brien, Mansfield and Legge (2000) showed no increase in reading rates for low contrast text.

One further source of support for Magnocellular deficit theories of dyslexia comes from metacontrast masking studies. In metacontrast masking, the perception of a target stimulus is affected by the presentation of a spatially adjacent masking stimulus. According to one theory, metacontrast masking occurs due to suppression of Parvocellular responses by the Magnocellular system (Breitmeyer & Ganz, 1976). This theory claims that both the target and the mask elicit brief Magnocellular responses followed by sustained Parvocellular ones. Suppression occurs when the M pathway response to the mask is superimposed on the P pathway response to the target that preceded it. Two studies have examined metacontrast masking in participants with dyslexia (Edwards, Hogben, Clark & Pratt, 1996; Williams, Molinet

& LeCluyse, 1989). Both studies found that masking was reduced in dyslexic readers compared to a control group. These findings were interpreted as supporting Magnocellular deficit theories of dyslexia. However, Skottun (2001) cast doubt on whether reduced metacontrast masking can be taken as evidence for reduced M pathway sensitivity. A review of studies involving metacontrast masking has shown that the masking effect is largest when the target precedes the masking stimulus by 30-100 msec (Lefton, 1973). However, given that the difference in latency between the M and P pathways has been shown to be as little as 5.5 msec (Nowak & Bullier, 1997) it is difficult to account for such optimal stimulus onset asynchronies by the differences between M and P cells.

In conclusion, the evidence from studies involving dyslexic readers discussed above indicates that there may well be a role for the M pathway in written word recognition and reading, although this evidence is far from unequivocal. One possible reason for this is that it may only be a subgroup of those with developmental dyslexia who suffer from a Magnocellular deficit (Borsting et al., 1996; Cestnick & Coltheart, 1999; Ridder, Borsting, Cooper, McNeel, Huang, 1997; Slaghuis & Ryan, 1999). Lovegrove et al. (1986) has estimated that, based on participants in their research, approximately 60-70% of people with dyslexia could have such a deficit.

7. The use of isoluminant stimuli

Given the uncertain nature of the evidence presented above, a different approach to examining the role of the M pathway in word recognition is clearly needed. One potential method, which has been used by a relatively small number of studies to date, is to take advantage of the difference in the M and P pathways' sensitivity to colour.

7.1. Introduction to isoluminance

Whereas M cells obtain input from all types of cones, about 90% of P cells obtain input from specific pairs of cone types (the remaining 10% sum the inputs from all cone types). Some P cells have excitatory inputs from red cones to their centres and inhibitory inputs from green cones to their surrounds and vice versa. Other P cells have blue centres and yellow surrounds (made by summing the response from red and green cones) and vice versa. Thus, whilst the majority of P cells produce centre and surround responses to specific colours, M cells respond to all wavelengths (e.g. De Valois & Jacobs, 1968; Wiesel & Hubel, 1966). This means that whilst the P pathway is sensitive to colour, the M pathway cannot distinguish between colours and so can distinguish only differences in luminance. Lesion studies confirm that damage to the P pathway leads to a complete loss of colour vision, whereas M pathway lesions leave colour vision intact (Merigan, Katz & Maunsell, 1991).

This difference in the ability of the pathways to process colour means that it is possible to impair abilities reliant specifically on the M pathway by using isoluminant (or equiluminant) displays. These are displays containing no luminance differences and differing only in chromaticity. For example, presenting red text on a green background, where the background and foreground have the same luminance. As there are no differences in luminance between the components of this display, the M pathway should not be able to distinguish between them. This technique has been used in many different areas to investigate the contributions of the two visual pathways, including depth perception and perspective (Livingstone & Hubel, 1987), object localisation, (Anderson & Yamagishi, 2000; Graves, 1996), scene segmentation (Leonards & Singer, 1997) and feature binding (Lehky, 2000).

7.2 Word/Letter recognition studies using isoluminance

A number of studies have been carried out using words/letters under different chromaticity/luminance conditions. Legge and Rubin (1986) carried out a study examining the effect of the colour of text on reading. They found that in normal readers, the wavelength of text did not have any real effect on reading rates, except at very low luminance levels (0.006cd/m^2). Research has shown, however, an effect of luminance contrast on reading speed, though the evidence in this area is not clear-cut. One of the earliest studies was carried out by Tinker and Paterson (1931), who examined reading times for different coloured inks on different coloured paper. They found that reading time was affected by the different paper/ink combinations. However, it was suggested that rather than colour itself affecting reading time, it was the luminance contrast between the paper and the ink. Unfortunately, the methodology used in this study limited their ability to test this conclusion effectively.

Legge, Parish, Luebker and Wurm (1990) carried out a study examining the effect of colour and luminance contrast on reading rates. It was found that high colour contrast isoluminant text can support reading rates as fast as those obtained with high luminance contrast text, despite the fact that colour information should be carried solely by the P pathway. It was only when colour contrast was low that reading rate was found to be affected by isoluminance. This finding would suggest that reading is not impaired when the M pathway activity is reduced by isoluminance, and that the sensory information required for word recognition is carried solely by the P pathway. This view is supported by a study by Travis, Bowles, Seton and Peppe (1990) who also found near-perfect reading at isoluminance. However, an experiment using a methodology similar to Legge et al. (1990) obtained slightly more promising

findings (Knoblauch, Arditi & Szlyk 1991). Knoblauch et al. compared reading rates for isoluminant text with those obtained with high and low luminance contrast achromatic text. The results suggested that reading levels were between the two: Reading rates with isoluminant text were faster than with low luminance contrast achromatic text, but slower than with high luminance contrast achromatic text. As a previous comparison had found no difference in performance between achromatic and chromatic text when luminance contrast is high, it can be extrapolated that reading rates with isoluminant stimuli would be lower than with non-isoluminant chromatic stimuli. Hence this study provides tentative evidence that impairment of the M pathway can reduce reading performance.

There are, however, a number of methodological issues associated with both the Legge et al. (1990) and Knoblauch et al. (1991) studies. One of the main problems is that these experiments examined the effect of luminance and chromatic contrasts by measuring reading rate, examining the number of words read per minute by asking participants to read sentences aloud. In the Knoblauch et al. study, sentences were scrolled through a 6 character wide window, and this was done at increasing speeds until participants were unable to read the text. It is probable that this is an ineffective method of examining perceptual phenomena in reading, and is likely to be affected by post perceptual factors to quite a large degree (see discussion of research by Santee & Egeth, 1982, in Chapter 3). As mentioned above, scrolling text across the screen has the effect of blurring the text, and effectively lowering the spatial frequency content of the stimuli. Furthermore, using such a small window to view the text through (6 characters) prevents participants from being able to take information from the periphery as they would in normal reading. If readers do use

low spatial frequency shape information whilst reading sentences, it is quite likely that they can and do extract this from the periphery, meaning that the design of these experiments could possibly prevent participants from taking advantage of information that would otherwise be processed by the M pathway. When combined with the small number of participants used in these studies and the lack of statistical analysis, it is difficult to make strong conclusions about the effect of luminance and chromatic contrasts.

Chase, Ashourzadeh, Kelly, Monfette and Kinsey (2003) carried out a word recognition experiment using isoluminant stimuli. It was found that when stimuli were presented at isoluminance, reaction times were faster when stimuli were viewed through a red filter. However, separate experiments found that when non-isoluminant stimuli were used, the red filter impaired reading performance. This was interpreted as evidence that the M pathway is the main visual pathway used in written word recognition. The reasoning behind this interpretation is that whilst M ganglion cells are generally thought of as purely broadband, there is evidence that their inhibitory surrounds are in fact red dominant (De Monasterio, 1978, Livingstone & Hubel, 1984). With non-isoluminant stimuli, Chase et al. (2003) argued that the red light inhibited the responding of the M pathway and thus impaired reading performance. When stimuli were presented at isoluminance, M pathway functioning was already reduced and word recognition performance was improved with filtered text due to the red light enhancing functioning in the P pathway (Breitmeyer & Breier, 1994).

Unfortunately, the conclusions that can be drawn from Chase et al. (2003) are limited by a number of factors related to the design of the experiments. First, this study relied on using onscreen luminance matching to create the stimuli, but it has

been shown that this does not necessarily produce isoluminance in the retinal image or post-retinal responses (e.g. Bilodeau & Faubert, 1997; Dobkins, Gunther & Peterzell, 2000; Livingstone & Hubel, 1987; see Chapter 2 for further discussion). Second, the experiments using isoluminant and non-isoluminant stimuli were not directly comparable. Whilst the experiment using isoluminant stimuli involved a word recognition task in which reaction time was the key measure, the other experiments utilised a passage reading task in which differences in accuracy but not reading time were discovered.

Support for M pathway involvement in word recognition has also come from studies involving the recognition of flanked letters (Lehky, 2000; Omtzigt, Hendricks & Kolk, 2002). The studies by Omtzigt et al. (2002) provide evidence to suggest that the M pathway plays a role in attentional selection. The experiments involved the recognition of briefly presented isolated letters and letters flanked by two distracters (e.g. xax). These stimuli were presented either at isoluminance (colour contrast condition) or in a luminance contrast condition in which the target differed from the background only in respect to its luminance. Omtzigt et al. found that there was no significant difference in recognition performance between the colour contrast condition and the luminance contrast condition for isolated letters. However, for flanked letters, performance was significantly poorer in the colour contrast condition than in the luminance contrast condition. Similar results with flanked letters were obtained by Lehky (2000) and these findings provide evidence for M pathway involvement in written word recognition and reading, although not for the mapping of the word-level channel described in the Holistically Biased Hybrid Model onto the M pathway. According to Allen et al. (1995), strings such as 'xax' should be processed

by the letter level channel, which maps onto the P pathway. Therefore no reduction in performance at isoluminance should be expected. However, these results do fit neatly with the attentional selection explanation. As letter ordering was irrelevant and saccades were minimised in this study, it is likely that any potential attentional function of the M system in carrying out a task such as this would relate to the letter identification function of attentional selection. Whereas it can be assumed that attention is automatically directed towards an isolated letter, recognition of a flanked letter presumably involves a process of attentional allocation to distinguish it from the two distracters. If attentional selection is impaired at isoluminance, it should therefore be expected that performance should be reduced for flanked letters but not for isolated letters, as was found in this study. Unfortunately, although the findings of Omtzigt et al. (2002) and Lehky (2000) do provide evidence that the M pathway is used in written word recognition, the usefulness of both studies is limited somewhat due to the way in which the isoluminant stimuli were produced. These issues surrounding the creation of isoluminant stimuli are discussed thoroughly in Chapter 2.

7.3 Criticisms of the use of isoluminant stimuli

Although isoluminance has been used in many experiments to separate the influences of the M and P channels, the technique is not without controversy, and has been drawn into doubt by several papers (e.g. Breitmeyer, 1992; Logothetis, Schiller, Charles & Hurlbert, 1990; Schiller & Logothetis 1990). The main potential problem is the debate over the exclusive ability of the Parvocellular system to operate at isoluminance. Logothetis et al (1990) carried out a study in which Rhesus monkeys had to detect red-green stimuli of various luminance and colour contrasts. They found that at isoluminance, abilities that are assumed to be carried by the Parvocellular

system were also impaired, and that abilities carried by the Magnocellular system, whilst being impaired were not completely wiped out. However, other researchers have found that M cells do not respond at isoluminance, whilst P cells can continue to respond normally (Derrington, Krauskopf & Lennie, 1984; Hicks, Lee & Vidyasagar, 1983; Lee, Martin & Valberg, 1988; Shapley, Reid & Kaplan, 1991). Furthermore, other research has shown that the P cells are specifically designed to respond at isoluminance (Reid & Shapley, 1992), making the findings of Logothetis et al. (1990) difficult to interpret. Shapley (1994) further points out that the conclusion reached by Logothetis et al. (1990), that reduced performance at isoluminance cannot be attributed to the contributions of the M and P pathways, does not follow from their data. Following their data, it should be expected that other groups of Parvocellular neurons would be silenced at different luminance contrasts, with no particular reduction in the number of Parvocellular neurons responding at isoluminance compared to other luminance contrasts.

Logothetis et al. (1990) carried out a further experiment, which indicated that there is variation in the luminance contrast ratio at which the balance point (the point where cells responded equally to Red and Green light) occurs for M cells. Using a single cell recording technique in Rhesus monkeys, they presented displays to the cells' receptive field that were at and around the behaviourally established isoluminance point. They found that whilst some M cells responded equally to red and green light, some cells responded more to one than the other. Overall they found that the M cells had a range of balance points, meaning that no single luminance ratio could silence all of the cells. However, the usefulness of this experiment is limited by the fact that the cells tested were in different locations across the visual field. As it

has been shown that isoluminance points vary across the visual field (See discussion of Bilodeau & Faubert, 1997; in Chapter 2), it would be expected that the balance points of these cells should be different from each other. Therefore this finding might not be a serious a problem for studies using isoluminant stimuli to impair abilities reliant on information carried by the M pathway.

Another potential barrier to using isoluminance in research examining word recognition is that of chromatic aberrations. Transverse chromatic aberrations can produce a wavelength-dependent spatial shift in the retinal image. With chromatic stimuli, spatial skewing occurs at lower wavelengths, which results in slight differences in luminance. It should be noted, however, that this is not so much of a problem for foveal presentations (see Knoblauch et al, 1991, for a discussion). These chromatic aberrations might explain why Logothetis et al. (1990) found that isoluminant stimuli produced only major impairment in abilities relying on the M pathway, rather than completely wiping them out. The small luminance differences occurring due to chromatic aberrations might be enough to allow a small amount of Magnocellular functioning.

Despite these possible difficulties, isoluminance remains a potentially useful technique for identifying whether the M pathway is used in word recognition and reading. It is not necessary to completely eliminate M pathway functioning in order to achieve this aim and a condition that can strongly bias the relative contributions of the M and P pathways would prove sufficient.

7.4 The effect of background colour

An additional technique that could be used to complement the effect of isoluminance in impairing recognition using the M pathway is the use of diffuse red

backgrounds. Findings using this technique have shown that presenting green stimuli on an isoluminant red background impairs abilities reliant on the M pathway more than red stimuli on a green background (e.g. Breitmeyer, May & Williams, 1989), a finding which presumably relates to the fact that, as mentioned above, the surrounds of many M cells are red dominant rather than purely broadband (e.g. De Monasterio, 1978; Livingstone & Hubel, 1984). This means that the presentation of a red background inhibits the responding of these cells. Edwards, Hogben, Clark and Pratt (1996) used this technique in a study examining metacontrast masking. They found that when a red background was used, the magnitude of the metacontrast masking was reduced (i.e. performance was increased), compared to when a white background of equal luminance was used. This finding fits in with the theory by Breitmeyer and Ganz (1976) that metacontrast masking occurs due to the suppression of P pathway responses by the M pathway.

8. The present research

The review of literature suggests that the Magnocellular system may play a key role in written word recognition, either in providing holistic shape information, in attentional selection or through some other function not yet identified. However, the evidence is far from conclusive. The most promising approach for investigating the role of the M pathway in the context of reading and written word recognition is the use of isoluminant stimuli, but only a limited number of studies in this area have been carried out to date and these suffer from methodological limitations. The aim of this research project was therefore to use isoluminance to ascertain whether the M pathway is used in word recognition and to shed light on the nature of its role.

8.1 Experiment 1.

Chapter 2 discusses the need for using an approach such as Heterochromatic Flicker Photometry (HFP) to create isoluminant stimuli. Although previous research using gratings has indicated that under some circumstances the luminance ratios obtained using HFP can vary according to spatial frequency, no studies have examined HFP using real world stimuli. Experiment 1 therefore compares HFP using four different stimulus types to identify whether the luminance values obtained are consistent. The different stimulus types included large squares, which a pilot study had identified as stimuli with which participants found it easy to carry out the HFP task, and text flickered on a large square background, a stimulus type close to that which might be used in a word recognition experiment. If no differences in the luminance values needed to achieve minimal flicker were found then this would indicate that isoluminance is not affected by stimulus type. If however, differences were found in the luminance ratio needed, this would highlight the importance of carrying out HFP using stimuli that are appropriate for those used in the experiment proper.

8.2 Experiments 2 and 3.

The experiments reported in Chapter 4 (Experiments 2 and 3) investigate the recognition of words and illegal nonwords under isoluminant and non-isoluminant conditions. If the M pathway is used in written word recognition, it would be expected that word recognition performance should be lower when stimuli are presented under isoluminant conditions, compared with when the stimulus is either lighter or darker than the background. Furthermore, if the isoluminance disadvantage occurred either exclusively with words or was greater in magnitude with words than

nonwords then this would suggest that words are initially processed differently to nonwords, with M pathway information being used only in the processing of the former, whilst the latter relies solely on P pathway information. Two different versions of the experiment were carried out in order to identify which of two variations of the HFP calibration task was most appropriate for producing isoluminant stimuli.

8.3 Experiment 4

The experiment reported in Chapter 5 (Experiment 4) represents a progression from those described in Chapter 4. This experiment compared recognition performance under isoluminant and non-isoluminant conditions using both illegal nonwords and pseudowords. As with the previous experiments, reduced performance at isoluminance would indicate M pathway involvement in the letter string recognition process. A difference in the magnitude of the isoluminance disadvantage for illegal nonwords and pseudowords would suggest that the two types of letter string were being processed using different processes.

8.4 Experiment 5

To investigate the idea that the M pathway is used solely in the recognition of conventionally presented words, the experiment reported in Chapter 6 (Experiment 5) employed a case mixing methodology. Words and illegal nonwords were presented either in lowercase, UPPERCASE or MiXeDcAsE under isoluminant and non-isoluminant conditions. If a reduction in performance at isoluminance was found for lowercase words but not for mixedcase words then this would suggest that the shape of mixed case stimuli is too unfamiliar to allow M pathway information to be utilised during recognition. If, however, performance was reduced at isoluminance for all

letter string types and under all case conditions this would indicate that the M pathway is used in the recognition of all letter strings even when shape information is distorted through case mixing.

8.5 Experiments 6 and 7

The experiments reported in Chapter 7 (Experiments 6 and 7) examined whether there is any evidence to suggest that whilst M pathway information is used in the processing of letter strings, other character strings are processed using only P pathway information. To investigate this, letter strings (illegal nonwords) and nonletter strings were presented under isoluminant and non-isoluminant conditions in a recognition task similar to that used in the previous experiments. If recognition performance was lower in the isoluminant condition than in the non-isoluminant condition for letter strings but not for non-letter strings then this would support the idea that M pathway information is used only for letter strings and not other multi-contoured linear arrays. However, if both letter and nonletter strings are initially processed in a similar fashion, then no differences in the magnitude of any isoluminance deficit would be expected.

8.6 Experiment 8

To investigate whether information from the M pathway is used in the recognition of isolated letters, the experiment reported in Chapter 8 (Experiment 8) compared the recognition of four-letter words with that of isolated letters under isoluminant and non-isoluminant conditions. If the role of the M pathway were limited to the recognition of words and letter strings then a performance deficit at isoluminance would be expected for words but not for isolated letters. If, however, M

pathway information is used in the recognition of both words and isolated letters
performance should be reduced at isoluminance for both stimulus types.

Chapter 2

Experiment 1

1. Creating isoluminant stimuli

1.1 The need for using Heterochromatic Flicker Photometry

The generation of isoluminant stimuli is not a straightforward matter. The simplest method is to match on-screen luminance so that both the foreground and background have the same physical luminance, as measured by a photometer. However, on-screen isoluminance does not guarantee that stimuli are isoluminant in either retinal images or post-retinal neural responses. A technique called Heterochromatic Flicker Photometry (HFP) can be used to ascertain more accurately what people perceive as isoluminant. In this technique, one stimulus is flickered with another stimulus of a different colour. Participants are required to adjust the luminance of one of the component colours until the amount of visible flicker is minimal.

HFP has been shown to be an effective method of creating isoluminant stimuli. Regan and Lee (1993) compared the results of the HFP task with visual evoked potentials (VEPs) recorded from electrodes attached to the human occipital scalp, and single cell responses from the retinal ganglion cells of macaques. It was found that the spectral-sensitivity curves were very similar for all three of these measures. This finding is supported by research by Di Russo, Spinelle and Morrone (2001). They obtained isoluminance using HFP and recorded VEPs from the midline and right side for each human participant for stimulus presentations at the isoluminance point and other nearby points. Di Russo et al. found that the HFP isoluminance setting equated with the lowest amplitude VEPs for all participants.

The importance of using HFP to create isoluminant stimuli rather than relying on on-screen luminance matching has also been demonstrated by studies in which the ratio of red and green needed for minimal flicker varied across the visual field. Bilodeau and Faubert (1997) examined the isoluminance points for red/green gratings using a variation of the HFP task. Participants were presented with red and green gratings moving in opposite directions and were required to adjust the luminance contrast of the red grating until they could no longer detect motion. Bilodeau and Faubert (1997) found that when gratings were presented to the fovea, the red and green component luminances required were not physically equal. Instead, a lower red contrast was needed to match the green (see also Dobkins, Gunther & Peterzell, 2000; Livingstone & Hubel, 1987). Moreover, Bilodeau and Faubert (1997) found that isoluminance points changed over the visual field, with the amount of red contrast needed to match the green increasing with greater retinal eccentricity. These findings affirm the notion that on-screen isoluminance does not necessarily produce isoluminance in the retinal image or post-retinal responses. Thus it is vital that a technique such as HFP is used for the creation of isoluminant stimuli.

1.2 The effect of stimulus type on HFP

An important consideration when carrying out written word recognition experiments using isoluminant stimuli is the extent to which different stimuli affect the luminance values obtained for minimal flicker in HFP. There is evidence from psychophysical research, using gratings as stimuli, to suggest that the values obtained may be affected by the spatial and temporal properties of the stimuli used in the task to achieve isoluminance. Cavanagh, MacLeod and Anstis (1987) examined red/green isoluminance at different temporal and spatial frequencies. They found little or no

effect of spatial frequency on the ratio of red to green required to achieve isoluminance. However, the luminance of green required to match the red increased with greater temporal frequency. Conversely, with green/blue stimuli, the isoluminance ratio was influenced by spatial, but not temporal frequency. Metha and Mullen (1996) found that not only did the ratio required for red/green isoluminance depend on temporal frequency, but also varied between individuals. An effect of spatial frequency of gratings on red/green isoluminance values was found by Dobkins et al. (2000), although only at low temporal frequencies. At low temporal frequencies, higher luminances of green were required to match the red as spatial frequency increased. However, no effect of spatial frequency was found at higher temporal frequencies. Further analysis suggested two separate mechanisms underlying isoluminance, with the Magnocellular system dominating at high temporal frequencies (8-16 Hz), but relatively more activity in the Parvocellular system at lower temporal frequencies (2-4 Hz). Therefore, to impair abilities reliant on the M pathway, higher temporal frequencies are required when creating isoluminant stimuli (i.e., above 8Hz).

Although most research in this area has relied on gratings as stimuli, an experiment by von Berg et al. (2002) studied the determination of isoluminance in the periphery with alternative stimuli using a minimum-motion technique. Using a ring made up of red and green segments, they examined the ratio of red to green luminance required to achieve isoluminance in the periphery at a range of eccentricities (1-12 deg). They found that the red:green ratio needed for isoluminance changed with increasing eccentricity and the nature of this change depended on whether the size of the segments was fixed or whether it was increased with greater eccentricity. Thus

there is some evidence to suggest that in the periphery at least, spatial scale does have an effect on the luminance ratio required for red/green isoluminance. Unfortunately, the paper fails to mention whether eye-tracking or any other method was employed to ensure central fixation was maintained during the procedure. Participants in experiments are generally poor at maintaining central fixation even for very short durations (Jordan, Patching & Milner, 1998), and any lack of controls may have affected the findings of this study.

1.3 The present study

Previous research has given an indication that the isoluminance point obtained with HFP can vary with both the spatial and temporal properties of the stimulus, with visual field position, and between different participants. The vast majority of this research has been carried out using gratings as stimuli. However, in order to investigate the role of the M pathway in written word recognition, words rather than gratings will be presented at isoluminance. It is unclear from the current literature exactly what effect changes in stimulus type may have on the values obtained for isoluminance when “real world” stimuli such as letter strings are used. Furthermore, the majority of previous research has been carried out using only a very small number of participants, meaning that the effect of individual differences across participants has not been accounted for in these studies.

Although Livingstone and Hubel (1987) made an effort to ensure that stimuli were as similar as possible in each section of the experiment when examining the loss of relative motion at isoluminance, in a large number of cases, researchers using real world stimuli carry out experiments where the displays in the calibration section differ substantially from those used in the experiment proper. For example, circular spots

during calibration and letters or letter strings in the experiment proper (Omtzigt et al., 2002; Swindale, Fendick, Drance, Graham & Hnik, 1996), circles (calibration) and line drawings (experiment; Doricchi, Incoccia & Galati, 1997), squares (calibration) and fragmented pictures (experiment; Brown & Koch, 2000), squares (calibration) and text (experiment; Legge et al., 1990), squares (calibration) and lines (experiment; Zeki, Perry & Bartels, 2003), rings (calibration) and lines (experiment; von Berg et al., 2002) and large rectangles (calibration) and small squares (experiment; Graves, 1996). Whilst the use of different displays for calibration and the experiment proper can be convenient, it relies on the assumption that the luminance values obtained from HFP are independent of the type of stimulus used. If this is not the case, there would be significant implications for how the experiments examining the role of the M pathway in written word recognition should be conducted. To address this issue, and to provide a foundation for subsequent experiments, Experiment 1 therefore compared HFP using four different stimulus conditions to examine whether the luminance values obtained are stimulus dependent. The stimulus conditions used were selected based on their suitability as potential calibration stimuli for the later experiments described in this thesis and are shown in Figure 2.1. (Note that figure numbers in this thesis begin with the chapter number).

The “Large Square” stimulus condition comprised of large red and green squares (a pilot study indicated that participants found it easy to identify the point of least flicker in this condition). The “Text” stimulus condition was composed of a red or green nonsense letter string (“xxxx”) flickered against a large square background of the other colour, and was chosen as it bore the greatest similarity to a typical stimulus used in a word recognition experiment. The “Mixed” stimulus condition was similar

to the Text stimulus condition except that instead of the letter string, a small rectangle covering the same area was flickered. The final stimulus condition, “Small Rectangle”, comprised small red and green rectangles of the same dimensions as in the Mixed stimulus condition, flickered against each other. If the isoluminance point

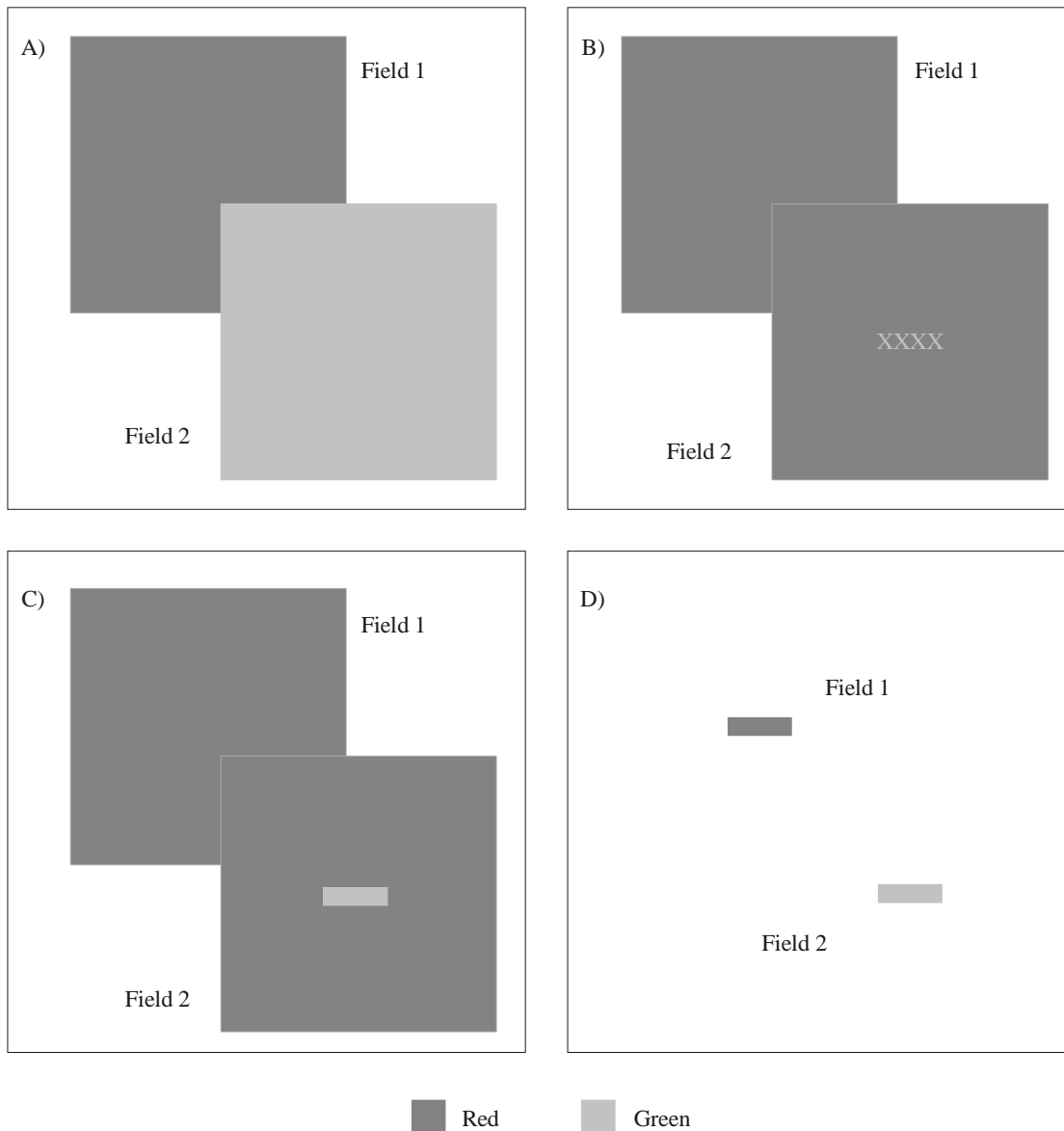


Figure 2.1. Stimulus conditions used in the experiment. a) Large Square, b) Text, c) Mixed, d) Small Rectangle. These displays were flickered at either 16 or 20 Hz. These examples are for the Green colour adjustment condition. For the Red condition, the colours in the Mixed and Text stimulus conditions were reversed.

obtained through HFP was independent of the stimuli used, this experiment should find no differences in the luminance values required for minimal flicker between the four stimulus conditions. If isoluminance is dependent on the stimuli used then differences between the luminance values obtained through HFP for the different stimulus conditions should be shown. Furthermore, any differences in the difficulty that participants had in perceiving minimal flicker would be indicated by the spread of the data for each condition. For instance, a wide range of luminance values for the different adjustment trials for a stimulus condition would indicate difficulties in perceiving minimal flicker. Two flicker rates were used (16Hz and 20Hz) and were chosen on the basis of a pilot study in which participants found it particularly easy to carry out the HFP task when these rates were used.

2. Method

2.1 Participants

Sixteen participants took part in two, one-hour sessions for which they were paid. All participants were aged between 16 and 35, and were native speakers of English. All participants reported having normal or corrected to normal vision, which was checked using a Bailey-Lovie chart (Bailey & Lovie, 1976). The participants were tested for colour blindness using the first 15 plates of Ishihara (1977) and only those with normal colour vision were allowed to participate.

2.2 Stimuli

The four different stimulus conditions used are shown in Figure 2.1. In the Large Square stimulus condition, the stimulus consisted of two squares, one red and one green, 256 pixels across, which were flickered against each other. At the viewing distance used, the squares subtended a visual angle of 8 deg. The Text stimulus

condition comprised a red or green letter string “xxxx” which was flickered against a square background of the other colour. Backgrounds were the same size as the squares used in the Large Square stimulus condition. The letter string was presented in a proportionally spaced, lowercase font (12pt Times New Roman Bold) and measured 7 pixels high by 32 wide, subtending a visual angle of 1deg horizontally. The Mixed stimulus condition was similar to the Text stimulus condition, except that the letter string was replaced by a small rectangle covering the same area as the letter string in the previous condition (7 pixels by 32 pixels). The Small Rectangle stimulus condition was composed of red and green rectangles, of the same size as in the Mixed stimulus condition, flickered against each other. The stimuli were flickered at either 16Hz or 20Hz.

2.3 Visual Conditions

The stimuli in each of the four stimulus conditions were presented on a black screen. The viewing distance was 67 cm. The chromatic and luminance characteristics of the monitor were measured using a Cambridge Research Systems ColorCAL colorimeter. The maximum luminances available for red, green and blue were 20.6, 55.7 and 5.7 cd/m^2 respectively. The CIE (x,y) coordinates of the monitor were (0.61, 0.34) for the red, (0.28, 0.60) for the green and (0.15, 0.07) for the blue phosphor. The luminance of the red and green stimuli used as backgrounds was 13.5 cd/m^2 , and the CIE coordinates were (0.61, 0.34) and (0.28, 0.59) respectively. Gamma correction was carried out so that each luminance adjustment affected the luminance of the stimulus by the same amount.

2.4 Design

All three variables were manipulated in a within-subjects design: stimulus (4 levels), flicker rate (2 levels: 16 Hz and 20 Hz) and colour adjusted (2 levels: Red and Green). For each condition there were 10 adjustment trials. The starting luminance of the colour being manipulated was randomly assigned for each trial. The order in which participants experienced the different conditions was counterbalanced.

2.5 Apparatus

The experiment was controlled by a Pentium II IBM-compatible PC fitted with a Cambridge Research Systems VSG 2/3 card. The stimuli were presented on a 21-inch Sony Trinitron monitor with a refresh rate of 160 Hz. Participants adjusted the luminance of the colour they were manipulating and their responses were recorded using a Cambridge Research Systems CT3 response box. The screen was visible through a black hood attached to the monitor with a viewfinder that participants looked through. This maintained viewing distance and aided fixation. The experiment was carried out in a darkened room.

2.6 Procedure

The experiment was split into two sessions of 80 trials each, with participants performing the task under two stimulus conditions in each session. Each participant performed a set of practice trials at the start of each session. During the experiment, participants were given a description of the stimuli being manipulated every time a new stimulus condition began, and were informed which colour it was they would be manipulating each time a block of trials was started with a new colour.

For each trial, participants were presented with a flickering display. By pressing the up and down keys on the response box they could increase and decrease

the luminance of one of the components. Participants were instructed to adjust the luminance so that the visible flicker was minimal. When they were satisfied that this had been achieved they pressed a button on the response box to confirm their response, and this was recorded. The next trial was then initiated. No feedback on performance was given to the participants during the experiment.

3. Results

Two participants were removed from the experiment, because they were unable to perform the task, and were replaced¹. The mean luminance values required to achieve minimal flicker for the different conditions are shown in Figure 2.2. The responses were analysed using a repeated-measures analysis of variance (ANOVA) with three within-subjects factors (Stimulus [large square, small rectangle, mixed, text], Colour Manipulated [red, green] and Flicker Rate [16 Hz, 20 Hz]). There were significant main effects of Stimulus, $F(3,45) = 93.550$, $MSE = 6.425$, $p < 0.001$, and Colour, $F(1,15) = 56.860$, $MSE = 43.315$, $p < 0.001$, and a significant interaction between the two, $F(3,45) = 32.185$, $MSE = 4.928$, $p < 0.001$. However, neither the main effect of Flicker rate nor any of the other interactions were significant ($ps > 0.10$). The interaction between Stimulus and Colour was examined more closely using Newman-Keuls tests. For the Green adjustment condition, the mean luminance for the Large Square stimulus condition ($M = 14.93 \text{ cd/m}^2$) was significantly less than for the Small Rectangle ($M = 16.27 \text{ cd/m}^2$, $p < 0.05$), Mixed ($M = 17.87 \text{ cd/m}^2$, $p < 0.001$) and Text stimulus conditions ($M = 25.26 \text{ cd/m}^2$, $p < 0.001$). The mean luminance for the Small Rectangle stimulus condition was also lower than for both

¹ Investigation found that these participants did not properly understand the requirements of the HFP task. As a result, a revised set of HFP instructions were used for Experiments 2-8, which sought to describe the task with greater clarity. These revised instructions proved to be effective and all participants in subsequent experiments were able to carry out the HFP task effectively.

the Mixed ($p < 0.001$) and Text stimulus conditions ($p < 0.001$). The Mixed stimulus condition also had a significantly lower mean luminance than the Text condition ($p < 0.001$). For the Red adjustment condition, the mean luminance for the Text stimulus condition ($M = 14.74 \text{ cd/m}^2$) was significantly higher than for the Large Square ($M = 11.76 \text{ cd/m}^2$, $p < 0.001$), Small Rectangle ($M = 11.43 \text{ cd/m}^2$, $p < 0.001$), and Mixed Rectangle stimulus conditions ($M = 11.59 \text{ cd/m}^2$, $p < 0.001$), none of which differed significantly from each other ($ps > 0.50$). For all stimulus conditions, the mean luminances for the Green adjustment condition were significantly higher than for the Red condition (all $ps < 0.001$).

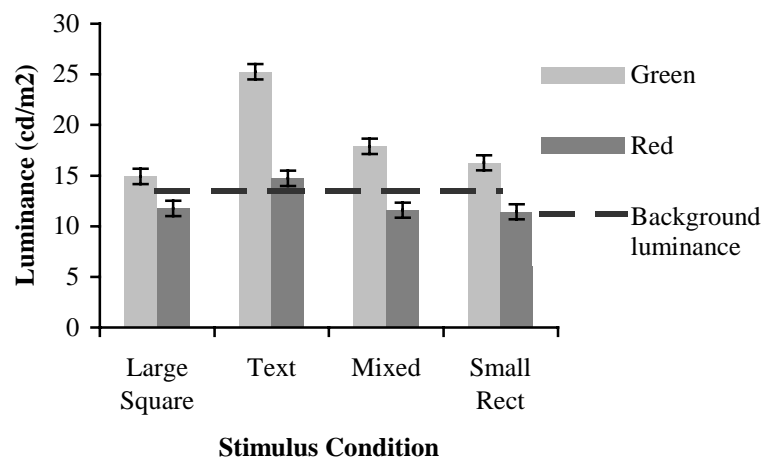


Figure 2.2 Mean luminances required to achieve minimal flicker in HFP for the different stimulus conditions, for manipulations of red and green. Background luminance indicates the luminance of the component of each stimulus that was not manipulated by participants.²

A by-participants analysis was also carried out. This showed a significant main effect of Participant, $F(15,225) = 2.841$, $MSE = 6.025$, $p < 0.001$. Post-hoc

² As standard error bars are considered inappropriate for repeated measures designs (Estes, 1997; Loftus & Masson, 1994), this figure and all following figures use statistical significance bars as recommended by Schunn (1999).

analysis revealed the mean luminance required to achieve minimal flicker for Participant 15 ($\underline{M} = 17.56 \text{ cd/m}^2$) was significantly higher than that for Participant 2 ($\underline{M} = 14.44 \text{ cd/m}^2$), Participant 4 ($\underline{M} = 14.56 \text{ cd/m}^2$) or Participant 16 ($\underline{M} = 13.15 \text{ cd/m}^2$, all $p_s < 0.05$). Post-hoc tests also showed that the mean luminance required to achieve minimal flicker for Participant 16 was significantly lower than that for Participant 3 ($\underline{M} = 16.46 \text{ cd/m}^2$), Participant 6 ($\underline{M} = 16.19 \text{ cd/m}^2$) and Participant 9 ($\underline{M} = 16.64 \text{ cd/m}^2$, all $p_s < 0.05$). No other by-participant comparisons were statistically significant ($p_s > 0.05$).

The standard deviations of the 10 responses in each condition were also analysed using a repeated measures ANOVA, with the same three within-subjects factors as before. This was carried out to reveal the consistency with which participants responded over the trials within each condition. The analysis showed a significant main effect of Stimulus, $F(3,45) = 13.140$, $\underline{MSE} = 5.176$, $p < 0.001$, of Colour, $F(1,15) = 15.995$, $\underline{MSE} = 9.926$, $p < 0.005$, and an interaction between the two, $F(3,45) = 3.137$, $\underline{MSE} = 4.421$, $p < 0.05$. There were no other significant results ($p_s > 0.05$). Newman-Keuls tests were used to examine the interaction between Stimulus and Colour. For the conditions where the Green stimuli were manipulated, the mean standard deviation for the Text stimulus condition ($\underline{M} = 4.651 \text{ cd/m}^2$) was larger than for the Mixed ($\underline{M} = 3.649 \text{ cd/m}^2$, $p < 0.05$), Small Rectangle ($\underline{M} = 3.189 \text{ cd/m}^2$, $p < 0.05$) or Large Square ($\underline{M} = 1.182 \text{ cd/m}^2$, $p < 0.001$) stimulus conditions. Both the Mixed and the Small Rectangle stimulus conditions had larger mean standard deviations than the Large Square stimulus condition ($p_s < 0.005$). There was no difference between the Mixed and Small Rectangle stimulus conditions ($p > 0.1$). For the Red stimuli the mean standard deviation of the Text stimulus condition ($\underline{M} =$

2.197 cd/m²) was larger than that for Large Rectangle stimulus condition ($\underline{M} = 1.182$ cd/m², $p < 0.05$). No other differences were significant ($p > 0.10$). For the Text, Mixed and Small Rectangle stimulus conditions, the mean standard deviations were significantly larger for the Green condition than for the Red ($p_s < 0.05$). No significant differences were shown between the Green and Red conditions for the Large Square stimulus condition ($p > 0.10$).

4. Discussion

The first finding to emerge from these results is the reaffirmation of the importance of using Heterochromatic Flicker Photometry to obtain isoluminance rather than merely matching luminances on-screen. The results showed a substantial difference between the actual on-screen luminance needed to obtain perceptual isoluminance when red or green was the colour being adjusted when the luminance of the other colour was fixed. For the Large Square, Small Rectangle and Mixed stimulus conditions, a higher luminance of green was needed to match the red, complementing the findings of previous research (Bilodeau & Faubert, 1997; Dobkins et al., 2000). Furthermore, the by-participants analysis revealed that the mean luminance required to achieve minimal flicker varied across participants. This confirms the finding of Metha and Mullen (1996) that isoluminance points vary between individuals.

However, the key finding of this study is that the red:green luminance ratio required for minimal flicker depends on the actual stimuli used for the HFP task. For the Text stimulus condition, the luminance of the manipulated colour required for minimal flicker was significantly higher than for any of the other stimulus conditions for both the Red and Green colour adjustment conditions. When green text was

manipulated, in particular, an on-screen luminance of almost twice that of the background was needed for flicker to appear minimal. Furthermore, for the Green colour adjustment condition, the luminance values required for minimal flicker were higher for the Mixed and Small Rectangle stimulus conditions, compared to the Large Square stimulus condition. These results provide an interesting comparison with research using gratings, which has not found any influence of spatial frequency on red/green isoluminance at temporal frequencies such as those used in the present study (Cavanagh et al., 1987; Dobkins et al. 2000).

The precise influence of the nature of the stimuli on HFP remains to be seen. There are at least two possible interpretations of this experiment's findings. One possibility is that the differences in the luminance ratios required to achieve minimal flicker for the different stimulus conditions may occur simply due to isoluminance points being affected by stimulus type. The actual reason behind the effect of stimulus type could be directly related to spatial frequency, although, as stated above, there is limited evidence from previous research to suggest that red/green isoluminance is affected by spatial frequency. Cavanagh et al. (1987) found no effects of spatial frequency on red/green isoluminance points. Dobkins et al. (2000) showed that the isoluminance point was not affected by spatial frequency, except at very low temporal frequencies (2Hz). In any case, if stimulus type does have a direct effect on the red/green ratio required for isoluminance, it is vital that in any study using isoluminant stimuli, the stimuli used in calibration match those used in the experiment proper. In order to carry out written word recognition experiments using isoluminance it would therefore be necessary to carry out HFP using stimuli such as the Text stimulus type used in Experiment 1.

A second possibility is that differences in the luminance ratios required for minimal flicker may occur due to differences in participants' flicker sensitivity for the stimulus type conditions used rather than as a direct consequence of differing isoluminance points. Makela, Rovamo and Whitaker (1994) examined flicker sensitivity at different temporal frequencies for circular stimuli of varying diameters. They found that flicker sensitivity increased with stimulus size up to a critical diameter, which was dependent on the temporal frequency. In the present experiment, the size of the component of the stimulus that was flickered (target component) varied across the different stimulus conditions. The Text stimulus condition, in which the letter string "xxxx" was flickered, had the target component with the smallest area. It is consistent with the Makela et al. (1994) finding that participants would be least sensitive to flicker in this stimulus condition. Therefore, it would be expected that participants would make a larger range of responses in the Text stimulus condition compared to the other stimulus conditions. Similarly, flicker sensitivity might also be reduced in the Mixed and Small Rectangle stimulus conditions compared to the Large Rectangle stimulus condition, which had by far the largest target component.

Any differences in the spread of responses for each stimulus condition could act as a precursor to a bias towards higher luminance values, due to an application of Weber's Law. It was observed that when adjusting the luminance of stimuli, despite the difference between each step being identical in terms of physical luminance, adjustments near the top of the luminance range appeared to have a smaller effect on the perceived flicker than those nearer the bottom. This phenomenon can be explained by Weber's Law, which states that $\frac{\Delta I}{I} = k$, where I signifies initial stimulus intensity, k is a constant, and ΔI is the change in stimulus intensity needed in

order to produce a just noticeable difference. In this case, as luminance increases, a larger change in actual luminance is necessary for the change to be perceivable to the observer. This may then lead to a bias towards higher values in those stimulus conditions where participants found it difficult to obtain consistent luminance values over the trials due to decreased flicker sensitivity. This difficulty was measured by looking at the standard deviations of the 10 trials that each participant carried out in each of the different conditions. In both colour conditions, the mean standard deviation was significantly larger in the Text stimulus condition than in the Large Square stimulus condition. Furthermore, in the Green colour adjustment condition, the Mixed and Small Rectangle stimulus conditions also had significantly larger mean standard deviations than the Large Square stimulus condition. With each participant registering a large range of luminance values in the Text stimulus condition in particular, it would be predicted that in these conditions the mean luminance values would be higher. The results of the experiment therefore show a close mapping between the luminance values obtained for minimal flicker, and the difficulty of the task, with those conditions in which participants found it harder to achieve consistent values, due to the small size of the target component, requiring higher luminance values to achieve minimal flicker. If this second interpretation of the findings is correct then the stimuli chosen for the calibration section of any word recognition experiment should not only been kept as similar as possible to those used in the experiment proper, but should also allow participants to perceive small differences in the amount of flicker and therefore obtain consistent and accurate luminance values in HFP.

In conclusion, Experiment 1 highlights the necessity of carrying out HFP for each participant in order to create isoluminant stimuli in the word recognition studies, rather than rely upon on-screen luminance matching. It also provides an indication that the isoluminance points obtained through HFP are affected by stimulus type, meaning care should be taken when choosing stimuli for the calibration sections of such experiments. However, it does not conclusively resolve the issue of what type of stimulus should be used in the calibration section. This situation was therefore dealt with by conducting two versions of the first word recognition experiment that differed only in the stimuli used in the calibration section. These differences are described in full in Chapter 4.

Chapter 3

General Methodology for Experiments 2-8

1. Accuracy and reaction time measures

In order to examine the effects of isoluminance on written word recognition effectively, it is vital that the experimental task used is sensitive to perceptual influences. There is a common belief that any manipulation that decreases accuracy of recognition will also increase reaction times and vice versa. Underlying this is the assumption that both accuracy and reaction time measures reflect the time needed for information processing. However, as Mordkoff and Egeth (1993) point out, everyday introspection suggests that these two tasks measure different processes. When we talk about errors made in accuracy tasks, our explanations normally implicate perceptual mechanisms. On the other hand, when explaining speed on a reaction time task, explanations are generally more varied, involving post-perceptual decisions and motor responses as well as perceptual factors. Research into letter recognition by Santee and Egeth (1982) supports this idea, indicating that under data-limited conditions, performance on accuracy tasks is affected by perceptual factors, and performance on reaction time tasks by later post-perceptual factors. Under resource-limited conditions, performance on both accuracy and reaction time tasks are sensitive to later post-perceptual factors. Santee and Egeth suggest that the reason why reaction time experiments are not sensitive to perceptual factors is that participants are generally instructed to respond quickly but accurately. This results in the participant having very high criteria for recognition in order to keep their error rate low, so any perceptual effects are masked. On this basis, techniques such as the Lexical Decision Task and naming, in which the key performance measure is reaction time, and where

stimuli are normally presented for long exposure durations, are not suitable for examining perceptual processes.

A technique that combines an accuracy measure with data-limited conditions is the Reicher-Wheeler task (after Reicher, 1969; Wheeler, 1970). As mentioned in Chapter 1, in his ground-breaking study, Cattell (1886) presented words and nonwords for very brief durations and required participants to report as much of the letter string as possible. Using this technique Cattell discovered that briefly presented words are identified more accurately than random letter strings. This is referred to as the Word Superiority Effect (or Lexical Status Effect). However, a problem with this task is that one cannot rule out the possibility that the word advantage occurred due to guessing strategies used by participants. If participants were able to identify a few letters of a word, this might enable them to guess the rest of the word. However, identifying a few letters of a nonword would not enable such guessing strategies. Reicher (1969) avoided this problem by using a procedure in which briefly presented stimuli were followed by a forced choice between two alternative letters whose serial position and probability of occurrence could not be predicted from any other letters in the stimulus display. For example, the target word word might be followed by a choice between the letters d and k. Both of these were equally likely to have been the final letter of the word, thereby eliminating the possibility of participants using guessing strategies favouring words. Despite the use of this task, the Word Superiority Effect was still demonstrated.

2. The present studies

It would therefore appear that the Reicher-Wheeler task is a technique well suited for examining the effects of isoluminance on written word recognition and was

therefore adopted as the principal experiment technique for this research project. All of the experiments that follow involved the presentation of isoluminant and non-isoluminant stimuli as targets in Reicher-Wheeler style tasks. In each of these experiments, performance at isoluminance was compared with performance with both stimuli in which the target was darker than the background and stimuli in which the target was lighter. Using both of these comparison conditions helped ensure that any effect on performance was due to isoluminance, as overall display luminance has been shown to have an effect on word recognition ability (e.g. Berman, Fein, Jewett, Benson, Law & Myers, 1996). However, it was thought unlikely that this factor would have had a large impact in these studies, as the differences in overall luminance between the conditions were small.

Using this methodology, it would be predicted that if participants normally use the M pathway to perceive a certain stimulus type such as words or nonwords, accuracy in the Reicher-Wheeler task should be significantly lower at isoluminance than in the conditions containing a luminance contrast. In comparison, if the perception of letter strings relies solely on visual information carried by the P pathway, no differences in accuracy should occur. However, as mentioned in Chapter 1, Logothetis et al. (1990) found that a significant proportion of Parvocellular neurons are also silenced at isoluminance. Logothetis et al. therefore concluded that any performance deficit occurring at isoluminance could be due solely to reduced P pathway functioning. However, despite this finding, there is compelling evidence to suggest that isoluminance is an appropriate technique to selectively impair M pathway functioning. A large number of other researchers have found no reduction in P pathway functioning at isoluminance (e.g. Hicks et al., 1983; Lee, Martin & Valberg,

1988; Shapley et al., 1991). Furthermore, Reid and Shapley (1992) have observed that P cells are in fact specifically designed to function at isoluminance, and Shapley (1994) has provided a convincing argument that the conclusions drawn by Logothetis et al. (1990) do not logically follow from their results. As the wealth of research in this area has shown that M pathway functioning is reduced at isoluminance, whilst P pathway functioning is relatively unaffected, it is therefore assumed for the purpose of this thesis that any reduction in accuracy in the Reicher-Wheeler task at isoluminance does indicate that the M pathway is utilised in the processing of that stimulus type.

3. Serial position curves

The methodology described above has a further benefit of being able to indicate whether the effect of impairing M pathway processing on written word recognition (if any) is to affect the manner in which words are processed, or merely to cause a general impairment in performance. This can be achieved through serial position analysis. Numerous studies (e.g. Jordan & Bevan, 1996; Jordan, Smith & Philips, 1995; Prinzmetal, 1992; Prinzmetal & Silvers, 1994; Rumelhart & McClelland, 1982) have shown that the exterior letters of letter strings are reported more accurately than letters in the interior positions, with performance levels in both exterior letter positions producing strikingly similar levels of report, indicating that the parallel processing of words may actually occur in an “outside-in” fashion, with the exterior letters combining to form a perceptual unit that is a substantial component of the word recognition process. This interpretation is supported by evidence from priming studies (Humphreys, Evett & Quinlan, 1990; McCusker, Gough & Bias, 1981) as well as a study showing that exterior letter pairs are reported more accurately than single letters (Jordan, 1990, 1995). The nature of the serial position curve

obtained for isoluminant stimuli may therefore give a useful indication of whether the processing of orthographic information occurs in a similar manner to that for stimuli presented under non-isoluminant conditions.

It has been claimed by some researchers that phenomena such as the U-shaped (or suppressed W-shaped) serial position curves found with the Reicher-Wheeler task occur largely due to low-level visual factors (e.g. Nazir, 2003). According to such an explanation, exterior letters experience less lateral inhibition as they are flanked only on one side. Interior letters, despite being closest to the centre of the fovea, suffer greater lateral inhibition and thus performance is reduced for these characters. Lateral inhibition undoubtedly plays some role in determining the shape of serial position curves. However, a number of studies have indicated that it is by no means the main determinant. Research has shown that placing black rectangles at the end of letter strings in order to increase lateral inhibition for these characters produces a similar serial position curve to that which occurs with blank spaces (Shaw, 1969). Moreover, when strings of nonletter characters (primarily Greek letters) are presented in a recognition task, performance is lowest for exterior characters and highest for interior ones, which should suffer from the most lateral inhibition (Mason, 1982). It is therefore clear that the cause of serial position curves goes beyond lateral inhibition.

4. General Methods

The following section describes in general terms the methodology employed for Experiments 2-8. Precise details of the methodology for particular experiments are included in the relevant experimental chapters.

4.1 Participants

All participants were native speakers of English and reported having normal or corrected to normal vision. Visual acuity was tested using a Bailey-Lovie chart (Bailey & Lovie, 1976). Participants were required to continue reading letters down the chart from a distance of 3 metres until they failed to identify any letters on one line. Performance was scored using the method recommended by Kitchin and Bailey (1981; Reeves, Wood & Hill, 1993). The total number of letters incorrectly read was recorded and an “error” score of 0.02 assigned to each; these scores were added to the last line on which any letters were read. To continue, participants were required to have a minimum, 3 metre, binocular acuity of -0.3 LogMar indicative of normal visual acuity. The participants were also tested for colour blindness using the first 15 plates of Ishihara (1977), and only those who responded correctly to all 15 were used in the experiment.

4.2 Stimuli

Testing was carried out using the Reicher-Wheeler 2-alternative forced choice task. Three main stimulus types were used throughout these experiments: words, illegal nonwords and pseudowords. Each stimulus string was four letters long. For each stimulus type, there were 48 pairs of stimuli. The members of each pair differed by just one critical letter (e.g. *aces* – *axes* or *skog* – *skig*), with critical letters occurring equally often at each of the four serial positions across the stimuli. The word stimuli had a mean frequency of written occurrence of 130 per million (Kucera and Francis, 1967). Nonwords had very low digram and exterior letter pair frequencies (mostly zero, and less than 10 in all circumstances; Jordan & Monteiro, 2003). Pseudowords were all legal combinations of letters that are not represented in

the English lexicon. The word, nonword and pseudoword pairs were all matched with regards to critical letters. A further 24 additional pairs of each stimulus type were created for use as practice stimuli at the beginning of each session. A list of these stimuli is provided in Annex A. In all experiments, the stimuli were either red on a green background or green on a red background, and were either isoluminant with the background, lighter than the background, or darker than the background.

4.3 Visual Conditions

Stimuli were presented on the computer screen in a 12pt font. The viewing distance was 67cm and the character strings subtended visual angles of approximately 1 deg horizontally. The background was a 256 pixel square, subtending an angle of 8 deg. When presented on screen, the centre of each stimulus item coincided with the fixation point. The two forced-choice alternatives were presented in black, within a small grey rectangle. This was done so that the forced choices were equally visible for all conditions.

The chromatic and luminance characteristics of the monitor were measured using a Cambridge Research Systems ColorCAL colorimeter. The maximum luminances available for red, green and blue were 34.3, 101.4 and 18.0 cd/m^2 respectively. The CIE(x,y) coordinates of the monitor were (0.62, 0.34) for the red, (0.28, 0.61) for the green and (0.15, 0.07) for the blue phosphor. The luminance of one component (either the text or the background) of the display was fixed at 16.5 cd/m^2 and the luminance of the other component in the Isoluminant condition was calculated for each participant using the procedure described in the calibration section below. The letter strings in the Lighter condition were 50% brighter than those in the Isoluminant condition and the letter strings in the Darker condition were 50% darker.

The grey rectangle on which the choices were presented was the same luminance as the coloured background.

4.4 Design

Each participant took part in a number of sessions, the precise number of sessions of which depended on the design of the particular experiment, as did the number of experimental trials in each session. The order of these sessions was counterbalanced across participants. Within each session, the order of the stimulus presentations was pseudorandomly organised for each participant. Cycles of stimulus items were created by randomly selecting one pair from each possible combination of Target Luminance condition and Critical Letter Position (and Stimulus Type in experiments where more than one type of stimulus was presented in each session). There was no obvious transition from one cycle to another. In each session, participants carried out 96 practice trials before the experimental trials began. There was no obvious transition between the practice and experimental sections. The primary dependent variable was accuracy of report, although response times, measured from target onset, were also recorded.

4.5 Apparatus

The experiments were controlled by a Pentium II IBM-compatible PC fitted with a Cambridge Research Systems (CRS) VSG 2/3 card. The stimuli were presented on a 21-inch Sony F500R Trinitron monitor running at a resolution of 800x600 with a refresh rate of 160Hz. Participants responded using a CRS CT3 response box. Chromatic and luminance characteristics of the monitor were measured using a CRS ColorCAL colorimeter. The software running the experiments was programmed in Borland Delphi 4, using VSG Software Library Version 6. The

screen was visible through a black hood attached to the monitor with a viewfinder that participants looked through. This maintained viewing distance and aided fixation.

The experiments were carried out in a darkened room.

4.6 Calibration

For each participant, the luminance of one component of the stimulus (either the foreground or the background) was calculated using the Heterochromatic Flicker Photometry (HFP) technique. This was done at the start of each session for either red on green, or green on red stimuli, depending on which session it was. 10 calibration trials were carried out in each session, and the average luminance obtained was used for the relevant component of the isoluminant stimuli in the Reicher-Wheeler task. Prior to starting these trials, participants were given several minutes to adapt to the lighting conditions to help ensure that the luminance ratios obtained for isoluminance were appropriate. In each trial, a stimulus appropriate to that used in the experiment proper (usually a letter string) was presented against a background of the other colour. The font used and the size of the background was the same as in the main section of the experiment in order to keep the stimuli used for calibration as similar as possible to those used in the experiment proper (see Experiment 1). One component of this display was flickered at a rate of 16Hz. Participants were required to use the up and down keys on the response box to adjust the luminance of this component until they perceived the flicker as being minimal. When they were satisfied that this had been achieved they had to press one of the side buttons on the response box to confirm their response. After this, the next trial was initiated. No feedback on performance was given to participants during the calibration.

4.7 Procedure

At the start of each trial, a fixation point appeared at the centre of the screen. Participants were instructed to fixate on this before initiating a display. When participants pressed a key on the response box, the fixation point was removed from the screen, followed 600ms later by a target stimulus that was either Isoluminant with, Lighter or Darker than the background. When the target was removed from the screen, there was a 625ms delay before the two forced choice alternatives were presented, one above the other. In order to make the choice, participants pressed either the upper or lower key on the response box to select the appropriate alternative. Participants were encouraged to respond as accurately and as quickly as possible, although the emphasis was placed on accuracy. Once the participants had responded the display reverted to the fixation point. No feedback on participants' performance was given during the experiment. Figure 3.1 illustrates the main displays viewed in a typical trial.

For the majority of these experiments, target exposure durations were reassessed for each participant after each cycle throughout the practice and experimental sections within each session. If the percentage correct in a cycle was greater than 87.5% then the exposure duration was decreased by 6.25ms. If it was greater than 95.83% then the exposure duration was decreased by 12.50ms. Exposure duration was increased by 6.25ms if the percentage correct was less than 67.5% and increased by 12.50ms if it was less than 54.17%. Within each cycle, all letter strings were presented for the same exposure duration. This procedure ensured that overall performance stayed at approximately 75% (the midrange of the scale), and that each

Target Luminance X Critical Letter Position (X Stimulus Type if appropriate)

condition was shown at the same exposure duration an equal number of times.

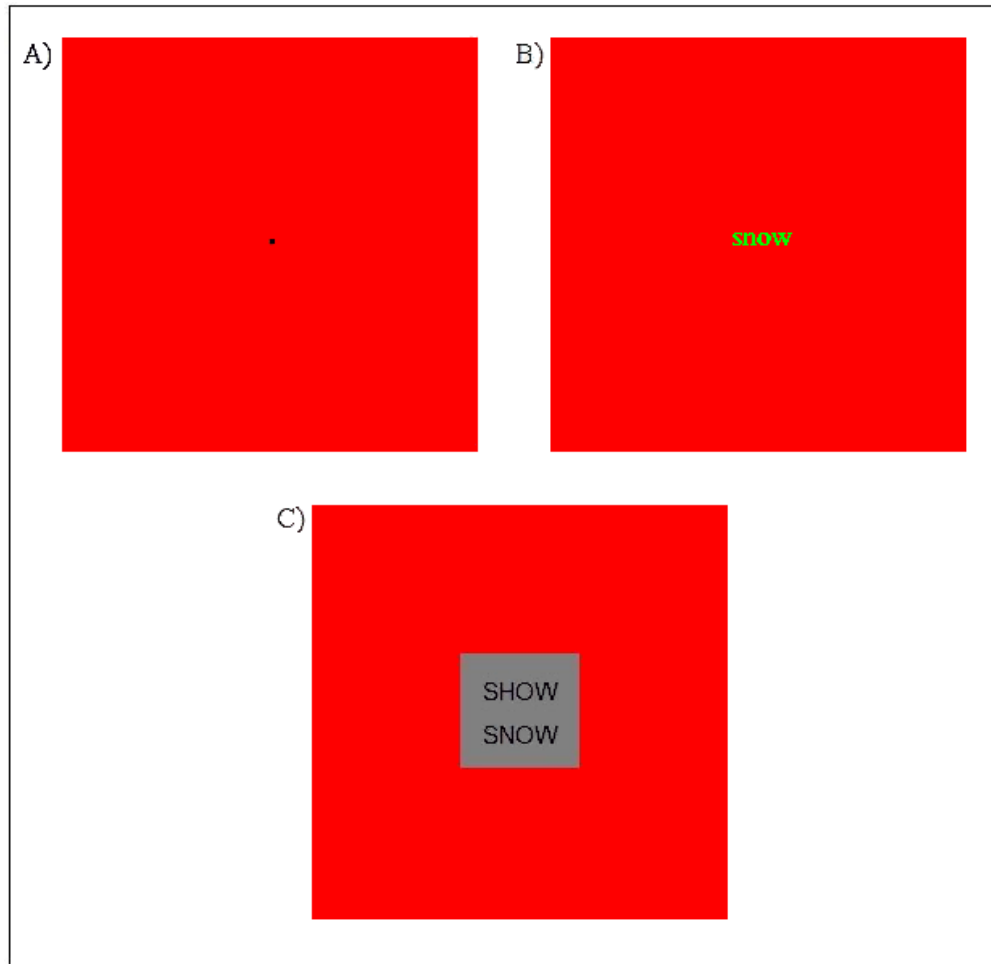


Figure 3.1. Illustration of the displays viewed in a typical Reicher-Wheeler trial (featuring green target stimuli on a red background; Not to scale). A) shows the fixation point which appeared at the start of each trial. When the participant pressed a key to start the trial the fixation point was removed and replaced 600ms later by the target stimulus, B). When the target was removed from the screen, there was a 625ms delay before the forced choice alternatives were presented, one above the other, as shown in C). Note that the above is a general representation and the precise nature of the targets and alternatives varied across experiments.

Chapter 4

Experiments 2 and 3

1. Experiment 2

This experiment involved the presentation of four-letter words and illegal nonwords under isoluminant and non-isoluminant (Darker, Lighter) conditions in a Reicher-Wheeler task, with the aim of identifying whether information provided by the M pathway is used in the recognition of written words. Participants took part in two sessions, with one session containing red letter strings presented on a green background, and the other containing green letter strings on a red background. In order to determine the isoluminance point for each participant, HFP was carried out before each session. During HFP a red or green letter string, 'xxxx', was flickered against a background of the other colour. This stimulus type was chosen for the HFP task as if the first explanation of the results of Experiment 1, that isoluminance points are directly affected by stimulus type, is correct then a string of 'x's should prove the most appropriate stimulus to flicker in the calibration section of this experiment.

If the M pathway is involved in written word recognition, a reduction in performance at isoluminance relative to non-isoluminant conditions should be obtained for words. However, if, as implied by Livingstone and Hubel (1987), only the P pathway subserves word recognition, then no isoluminance impairment should be expected for either words or nonwords. Should a performance deficit occur at isoluminance, further predictions can also be made that will allow differentiation between the two main explanations of the role of the M pathway in word recognition. According to the Holistically Biased Hybrid model (Allen et al., 1995), as the letter-strings presented in this experiment are on screen for a very short time period, a larger

isoluminance disadvantage for words than for nonwords should be expected. This is because as words are familiar letter strings, they can normally be processed by the faster word-level channel. However, when words are presented at isoluminance, the impaired functioning of the M pathway means that they have to be processed using the letter-level channel, reducing performance. Whilst an isoluminance disadvantage should be expected for words, the model would also predict little or no isoluminance disadvantage for nonwords. This is because when nonwords are presented for brief durations, due to their unfamiliar shape, there is insufficient activation of the word-level channel to facilitate recognition and they are instead processed by the letter-level channel. Therefore it is the P pathway that should be used for nonwords under all luminance conditions, and so no reduction in performance should be expected at isoluminance.

With regards to the attentional selection explanation, as attentional selection, and thus M pathway involvement, will occur with both words and nonwords, it would be expected that performance should suffer at isoluminance for both stimulus types. Furthermore, any involvement of the M pathway in attentional selection identified in this experiment will centre around the covert identification and ordering of the letters in the strings, as all stimuli are presented foveally. In the experiments by Omtzigt et al. (2002) described in Chapter 1, the spotlight of attention was presumably directed towards the central letter, either by a pre-attentive mechanism automatically shifting attention towards the letter differing from the other two or by a voluntary shift due to the knowledge that the critical letter is always the central letter. However, it is not clear where the spotlight of attention would be directed when words or nonwords are presented. Based on the evidence from serial position curves and priming studies

described in Chapter 3, one possibility is that the attentional spotlight is directed to the exterior letter positions. If this is the case then it might be expected that the typical U-shaped serial position curves obtained with the Reicher-Wheeler task do not occur when stimuli are presented at isoluminance.

2. Method – Experiment 2

2.1 Participants

Sixteen participants, from the population described in the General Methods section, took part in two one-hour 15 minute sessions for which they were paid.

2.2 Stimuli

The word and illegal nonword stimuli described in the General Methods section were used in this experiment.

2.3 Visual conditions

Target words and nonwords were presented on the computer screen in a proportionally spaced, lowercase font (12pt Times New Roman Bold). The two forced-choice alternatives were presented in uppercase Arial so that no shape information could be used to aid guessing, and in black, within a small grey rectangle.

The luminance of the red and green used for the background was approximately 16.5cd/m^2 and the CIE(x,y) coordinates were (0.28, 0.61) and (0.62, 0.34) respectively. The CIE(x,y) coordinates of the red and green used for the letter strings were (0.62, 0.34) and (0.28, 0.61) respectively. The luminance of the letter strings in the Isoluminant condition was calculated for each participant using the procedure described in the calibration section.

2.4 Design

Each participant took part in two sessions. In one session participants saw red words (Isoluminant, Lighter, Darker) presented on a green background, and in the other, green words on a red background. The participants were presented each letter string once in each of these Target Luminance conditions. Thus there were 576 experimental trials in each session. The order of these sessions was counterbalanced across participants. Within each session, stimuli were shown in cycles of 24 items, counterbalanced across Stimulus Type (pseudoword, illegal nonword), Target Luminance (Lighter, Darker, Isoluminant) and Critical Letter Position.

2.5 Calibration

In each HFP trial, a letter string, 'xxxx', was presented against a background of the other colour. The font used (Times New Roman Bold 12pt) and the size of the background was the same as in the main section of the experiment. Participants were required to adjust the luminance of the letter string until they perceived the flicker as being minimal.

2.6 Procedure

The procedure, and all other aspects of this experiment were identical to those specified in the General Methods section.

3. Results – Experiment 2

HFP was used to create isoluminant stimuli for each participant. The mean text luminance needed to obtain minimal flicker for stimuli with a background luminance of 16.5cd/m^2 was 22.3cd/m^2 for red on green stimuli, and 36.3cd/m^2 for green on red. The standard deviation of each participant's 10 trials was calculated in order to give an indication of how consistent their responses were. For red on green

stimuli the mean standard deviation was 4.169cd/m^2 and for green on red, the mean standard deviation was 5.265cd/m^2 .

The mean percentage correct for the red on green stimuli was 74.89%, and 75.09% for the green on red stimuli, showing that adjustments of the exposure duration were effective in keeping performance in the mid range. An analysis of variance carried out on the exposure duration necessary to achieve 75% performance for red and green stimuli showed no differences between the exposure durations for red on green and those for green on red stimuli (16.84ms vs. 13.50ms $F(1,15) = 2.375$, $p > 0.10$).

The accuracy data were examined using a repeated measures analysis of variance with four within-subjects variables (Target Colour [red, green], Stimulus Type [words, nonwords], Critical Letter Position, and Target Luminance [Darker, Isoluminant, and Lighter]). The results of the ANOVA showed significant main effects of Stimulus Type $F(1,15) = 249.678$, $MSE = 127.567$, $p < 0.001$, Critical Letter Position $F(3,45) = 28.558$, $MSE = 134.6332$, $p < 0.001$, and Target Luminance $F(2,30) = 23.995$, $MSE = 211.614$, $p < 0.001$ and interactions between Stimulus Type and Critical Letter Position $F(3,45) = 13.741$, $MSE = 79.184$, $p < 0.001$, and between Target Colour and Target Luminance $F(2,30) = 211.150$, $MSE = 467.591$, $p < 0.001$. Neither the main effect of Target Colour, nor any of the other interactions were significant ($p > 0.05$).

Newman-Keuls tests were used to analyse the interaction between Target Colour and Target Luminance (Figure 4.1). With regards to the interpretation of this interaction, the only meaningful comparisons among the six conditions were the comparisons within Target Luminance, as different exposure durations were used for

the green on red, and red on green stimuli. The results showed that for the green target stimuli, performance with Isoluminant stimuli ($\underline{M} = 75.71\%$) was poorer than performance with Lighter stimuli ($\underline{M} = 83.37\%$; $p < 0.01$), but better than performance with Darker stimuli ($\underline{M} = 66.21\%$; $p < 0.01$). The difference between Darker and Lighter stimuli was also significant ($p < 0.01$). For the red target condition, no differences were found between the Isoluminant stimuli ($\underline{M} = 71.94\%$) and either Darker ($\underline{M} = 76.27\%$) or Lighter ($\underline{M} = 76.46\%$; $p_s > 0.20$) stimuli, which did not differ from each other ($p > 0.90$).

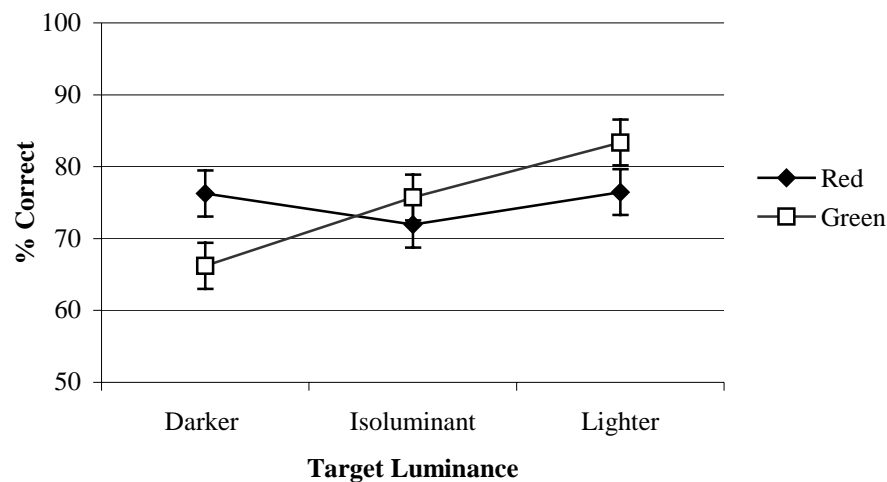


Figure 4.1. Mean percentage of correct responses for different Target Luminances for red letter strings (on a green background) and green letter strings (on a red background).

The analysis of the interaction between Stimulus Type and Critical Letter Position (Figure 4.2) was also examined using Newman-Keuls tests. The results showed that for words, performance in Position 1 ($\underline{M} = 83.33\%$), Position 2 ($\underline{M} = 81.38\%$) and Position 4 ($\underline{M} = 83.46\%$) were all better than in Position 3 ($\underline{M} = 77.56\%$; all $p_s < 0.01$). None of the other differences were significant ($p > 0.10$). For

nonwords, performance in Position 1 ($\underline{M} = 76.00\%$) was better than performance in Position 4 ($\underline{M} = 72.26\%$) and both of these had better performance than in Positions 2 ($\underline{M} = 62.84\%$) and 3 ($\underline{M} = 63.12\%$; $p_s < 0.01$), which did not differ significantly from each other ($p > 0.20$). Performance with words was significantly better than with nonwords in all critical letter positions (all $p_s < 0.01$).

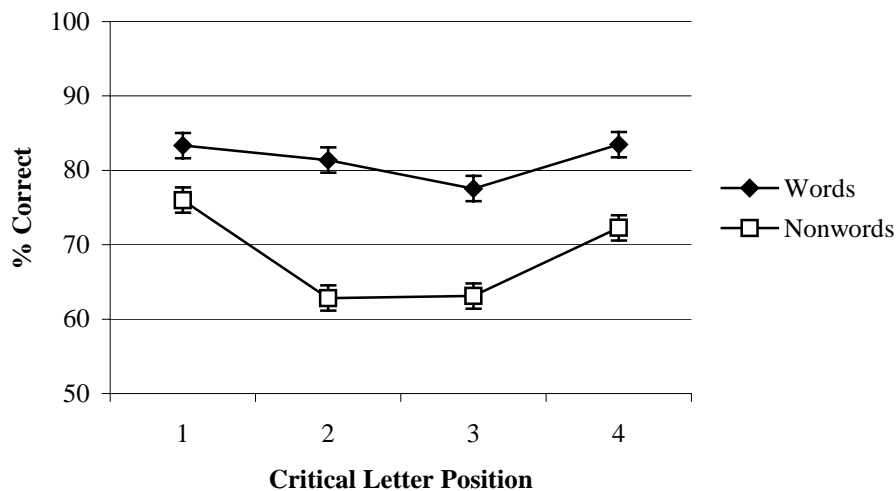


Figure 4.2. Mean percentage of correct responses for different Critical Letter Positions for words and illegal nonwords

In order to ensure that the effects found above were not due to a speed-accuracy trade-off, an analysis of variance was carried out on the response time data. The results of the analysis showed main effects for Stimulus Type $F(1,15) = 52.985$, $MSE = 296544.9$, $p < 0.001$ and Critical Letter Position $F(3,45) = 23.709$, $MSE = 34492.9$, $p < 0.001$, and an interaction between the two $F(3,45) = 5.017$, $MSE = 18279.5$, $p < 0.01$. The main effect of Target Luminance was close to significance $F(2,30) = 3.036$, $MSE = 58117.1$, $p > 0.06$, but, unlike the accuracy data, the

interaction between Target Colour and Target Luminance was not significant ($p > 0.50$). No other main effects or interactions were close to significance ($p > 0.05$).

Newman-Keuls tests were carried out on the interaction between Stimulus Type and Critical Letter Position (Figure 4.3) in order to examine it more closely. For words, the data showed that response times for Position 1 ($M = 1436\text{ms}$) were significantly shorter than those for Positions 2 ($M = 1520\text{ms}$), 3 ($M = 1550\text{ms}$) and 4 ($M = 1500\text{ms}$; $p_s < 0.01$). Furthermore, response times for Position 4 were significantly shorter than for Position 3 ($p < 0.05$), but did not differ from Position 2 ($p > 0.30$). No significant differences were found between Positions 2 and 3 ($p > 0.10$). For the nonword stimuli, response times for Position 1 ($M = 1663\text{ms}$) were significantly shorter than those for Positions 2 ($M = 1848\text{ms}$; $p < 0.01$), 3 ($M = 1831\text{ms}$; $p < 0.01$) and 4 ($M = 1807\text{ms}$; $p < 0.01$), which did not differ from each other ($p_s > 0.05$).

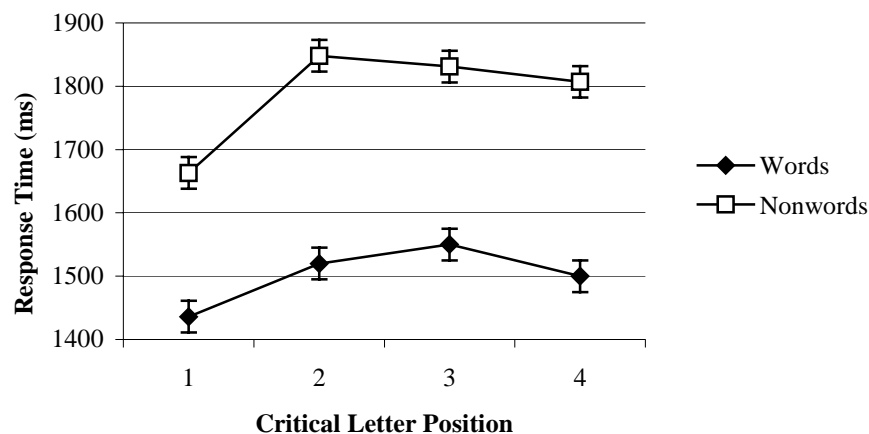


Figure 4.3. Mean response times for different Critical Letter Positions for words and nonwords

4. Discussion – Experiment 2

The results obtained from the HFP task were similar to those found in the Text condition of Experiment 1. In both conditions, the actual luminance of the text needed for isoluminance was higher than the background luminance, and the luminance of the text for the green on red condition was higher than that for the red on green condition.

Analysis of the accuracy data showed an interaction between Stimulus Type (word/nonword) and Critical Letter Position. For words, performance in the first, second and fourth positions was significantly better than in the third. For nonwords performance in the first position was best, followed by the fourth position, with performance being the lowest in the second and third positions. A large Word Superiority Effect was also shown at all serial positions, with performance with words being better than that with nonwords. Analysis of the response time data indicates that this was not due to any kind of speed-accuracy trade off. For words, response times for the first position, which had the highest accuracy, were the shortest. Similarly, participants responded faster and with greater accuracy in position four than in position three. For nonwords, response times for position one, which again had the highest accuracy levels, were the shortest. The Word Superiority Effect was also shown clearly in the response time data, with response times for words shorter than for nonwords at all serial positions. The accuracy data from this experiment closely match those obtained in a number of previous experiments, which have also found better performance for exterior over interior letters (e.g. Jordan & Bevan, 1996; Jordan, Patching & Milner, 2000). This data is similar, except that for words, performance in the second position is equal to that in the first and fourth positions.

One possibility is that this finding is due to a ceiling effect on accuracy, hiding the expected U-shaped function.

Whilst the findings described above were consistent with the predictions made before the experiment, the interaction between Target Colour and Target Luminance was unexpected. When the stimuli consisted of red targets on a green background, no effect of Target Luminance was found. However, there were differences with green targets. Accuracy at isoluminance was lower than that for Lighter stimuli, but higher than the levels obtained in the Darker condition. No response time differences were observed between the different Target Luminance conditions, so this seems unlikely to be due to a speed-accuracy trade-off.

These findings suggest that it is unlikely that the HFP task used in the calibration section of this experiment was effective in identifying participants' isoluminance points. For green on red stimuli, accuracy under isoluminant visual conditions was greater than in the Darker condition, despite targets in the latter condition differing from the background in terms of both luminance and colour contrast. The most likely explanation of this finding is that it is due to a manifestation of the bias towards higher luminance values described in the discussion of Experiment 1. It was noted that such a bias could occur due to a combination of Weber's Law and the finding that flicker sensitivity is dependent on stimulus size (Makela et al., 1994). Experiment 1 highlighted that it was especially difficult to obtain consistent luminance values over the trials in the Text condition, on which the calibration stimuli for Experiment 2 were based, meaning such a bias towards higher luminances might be expected. This explanation fits neatly with the finding that performance in the Reicher-Wheeler task in this experiment was lowest in the Darker condition for green

on red stimuli. In this condition, as with the previous experiment, the actual luminance of green targets needed to achieve minimal flicker in the HFP task was over twice the luminance of the background. However, in the conditions of Experiment 1 for which the luminance values obtained were more consistent, the luminance of green targets at which minimal flicker was obtained was a lot closer to the background luminance. If the bias were occurring then it would be expected that the visual conditions in the Darker condition may more accurately reflect true isoluminance and thus the lower performance in this condition could possibly reflect the reduced functioning of the M pathway. Although anecdotal, further support for this explanation comes from reports of the appearance of stimuli under the three luminance conditions. It has generally been reported that isoluminant text has a subjectively different appearance to it, with letters appearing fuzzy, especially when presented for short exposure durations (e.g. Lehky, 2000). However, in this experiment this sensation was reported for green text in the Darker condition rather than in the Isoluminant condition.

One alternative explanation is that the decline in performance with decreased target luminance for green on red stimuli was due to a decrease in the overall luminance of the display (e.g. Berman et al., 1996). However, this account is unlikely to be correct as the differences in overall luminance were very small. Furthermore, it should be expected that such an effect would occur with both green on red and red on green stimuli, but this study provided no evidence of an effect of Target Luminance for red letter strings presented on a green background.

5. Experiment 3

The findings of Experiment 2 suggest that in order to effectively achieve isoluminance, the stimuli used for HFP should not only be as similar as possible to those used in the experiment proper but should also allow participants to perceive small differences in the amount of flicker, and therefore obtain consistent and accurate luminance values. Experiment 3 was therefore a replication of Experiment 2 in which the stimuli used in HFP were replaced with ones thought to be more appropriate based on interpretation of the findings of Experiment 1 described above. Instead of having a string of 'x's flickered against a square background of the other colour, the background was flickered whilst the letter string remained constant. This met both of the requirements stated above: it was as similar as possible to the stimuli used in the Reicher-Wheeler task, and the increased size of the area that was flickered allowed participants to make consistent responses. One slight concern with using this stimulus type was the size of the area that was flickered. As shown by Bilodeau and Faubert (1997), isoluminance points change across the visual field, meaning that it might not be possible for participants to achieve minimal flicker for the entire stimulus. In order to deal with this concern, participants were instructed to fixate on the letter string throughout each trial and to attend to this area when assessing the level of flicker.

If accuracy were reduced in the Isoluminant condition compared with the Darker and Lighter conditions for at least one stimulus type, and there were no other stimulus types where performance in either the Darker or Lighter conditions was poorer than in the Isoluminant condition then this would give a clear indication that the HFP task was effective at creating isoluminant stimuli. All predictions relating to

the role of the M pathway in written word recognition were the same as those for Experiment 2.

6. Method – Experiment 3

6.1 Participants

Sixteen participants, from the population specified in the General Methods section, took part in two one-hour 15-minute sessions for which they were paid.

6.2 Visual conditions

The luminance of the red and green used for the letter strings in the Isoluminant condition was approximately 16.5cd/m^2 and the CIE(x,y) coordinates were (0.28, 0.61) and (0.62, 0.34) respectively. The letter strings in the Lighter condition were 50% brighter (24.8cd/m^2), and the letter strings in the Darker condition were 50% darker (8.3cd/m^2). The CIE(x,y) coordinates of the red and green used for the backgrounds were (0.62, 0.34) and (0.28, 0.61) respectively. The luminance of the backgrounds was calculated for each participant using the procedure detailed below.

6.3 Calibration

In each HFP trial, a letter string, 'xxxx', was presented against a background of the other colour. The font used (Times New Roman Bold 12pt) and the size of the background was the same as in the main section of the experiment in order to keep the stimuli used for calibration as similar as possible to those used in the experiment proper. Participants were required to use the up and down keys on the response box to adjust the luminance of the background until they perceived the flicker as being minimal. When they were satisfied that this had been achieved they had to press one of the side buttons to confirm their response. The next trial was then initiated. No

feedback on performance was given to the participants during this calibration. All remaining aspects of this experiment were identical to those of Experiment 2.

7. Results – Experiment 3

The mean background luminance required to obtain minimal flicker when the luminance of the other colour was set to 16.5cd/m^2 was 18.6cd/m^2 for green and 16.0cd/m^2 for red. As with Experiment 2, the standard deviation of each participants 10 trials was calculated in order to give an indication of how consistent their responses were. For green backgrounds the mean standard deviation was 2.780cd/m^2 and for red, the mean standard deviation was 2.228cd/m^2 .

In the Reicher-Wheeler task, the mean percentage of correct response was 74.41% for the red on green stimuli and 74.35% for the green on red stimuli, showing that the exposure duration adjustments were effective in keeping performance in the midrange. An analysis of variance was carried out on the mean exposure duration necessary to achieve approximately 75% accuracy for red and green stimuli. No differences were found between the mean exposure duration required for red on green and that for green on red stimuli (14.69 ms vs. 16.54ms, $p > 0.10$).

The accuracy data were examined using a repeated measures ANOVA with four within-subjects variables (Target Colour [red, green], Stimulus Type [words, nonwords], Critical Letter Position, and Target Luminance [Darker, Isoluminant, and Lighter]). The results of the ANOVA showed significant main effects of Stimulus Type, $F(1,15) = 67.858$, $MSE = 494.207$, $p < 0.001$, Critical Letter Position, $F(3,45) = 28.565$, $MSE = 226.721$, $p < 0.001$, and Target Luminance, $F(2,30) = 24.794$, $MSE = 173.637$, $p < 0.001$, and an interaction between Stimulus Type and Critical Letter Position, $F(3,45) = 7.641$, $MSE = 155.999$, $p < 0.001$. No other main effects or

interactions were significant ($p > 0.10$). Newman-Keuls tests were used to examine the main effect of Target Luminance (Figure 4.4). Performance with Isoluminant stimuli ($M = 70.59\%$) was lower than with either Darker ($M = 78.76\%$, $p < 0.001$) or Lighter stimuli ($M = 75.29\%$, $p < 0.001$). Performance in the Darker condition was also higher than in the Lighter condition ($p < 0.01$).

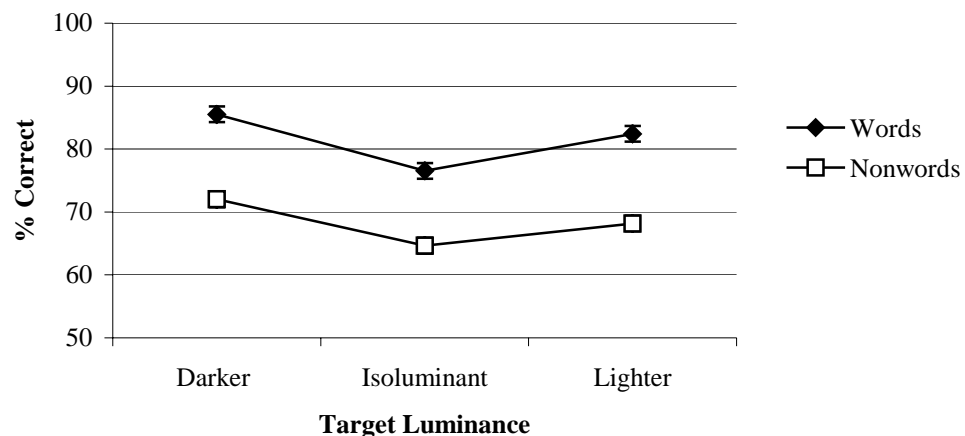


Figure 4.4 Mean percentage of correct responses for different Target Luminances for words and illegal nonwords

Newman-Keuls tests were also used to examine the interaction between Critical Letter Position and Stimulus Type (Figure 4.5). The results showed that for words, performance in Position 1 ($M = 84.59\%$) and Position 4 ($M = 84.20\%$) was better than in both Position 2 ($M = 79.38\%$) and Position 3 ($M = 77.78\%$; all $p < 0.05$). There were no significant differences between Positions 1 and 4 or between Positions 2 and 3 ($p > 0.20$). For nonwords, performance in Position 1 ($M = 77.47\%$) was better than performance in Position 4 ($M = 73.00\%$) and both of these had higher levels of than Position 2 ($M = 61.72\%$) and Position 3 ($M = 60.89\%$; $p < 0.05$), which did not differ significantly from each other ($p > 0.20$). Performance

with words was significantly better than nonwords in all Critical Letter Positions (all $p_s < 0.01$).

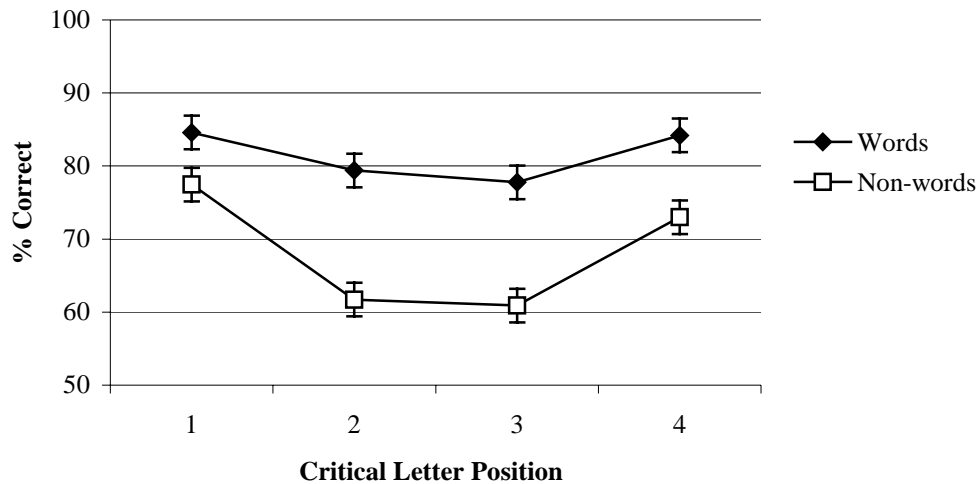


Figure 4.5 Mean percentage of correct responses for different Critical Letter Positions for words and illegal nonwords.

Analysis was also carried out on the magnitude of the performance differences, in terms of the percentage of correct responses, between words and nonwords, to see if these changed across stimulus conditions. A repeated measures analysis of variance was carried out with three within-subjects variables (Target Colour, Critical Letter Position and Target Luminance). The results of the ANOVA showed a significant main effect of Critical Letter Position $F(3,45) = 7.641$, $MSE = 391.998$, $p < 0.001$. No other main effects or interactions were significant ($p_s > 0.10$). Post-hoc analysis of the effect of Critical Letter Position using Newman-Keuls tests revealed that the performance difference between words and nonwords was significantly smaller in Positions 1 ($M = 7.12\%$) and 4 ($M = 11.20\%$) than in Positions 2 ($M = 17.66\%$) and 3 ($M = 16.88\%$; $p_s < 0.05$). The differences between

Positions 1 and 4 and between Positions 2 and 3 were not statistically significant ($p > 0.10$).

In order to ensure that the effects found above were not due to a performance-accuracy trade-off, an analysis of variance was carried out on the response time data. The results of the analysis showed main effects for Stimulus Type, $F(1,15) = 52.985$, $MSE = 224725.6$, $p < 0.001$, and Critical Letter Position, $F(3,45) = 23.709$, $MSE = 43660.9$, $p < 0.001$, and interactions between Stimulus Type and Critical Letter Position, $F(3,45) = 5.017$, $MSE = 23304.7$, $p < 0.05$, and between Stimulus Type and Target Luminance, $F(2,30) = 21.533$, $MSE = 19279.6$, $p < 0.001$. None of the other main effects or interactions were close to significance. Newman-Keuls tests were carried out on the interaction between Stimulus Type and Target Luminance (Figure 4.6) and showed that for words, the mean response time for Isoluminant stimuli ($M = 1584\text{ms}$) was significantly longer than for both Darker ($M = 1482\text{ms}$) or Lighter stimuli ($M = 1529\text{ms}$, $p < 0.01$). The mean response time for Lighter stimuli was also significantly longer than that for Darker stimuli ($p < 0.05$). For nonwords, no significant differences were found between Isoluminant ($M = 1784\text{ms}$), Darker ($M = 1798\text{ms}$) and Lighter stimuli ($M = 1785\text{ms}$, all $p > 0.20$). For all Luminance Conditions, response times were lower for Words than for Non-words (all $p < 0.01$).

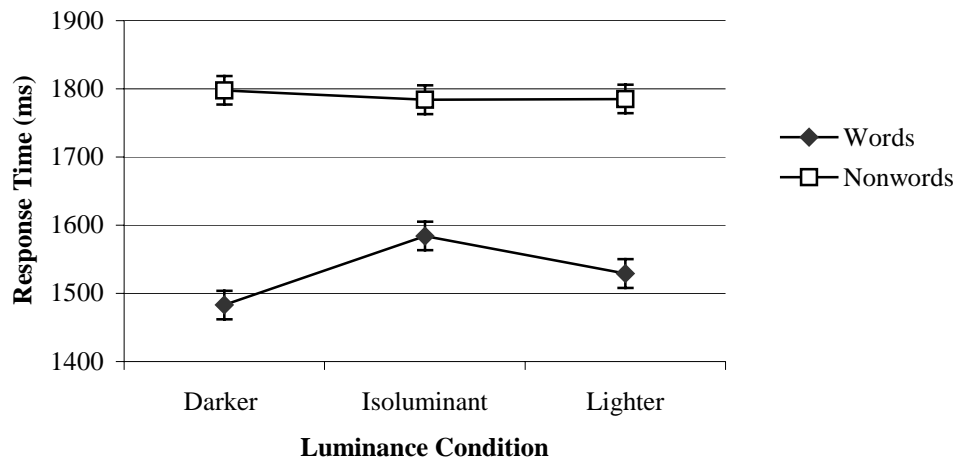


Figure 4.6 Mean response times for different Target Luminances for words and illegal nonwords

The interaction between Stimulus Type and Critical Letter Position was also examined using Newman-Keuls tests (Figure 4.7). The tests showed that for words, response times for Position 1 ($M = 1440\text{ms}$) were significantly shorter than those for Positions 2 ($M = 1585\text{ms}$), 3 ($M = 1577\text{ms}$) and 4 ($M = 1524\text{ms}$, $p_s < 0.001$). Response times for Position 4 were also shorter than those for Positions 2 and 3 ($p_s < 0.001$), which did not differ significantly from each other ($p > 0.20$). For nonwords, response times for Position 1 ($M = 1655\text{ms}$) were significantly shorter than those for Position 4 ($M = 1753\text{ms}$, $p < 0.001$), and both of these had shorter times than Position 2 ($M = 1888\text{ms}$) and Position 3 ($M = 1858\text{ms}$, $p_s < 0.001$). No significant differences in response time were found between Positions 2 and 3 ($p > 0.10$). Words had significantly shorter response times than nonwords for all positions (all $p_s < 0.001$).

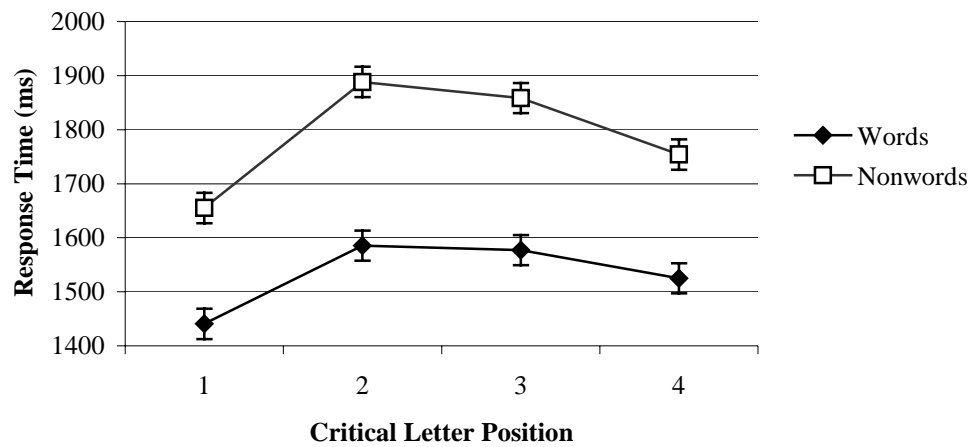


Figure 4.7 Mean response times for different Critical Letter Positions for words and illegal nonwords

11. Discussion – Experiment 3

Experiment 3 provides a number of extremely important findings, not least the confirmation that the stimulus type used in the HFP calibration section is suitable for creating isoluminant stimuli. Analysis of the accuracy data revealed a main effect of Target Luminance, with performance in the Isoluminant condition significantly lower than in either the Darker or Lighter conditions. This strongly indicates that the Magnocellular system does play a role of some kind in written word recognition and goes against the view that word recognition, like all object recognition, is carried out using only information carried by the P pathway (e.g. Livingstone & Hubel, 1987). When participants were forced to rely solely on the P pathway, performance was lower than when both the M and P pathways were available. Analysis of the response time data indicates that this effect was not due to any kind of speed-accuracy trade off. For words, mean response times in the Isoluminant condition were significantly

longer than in either the Darker or Lighter conditions. For nonwords, there were no differences found between the Target Luminance conditions.

These findings do not fit neatly with those of Legge et al. (1990) whose research indicated that reading speed for isoluminant text was no different than reading speed for high luminance contrast text. The reason for these apparently contradictory findings may be the differences in the tasks used. It is likely that reading rate is not as sensitive a measure of perceptual factors as the accuracy measure obtained from the Reicher-Wheeler task. Furthermore, unlike the Reicher-Wheeler task, the reading task used by Legge et al. is open to overt guesswork. Jordan and Thomas (2002) point out that when participants are simply required to read text, they may enhance their performance by correctly guessing the identities of words using partial word information and other contextual cues, which could have diluted the effect of presenting the text at isoluminance.

Although this study offers strong support for the view that the M pathway is used in written word recognition, the findings do not fit in with the explanation proposed by Allen et al. (1995). If the assumptions of the Holistically Biased Hybrid Model were correct, an interaction between Target Luminance and Stimulus Type should have occurred, with very little or no impairment in the Isoluminant condition for nonwords. However, the size of the isoluminance disadvantage was very similar for both words and nonwords. The accuracy difference between the Darker and Isoluminant conditions was approximately 9% for words and 7.5% for nonwords. The difference between the Lighter and Isoluminant conditions was approximately 6% for words and 4% for nonwords. Whilst the isoluminance deficit was slightly smaller numerically for nonwords, the interaction was nowhere near significance.

Similarly, with the analysis of the magnitude of the Word Superiority Effects, no differences were found between the Isoluminant and Darker and Lighter conditions. Based on the theory of Allen et al., it would be predicted that the magnitude of the Word Superiority Effect should be reduced at isoluminance as the recognition of both words and nonwords should rely on the letter-level channel. Therefore, the accuracy data from this experiment do not provide support for the mapping of the word and letter-level channels onto the M and P pathways. Instead, it would appear that both words and nonwords use the same visual pathway route for lexical access. However, the response time data do indicate a possibility that isoluminance affects words and nonwords differently. The absence of an increased mean response time in the Isoluminant condition for nonwords could indicate that nonwords were affected by isoluminance less than words. However, there is a possibility that this may simply be due to response time not being as sensitive a measure as accuracy. As discussed in Chapter 3, previous research has shown that even under data-limited conditions, response time is not sensitive to perceptual factors due to masking by post-perceptual factors (Santee & Egeth, 1982). It is quite probable that the processing of nonwords drifted on so long that no differences in the response times for different Target Luminance conditions were apparent for these stimuli.

Experiment 3 was not designed to directly test the attentional selection explanation of M pathway involvement in written word recognition. However, it was hypothesised that if the attention spotlight is directed to the exterior letter positions in the recognition of words, then the typical U-shaped serial position curve should not occur with isoluminant stimuli. Analysis of the accuracy data did reveal an interaction between Stimulus Type and Critical Letter Position. For both words and

nonwords, performance in the exterior letter positions was superior to performance in the interior positions. Again, analysis of the response time data indicated that this was not due to a speed-accuracy trade-off. This 'U' shaped function was very similar to those seen in other studies measuring accuracy using the Reicher-Wheeler task (e.g. Jordan & Bevan, 1996; Jordan et al., 2000). However, the interaction between Critical Letter Position and Target Luminance was not significant. This indicates that whilst presenting stimuli at isoluminance results in a general impairment in performance, it is unlikely that the way in which words and nonwords are processed is affected, as the same 'U' shape function was found in both the Isoluminant condition and the Darker and Lighter conditions.

Chapter 5

Experiment 4

1. Pseudowords

The aim of Experiment 4 was to provide an extension of the findings of Experiment 3. Experiment 4 used the same experimental design, with the only difference being the types of stimuli employed. Instead of comparing words and illegal nonwords, performance with illegal nonwords was compared with performance with pseudowords in order to further investigate the effects of isoluminance on written word recognition in the Reicher-Wheeler task. Pseudowords are letter-strings that are orthographically regular combinations of letters, but are not part of the English language, and are therefore meaningless. The strings skog, clib and virk are all examples of pseudowords. Pseudowords provide an interesting comparison with illegal nonwords, as they are graphemically and phonologically similar to words, yet have no lexical entry associated with them. A common finding with pseudowords is the Pseudoword Superiority Effect. Gibson, Pick, Osser and Hammond (1962) used Cattell's (1886) whole report procedure, and found that pseudowords were reported more accurately than illegal nonwords. Similar results were obtained by Baron and Thurston (1973) using the Reicher-Wheeler task. Further research has since suggested that this effect only occurs when participants expect to encounter pseudowords (Aderman & Smith, 1971; Carr, Davidson & Hawkins, 1978).

The Holistically Biased Hybrid model of written word recognition (Allen et al., 1995) is able to account for the Pseudoword Superiority Effect by claiming that, even for short exposure durations, the spatial frequency pattern of a pseudoword is familiar enough to allow processing in the word-level channel. However, for briefly

exposed stimuli, illegal nonwords are assumed to be processed analytically by the letter-level channel, as they do not meet the low-pass familiarity threshold. Based on this interpretation, it would be expected that Experiment 4 should find a performance disadvantage for pseudowords in the Isoluminant condition, but no such impairment for nonwords. As with Experiments 2 and 3, it would be expected from the attentional selection explanation of the role of the M pathway that performance should be reduced at isoluminance for both nonwords and pseudowords, as the M pathway should be involved in the processing of both stimulus types. Furthermore, if the attentional spotlight is directed towards the exterior letter positions by the M pathway, then the typical U-shaped serial position curve should not occur under isoluminant conditions.

2. Method

2.1 Participants

Sixteen participants, from the population described in the General Methods section, took part in Experiment 4. They carried out two one-hour 15-minute sessions for which they were paid.

2.2 Stimuli

The stimuli used in this experiment were the pseudoword and illegal nonword stimuli described in the General Methods section in Chapter 3.

2.3 Visual conditions

Pseudowords and illegal nonwords were presented on the computer screen in a proportionally spaced, lowercase font (12pt Times New Roman Bold). The two forced-choice alternatives were presented in uppercase Arial so that no shape information could be used to aid guessing, and in black, within a small grey rectangle.

The luminance of the red and green used for the letter strings in the Isoluminant condition was approximately 16.5cd/m^2 and the CIE(x,y) coordinates were (0.62, 0.34) and (0.28, 0.61) respectively. The letter strings in the Lighter condition were 50% brighter (24.8cd/m^2), and the letter strings in the Darker condition were 50% darker (8.3cd/m^2). The CIE(x,y) coordinates of the red and green used for the backgrounds were (0.62, 0.34) and (0.28, 0.61) respectively. The luminance of the backgrounds was calculated for each participant using the procedure detailed below. The grey rectangle that the choices were presented on was the same luminance as the coloured background.

2.4 Design

Each participant took part in two sessions. In one session participants saw red letter strings (Isoluminant, Lighter, Darker) presented on a green background, and in the other green letter strings on a red background. Participants were presented each letter string once in each of these target luminance conditions. Thus there were 576 experimental trials in each session. The order of these sessions was counterbalanced across participants. Each participant saw all 96 practice trials in each session. There was no obvious transition between the practice and experimental sections. Stimuli were shown in cycles of 24 items, counterbalanced across Stimulus Type (pseudoword, illegal nonword), Target Luminance (Lighter, Darker, Isoluminant) and Critical Letter Position.

2.5 Calibration

10 HFP trials were carried out at the start of each session and the average luminance obtained was used for the background of the stimuli in the Reicher-Wheeler task. In each trial, a letter string, 'xxxx', was presented against a background

of the other colour. The font used (Times New Roman Bold 12pt) and the size of the background were the same as in the main section of the experiment in order to keep the stimuli used for calibration as similar as possible to those used in the experiment proper. Participants were required to adjust the luminance of the background until they perceived the flicker as being minimal. When they were satisfied that this had been achieved they had to press one of the side buttons to confirm their response.

2.6 Procedure

Participants were not explicitly told to expect pseudowords, but were aware of their presence through the examples given in the instructions. The procedure, and all remaining aspects of this experiment are identical to those specified in the General Methods section.

3. Results

The mean luminance required to obtain minimal flicker in the HFP task was 15.1cd/m^2 where red was the colour being adjusted and 16.7cd/m^2 where green was the colour adjusted. The mean standard deviation was 2.031cd/m^2 for red adjustment trials and 1.709cd/m^2 for green. As would be expected, these values are similar to those obtained in Experiment 3 and the relatively small mean standard deviations indicate that participants were consistent in their responses.

Participants achieved a mean percentage correct of 74.41% for the Red on Green stimuli and 74.64% for the Green on Red stimuli. This demonstrates that the adjustments of the exposure duration made after each cycle of trials were effective in keeping overall performance in the midrange. Mean exposure durations were 17.66ms and 18.88ms for Red on Green and Green on Red stimuli respectively, and

there was no evidence of any difference between the two colour conditions $F(1,15) = 0.387$, $MSE = 30.749$, $p > 0.20$.

An Analysis of Variance with four within-subjects variables (Target Colour [red, green], Stimulus Type [pseudoword, nonword], Critical Letter Position, and Target Luminance [Darker, Isoluminant, Lighter]) was carried out. There were significant main effects of Stimulus Type, $F(1,15) = 191.154$, $MSE = 103.828$, $p < 0.001$, Critical Letter Position, $F(3,45) = 37.822$, $MSE = 177.478$, $p < 0.001$, and Target Luminance, $F(2,30) = 30.754$, $MSE = 89.667$, $p < 0.001$, and an interaction between Stimulus Type and Critical Letter Position $F(3,45) = 8.909$, $MSE = 115.297$, $p < 0.001$. Neither the main effect of Target Colour or any of the other interactions reached significance ($ps > 0.05$). Newman-Keuls post hoc tests were used to examine the main effect of Target Luminance more closely (Figure 5.1). Performance with Isoluminant stimuli ($M = 70.93\%$) was lower than with either Darker ($M = 77.36\%$, $p > 0.001$) or Lighter stimuli ($M = 75.29\%$, $p > 0.001$). Performance in the Darker condition was also higher than in the Lighter condition ($p > 0.05$).

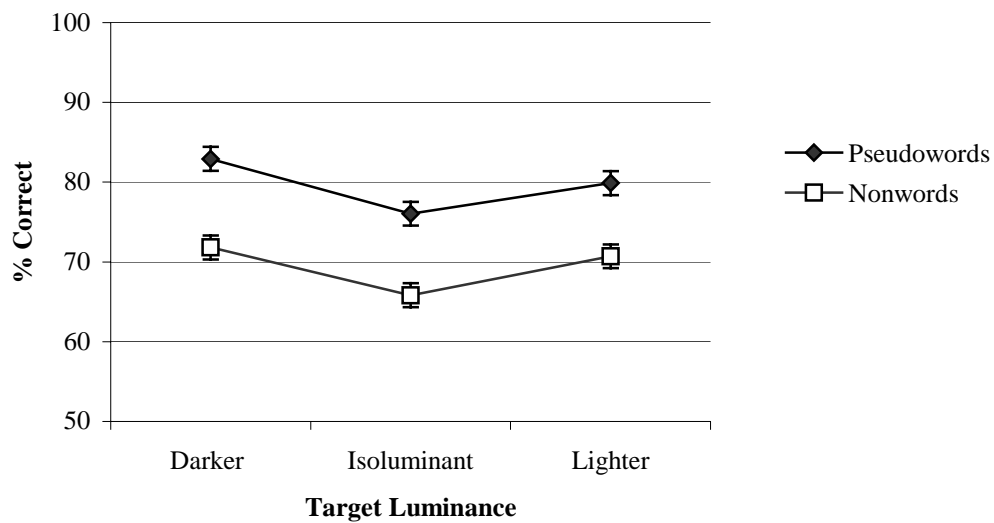


Figure 5.1. Mean percentage of correct responses for different Target Luminances for pseudowords and illegal nonwords.

Post hoc tests were also carried out on the interaction between Stimulus Type and Critical Letter Position (Figure 5.2). For pseudowords, performance in Position 1 (\underline{M} = 83.90%) and in Position 4 (\underline{M} = 81.47%) was significantly better than in Position 2 (\underline{M} = 77.08%) and Position 3 (\underline{M} = 76.00% , $p_s < 0.05$). There were no significant differences between Positions 1 and 4 ($p > 0.10$) or between Positions 2 and 3 ($p > 0.20$). For nonwords, performance in Position 1 (\underline{M} = 79.38%) was better than in Position 4 (\underline{M} = 72.83% , $p < 0.001$), and both of these had higher levels of performance than Positions 2 (\underline{M} = 61.89%) and 3 (\underline{M} = 63.67%, $p_s < 0.001$), which did not differ from each other ($p > 0.20$). Performance with pseudowords was significantly better than with nonwords for all Critical Letter Positions (all $p_s < 0.05$).

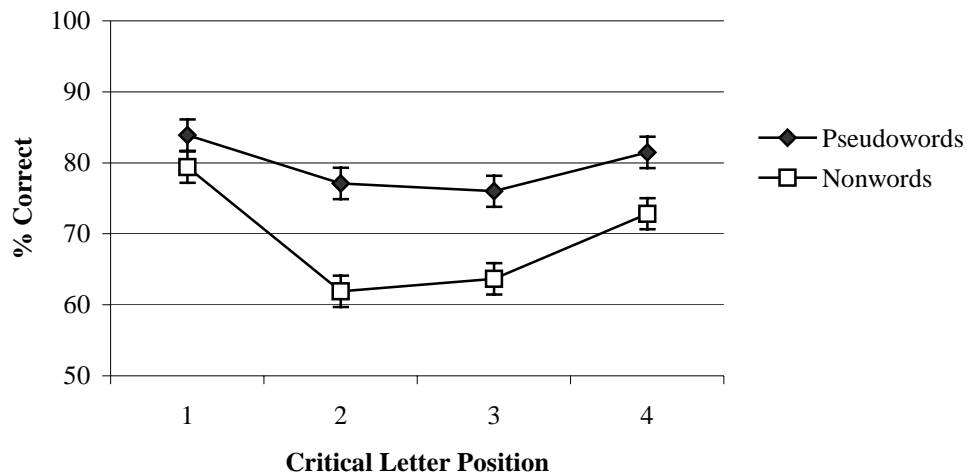


Figure 5.2. Mean percentage of correct responses for different Critical Letter Positions for pseudowords and illegal nonwords

Additional analysis was carried out on the magnitude of the accuracy differences between pseudowords and nonwords to see if these varied across conditions. A repeated measures analysis of variance was carried out with three within-subjects variables (Target Colour, Critical Letter Position, Target Luminance). The results of the ANOVA showed a significant main effect of Critical Letter Position $F(3,45) = 8.909$, $MSE = 230.594$, $p < 0.001$. No other main effects or interactions were significant ($ps > 0.05$). Newman-Keuls tests were carried out in order to examine the effect of Critical Letter Position. It was shown that the mean performance difference between nonwords and pseudowords for Position 1 ($M = 4.51\%$) and Position 4 ($M = 8.64\%$) were significantly smaller than for Position 2 ($M = 15.19\%$, $ps < 0.05$). The performance difference for Position 1 was also significantly smaller than the difference for Position 3 ($M = 12.33\%$, $p < 0.01$). None of the other performance differences were significant ($ps > 0.05$).

An ANOVA was also carried out on the response time data to ensure that the effects found above were not due to a speed-accuracy trade-off. The same four within-subjects variables were used. There were significant main effects of Stimulus Type, $F(1,15) = 71.740$, $MSE = 77455.5$, $p < 0.001$, Critical letter Position, $F(3,45) = 15.288$, $MSE = 74137.9$, $p < 0.001$, and Target Luminance $F(2,30) = 4.024$, $MSE = 39491.7$, $p < 0.05$. However, neither the main effect of Target Colour or any of the interactions reached significance ($ps > 0.05$). The main effect of Stimulus Type revealed that pseudowords ($M = 1585ms$) were responded to significantly faster than nonwords ($M = 1755ms$). Newman-Keuls tests were used to examine the main effect of Target Luminance (Figure 5.3). The mean response time for Isoluminant stimuli ($M = 1698ms$) was significantly longer than that for either Darker ($M = 1652ms$) or Lighter ($M = 1660ms$, $ps < 0.05$) stimuli, between which there was no significant difference ($p > 0.20$).

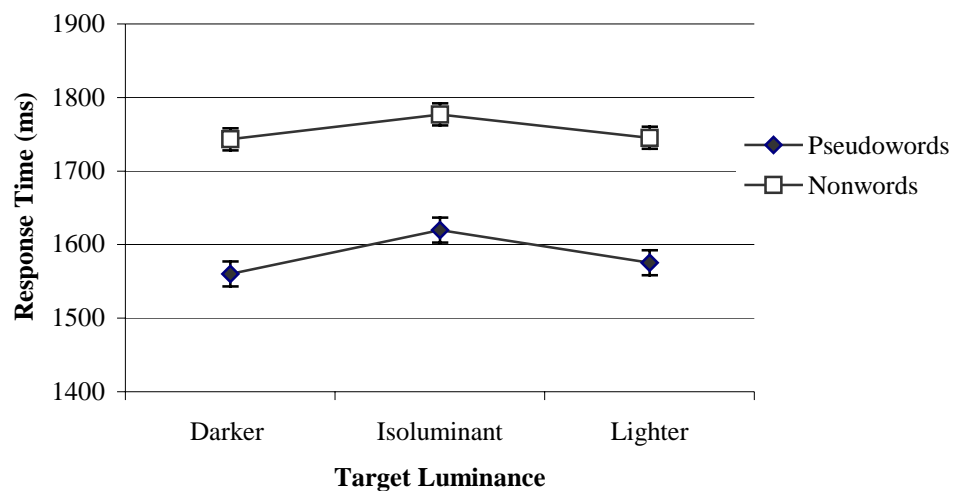


Figure 5.3. Mean response times for different Target Luminances for pseudowords and illegal nonwords.

The main effect of Critical Letter Position was also examined using Newman-Keuls tests (Figure 5.4). The mean response time for Position 1 ($\underline{M} = 1566\text{ms}$) was significantly shorter than for Position 2 ($\underline{M} = 1740\text{ms}$), Position 3 ($\underline{M} = 1713\text{ms}$) and Position 4 ($\underline{M} = 1661\text{ms}$, $p < 0.01$). Response times for Position 4 were also significantly shorter than those for Position 2 ($p < 0.05$). There were no significant differences between response times for Positions 2 and 3 ($p > 0.20$) or Positions 3 and 4 ($p > 0.05$).

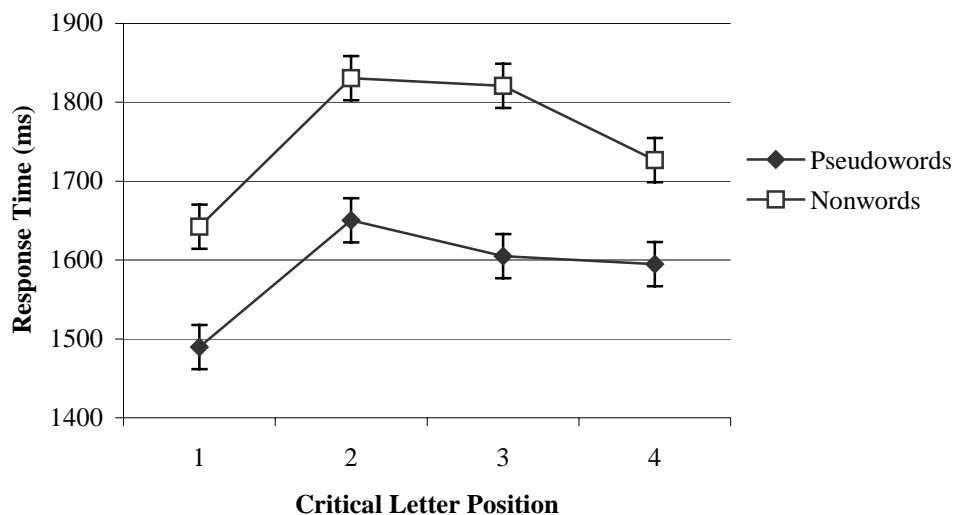


Figure 5.4. Mean response times for different Critical Letter Positions for pseudowords and illegal nonwords

4. Discussion

The findings of Experiment 4 closely resembled those from Experiment 3. As with Experiment 3, there was a main effect of Target Luminance, with accuracy in the Isoluminant condition significantly lower than in either the Darker or Lighter

conditions. This finding provides further support for the view that information carried by the M pathway does play some role in the recognition of written letter strings, contrary to the findings of researchers such as Legge et al. (1990) and Livingstone and Hubel (1987). The response time data confirmed that this isoluminance deficit was not due to a speed-accuracy trade-off: A main effect of Target Luminance was identified, with longer response times in the Isoluminant condition than in the Darker or Lighter conditions.

It should be noted that unlike the previous experiment, the response time data revealed no interaction between Stimulus Type and Target Luminance. Response times for illegal nonwords were longer in the Isoluminant condition than in the non-isoluminant conditions. This means that it is unlikely that the absence of any increase in response times for nonwords at isoluminance in Experiment 3 was due to M pathway information not being used in the processing of these stimuli. A more likely explanation is that response time measurements are not sensitive enough to perceptual factors to consistently show the effect of presenting illegal nonwords at isoluminance.

The reduction in accuracy at isoluminance was roughly equivalent for pseudowords and nonwords with a difference between the Darker and Isoluminant conditions of approximately 7% for pseudowords and 6% for nonwords. The difference between the Lighter and Isoluminant conditions was approximately 4% for pseudowords and 5% for nonwords (see Figure 5.1). In common with earlier research (e.g. Baron & Thurston, 1973; Gibson et al. 1962) there was a strong Pseudoword Superiority Effect. Analysis of the magnitude of the accuracy differences between pseudowords and nonwords provided no evidence that this advantage for pseudowords was affected by isoluminance, with the difference in performance

between pseudowords and nonwords being approximately 10% for Isoluminant stimuli compared to an 11% difference for Darker and a 9% difference for Lighter stimuli. The maintenance of the Pseudoword Superiority Effect at isoluminance suggests that the perception of pseudowords and illegal nonwords may occur using broadly the same processes even in the absence of luminance contrast information, indicating that this information is not necessary for written word recognition to occur normally.

Although these findings provide further support for the view that the M pathway plays a role in the recognition of words, they do not provide any evidence to support the view of Allen et al. (1995) that the word-level and letter-level channels of the Holistically Biased Hybrid Model map onto the M and P pathways respectively. According to Allen et al., as the spatial frequency pattern of pseudowords is familiar enough to allow use of the word-level channel, a performance disadvantage should be found for pseudowords, but not for nonwords. However, whilst this experiment provided evidence of an isoluminance deficit for pseudowords, performance was similarly reduced at isoluminance for nonwords. Likewise, response times were similarly increased at isoluminance for both pseudowords and nonwords, providing no evidence to suggest that humans process pseudowords and illegal nonwords using different pathways.

In common with Experiment 3, there was an interaction between Stimulus Type and Critical Letter Position, and for both pseudowords and nonwords performance in the exterior letter positions (Positions 1 and 4) was superior than for the interior letter positions (Positions 2 and 3). However, there was no evidence of an interaction between Critical Letter Position and Target Luminance, with the same U-

shaped function being found at all three luminance conditions. The absence of any evidence of an influence of Target Luminance on the size of the Pseudoword Superiority Effect or the shape of the serial position curve further implies that whilst presenting letter strings at isoluminance does produce a general impairment in recognition performance, it does not affect the way in which orthographic processing is carried out.

The reduction in performance at isoluminance for both nonwords and pseudowords is consistent with attentional selection accounts of the role of the M pathway, as the identification and ordering of letters is required in the Reicher-Wheeler task for both stimulus types. However, if the attentional spotlight is directed towards the exterior letter positions by the M pathway, then no differences between the different serial positions should be expected for isoluminant stimuli. This hypothesis was not supported by the data, as no interaction between Critical Letter Position and Target Luminance was found for either accuracy or response times, with typical serial position curves occurring under isoluminant conditions.

Chapter 6

Experiment 5

1. Case mixing

A large number of studies have been carried out using CaSe MiXiNg to investigate whether written word recognition is based on holistic visual information or on individual letter identification (e.g. Allen et al, 1995; Coltheart & Freeman, 1974; McClelland, 1976; Mayall, Humphreys & Olson, 1997; Mayall, Humphreys, Mechelli, Olson & Price, 2001). The rationale behind the case mixing methodology is that the presentation of mixedcase stimuli should disrupt word shape information and thus prevent holistic processing. McClelland (1976) presented such stimuli in a version of the Reicher-Wheeler paradigm. Participants were required to identify a letter embedded in a word, pseudoword or illegal nonword. It was found that when mixedcase words (and pseudowords) were presented, performance was reduced relative to that with lowercase stimuli. However, no such mixedcase disadvantage was obtained for nonwords. This supports the view that word-shape information is used to facilitate access to the lexicon. According to this view, if words were recognised in an analytical fashion then no such interactions should be found, as each letter would be identified individually. Similar findings have been obtained by experiments using the lexical decision task. For example, Allen et al. (1995) found that under data-limited conditions, the mixed case disadvantage obtained is larger for words than for nonwords. However, under resource-limited conditions, a larger mixedcase disadvantage was obtained for nonwords. These findings are consistent with the Holistically Biased Hybrid model of written word recognition (Allen et al., 1995): For long exposure durations, the model predicts that both lowercase words and

nonwords should be processed using the word-level channel. However, for mixedcase presentations, the spatial frequency pattern of the stimuli would not be familiar enough to reach the activation threshold for holistic processing, and both words and nonwords would therefore be processed by the letter-level channel. The larger mixedcase disadvantage for nonwords would result from the increased length of the superposition process, which would take longer for nonwords due to their unfamiliar orthographic structure. For brief exposure durations, whilst lowercase words would be processed holistically, mixedcase words would be processed by the letter-level channel as activation in the word-level channel would not be high enough. As both lowercase and mixedcase nonwords are processed analytically, the mixedcase disadvantage for these stimuli would be relatively small.

There is, however, some disagreement over the origin of case mixing effects. Analytical theorists have suggested that the mixedcase disadvantage is due to a disruption to letter level processing (e.g. Paap, Newsome & Noel, 1984). It has been argued that case mixing may result in greater lateral inhibition and/or make some letter segments (such as the ascenders of b, d, h, l, etc) more difficult to perceive. However, if this were the case, it would be expected that in studies such as McClelland (1976) there would be a mixedcase disadvantage for nonwords as well as words, but the study provided no evidence of such an effect. Furthermore, Allen, Madden, Weber and Groth (1993) found that participants took longer to respond to mixedcase words in a lexical decision task when spaces were inserted between each letter. If lateral inhibition were a major factor in case mixing effects, performance should have improved under such conditions.

A further possibility is that whilst participants can become tuned to a single case, they are unable to become proficient at processing mixed case stimuli even with considerable practice (Sanocki, 1987, 1988). However, Rudnicky and Kolers (1984) found that there was a greater cost for switching case within a word than between words. Both the within and between word conditions involved the same amount of switching between cases so the case-specific tuning hypothesis would predict that performance should be reduced equally for both conditions. However, performance was disrupted significantly more in the within word condition, presumably because this prevented readers from processing words in a holistic fashion.

Additional support for the proposal that case mixing is an effective technique for studying word-shape has come from a PET study by Mayall et al. (2001). They found that activation in the right parietal cortex is increased when words are presented in mixedcase as opposed to lowercase, suggesting an increased attentional demand. This is not associated with mixing case per se, as the effect was far greater with words than with either pseudowords or illegal nonwords. Mayall et al. suggest that these increased demands on attentional processes may occur due to case mixing disrupting holistic processing or the use of transletter features, inducing the serial processing of letters.

2. The present study

Experiments 3 and 4 provided a strong indication that the M pathway does play a role in written word recognition. Experiment 5 aimed to further investigate the nature of the M pathways' role using a case mixing methodology. As it has been shown that the M pathway is the most sensitive to low spatial frequency information at high temporal frequencies (Merigan et al., 1991), presenting stimuli at

isoluminance may affect case mixing effects. Experiment 5 therefore encompassed the presentation of words and illegal nonwords in the Reicher-Wheeler task in the same three Target Luminance conditions used in the previous experiments (Isoluminant, Darker, Lighter), but participants carried out three experimental sessions with a different case condition used in each (lowercase, UPPERCASE or MiXeD cAsE). A blocked design, in which the different case conditions were separate rather than intermixed was used for two main reasons. First, it allowed the stimuli used in the HFP task carried out before each session to be appropriate for that particular session. This ensured that the luminance values obtained for isoluminance in the calibration section were as accurate as possible. Second, it allowed performance in each of the case conditions to be equivalent. The exposure duration for target stimuli was adjusted within each session to keep performance in the midrange (approximately 75% correct). Whilst this prevented direct comparisons between levels of performance for the different conditions, it meant that any interactions could be attributed to case mixing effects, rather than ceiling or floor effects occurring due to differences in task difficulty.

Based upon the findings of Experiment 3, it was predicted that for lowercase stimuli, there should be a reduction in performance in the Isoluminant condition relative to the Darker and Lighter conditions for both words and nonwords. Comparison with the findings from the mixedcase condition should provide information as to whether this impairment at isoluminance is due to the absence of word shape information carried by the M pathway. If the performance deficit at isoluminance occurs due to the absence of word shape information preventing holistic processing it would be predicted that for mixedcase stimuli, there should be little or

no reduction in performance in the Isoluminant condition, due to the shape of the mixedcase stimuli being too unfamiliar to allow holistic processing. Based on the findings of previous case mixing research, it was predicted that results for uppercase stimuli should be similar to those found with mixedcase stimuli although the magnitude of any effects should be reduced.

As mentioned above, overall performance in each of the case conditions was kept at 75%, meaning that the larger mixed case disadvantages for words found in previous research (e.g. Allen et al. 1995; McClelland, 1976) would not be replicated in this study. However, it would be consistent with findings such as these to predict that the performance difference between words and nonwords should be smaller for mixedcase stimuli than for lowercase. This is because the effect of case mixing should be greatest for words, meaning that performance should be closer to that obtained with nonwords.

3. Method

3.1 Participants

Twenty-four participants, from the population described in the General Methods section in Chapter 3, took part in three one-hour 15 minute sessions for which they were paid.

3.2 Stimuli

The stimuli used in this experiment were the word and illegal nonword stimuli described in the General Methods section. Half the participants were shown red stimuli on a green background and the other half green stimuli on a red background. The stimuli were either isoluminant with the background, lighter, or darker than the background.

3.3 Visual conditions

Stimuli were presented under three case conditions: lowercase, UPPERCASE and MiXeD cAsE, in which the letters within the string alternated between lower and uppercase. In the mixed case condition, two versions of the stimulus list were used, with half the participants seeing each version. In one version, one letter string from each pair was presented with an uppercase critical letter, whilst the other string was presented with a lowercase critical letter. This was reversed in the other version of the list. Stimuli were presented in a specially adapted 12pt font, based on Times New Roman Bold, in which lowercase and uppercase letters shared the same width. The two forced-choice alternatives were presented in black on a small grey rectangular background so that the choices were equally visible for all conditions. Only the critical letters of the two alternatives were displayed with the other letter positions being replaced by dashes. The two alternatives were presented in the opposite case to that used for the critical letter of the target stimulus so that no shape cues from the alternatives could be used to aid guessing. For example, the target word work was followed by the two alternatives ---D and ---K.

The luminance of the red and green used for the letter strings in the Isoluminant condition was 16.5cd/m^2 and the CIE(x,y) coordinates were (0.62, 0.34) and (0.28, 0.61) respectively. The letter strings in the Lighter condition were 50% brighter (24.8cd/m^2), and the letter strings in the Darker condition were 50% darker (8.3cd/m^2). The luminance of the coloured background was calculated for each participant at the beginning of each session using the calibration procedure detailed below. The grey rectangle that the choices were presented on was the same luminance as the coloured background.

3.4 Design

Participants were presented each letter string once in each of the Target Luminance and Case conditions. Thus there were 1728 experimental trials in total. These were split across three sessions with 576 experimental trials in each one. A blocked design was used in which participants carried out the task under one of the case conditions in each session, and the order of the sessions was fully counterbalanced across participants. Within each session, the order of the stimulus presentations was pseudorandomly organised for each participant. Cycles of 24 stimulus items were created by randomly selecting one pair from each possible combination of Stimulus Type, Luminance Condition and Critical Letter Position.

3.5 Calibration

10 HFP trials were carried out in each session, and the average luminance obtained was used for the backgrounds of the stimuli in the Reicher-Wheeler task. The stimuli used in HFP were either red on green, or green on red depending on which colour condition the participant was in. The stimuli consisted of a letter string of four x's presented against a background of the other colour. The displays in the calibration section were kept as similar as possible to those in the experiment proper to ensure valid luminance values for isoluminance were obtained (see Experiment 1). The letter string was presented in the same case (lowercase, UPPERCASE, MiXeDcAsE) as stimuli in the subsequent Reicher-Wheeler task, and in the same specially adapted font used in the experiment proper. Participants were required to adjust the luminance of the background until they perceived the flicker as being minimal.

3.6 Procedure

The procedure, and all remaining aspects of this experiment are identical to those specified in the General Methods section.

4. Results

The HFP data were examined using an analysis of variance with one between-groups variable (Colour Adjusted [red, green]) and one within subjects variable (Case [lower, MiXeD, UPPER]). Neither of the main effects or the interaction between Colour Adjusted and Case Condition was significant (all p s > 0.10). The mean background luminance required to obtain minimal flicker in green adjustment trials was 17.2cd/m² for lowercase, 16.8cd/m² for mixedcase and 16.7cd/m² for uppercase. For red adjustment trials, the mean luminance required for minimal flicker was 15.5cd/m² for lowercase, 14.8cd/m² for mixedcase and 15.5cd/m² for uppercase. A 2x3 split plot ANOVA featuring the same variables was also carried out on the standard deviations of each participants 10 responses, in order to give a measure of consistency. Again, neither of the main effects nor the interaction reached significance (all p s > 0.20). For green adjustment trials the mean standard deviations were 1.804cd/m² for lowercase, 1.495cd/m² for mixedcase and 1.664cd/m² for uppercase, and for red adjustment trials, the mean standard deviations were 2.377cd/m² for lowercase, 2.142cd/m² for mixedcase and 2.434cd/m² for uppercase.

In the Reicher-Wheeler task, the mean percentage correct was 75.49% for lowercase, 75.02% for mixedcase and 75.10% for uppercase stimuli, indicating that the exposure duration adjustments were effective in keeping performance in the midrange. An analysis of variance was carried out on the exposure duration necessary to achieve 75% performance in the different case conditions. There was a main effect

of Case Condition $F(2,46) = 18.781$, $MSE = 13.140$, $p < 0.001$, with the mean exposure duration required for lowercase stimuli ($M = 12.36\text{ms}$) significantly shorter than that required for uppercase stimuli ($M = 15.49\text{ms}$, $p < 0.01$) and both of these shorter than the exposure duration required for mixedcase stimuli ($M = 18.77\text{ms}$, $ps < 0.01$). Neither the main effect of Colour Adjusted, nor the interaction between Case and Colour Adjusted reached significance ($ps > 0.20$).

The accuracy data were examined using a split plot analysis of variance with one between-groups variable (Target Colour [red, green]) and four within-subjects variables (Case [lower, MiXeD, UPPER], Stimulus Type [words, nonwords], Critical Letter Position and Target Luminance [Darker, Isoluminant, Lighter]). The results of the ANOVA showed significant main effects of Stimulus Type, $F(1,22) = 167.571$, $MSE = 147.947$, $p < 0.001$, Critical Letter Position, $F(3,66) = 30.653$, $MSE = 153.479$, $p < 0.001$, and Target Luminance, $F(2,44) = 15.131$, $MSE = 459.162$, $p < 0.001$, and interactions between Case and Stimulus Type, $F(2,44) = 4.970$, $MSE = 110.569$, $p < 0.05$, and between Stimulus Type and Critical Letter Position $F(3,66) = 8.520$, $MSE = 68.612$, $p < 0.001$. No other main effects or interactions were significant ($ps > 0.05$). Newman-Keuls tests were used to examine the main effect of Target Luminance (Figure 6.1). The percentage of correct responses obtained with Isoluminant stimuli ($M = 71.24\%$) was lower than with either Darker ($M = 77.76\%$, $p < 0.001$) or Lighter stimuli ($M = 76.58\%$, $p < 0.001$). There was no difference between performance in the Darker and Lighter conditions ($p > 0.20$).

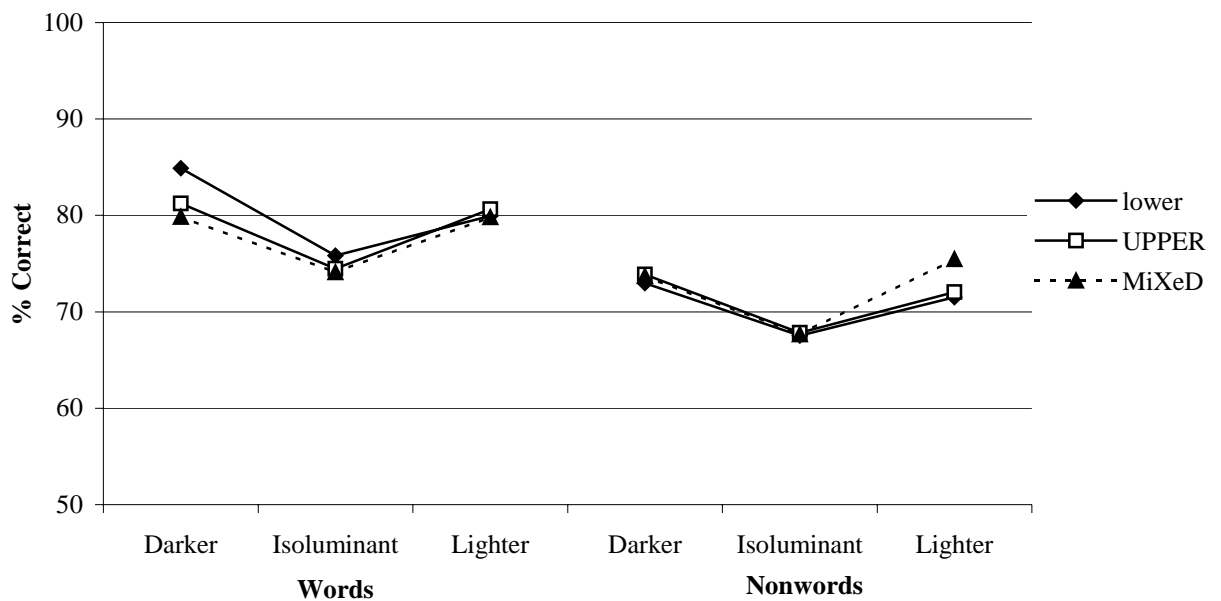


Figure 6.1. Mean percentage of correct responses for different Target Luminances split by Stimulus Type and Case.³

Newman-Keuls tests were also used to examine the interaction between Stimulus Type and Critical Letter Position (Figure 6.2). The results showed that for words, performance in Position 1 ($M = 81.44\%$) and Position 4 ($M = 80.27\%$) was better than in both Position 2 ($M = 77.28\%$) and Position 3 ($M = 76.93\%$; $p_s < 0.001$). There were no significant differences between Positions 1 and 4 or between Positions 2 and 3 ($p > 0.10$). For nonwords, performance in Position 1 ($M = 77.23\%$) was better than in Position 4 ($M = 72.42\%$) and both of these had higher levels of performance than Position 2 ($M = 68.21\%$) and Position 3 ($M = 67.75\%$; $p_s < 0.001$), which did not differ significantly from each other ($p > 0.20$). Performance with words was significantly better than with nonwords in all Critical Letter Positions (all $p_s < 0.001$).

³ No statistical significance bars are shown on this figure in order to aid visibility.

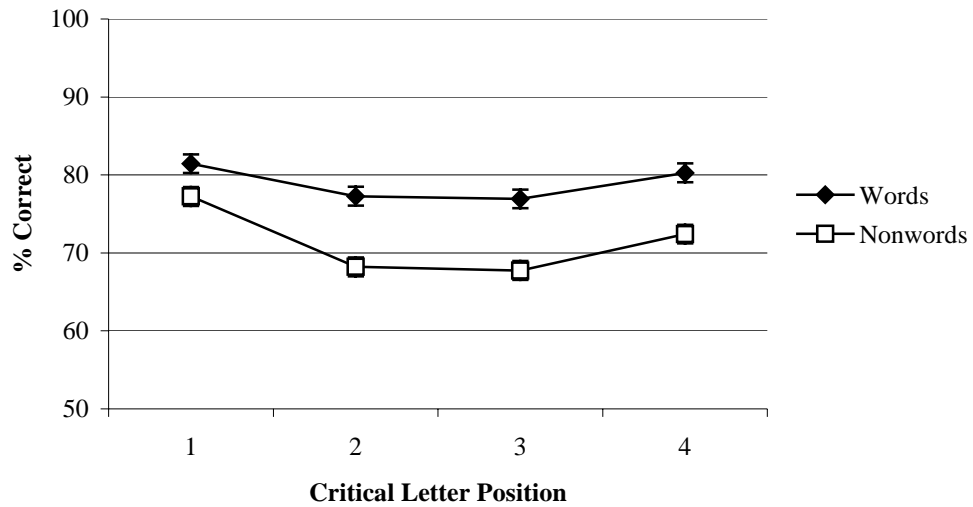


Figure 6.2. Mean percentage of correct responses for different Critical Letter Positions for words and illegal nonwords.

Closer examination of the interaction between Case and Stimulus Type (Figure 6.3) using Newman-Keuls post-hoc tests revealed that for words, performance with lowercase stimuli ($\underline{M} = 80.22\%$) was significantly better than with mixedcase stimuli ($\underline{M} = 77.92\%$, $p < 0.05$). Performance with uppercase stimuli ($\underline{M} = 78.79\%$) did not differ significantly from either of the other two case conditions ($ps > 0.10$). For nonwords, performance with lowercase stimuli ($\underline{M} = 70.67\%$) did not differ significantly from performance with either uppercase ($\underline{M} = 71.25\%$) or mixedcase stimuli ($\underline{M} = 72.28\%$; $ps > 0.10$). For all case conditions, accuracy was greater with words than with nonwords ($ps < 0.001$).

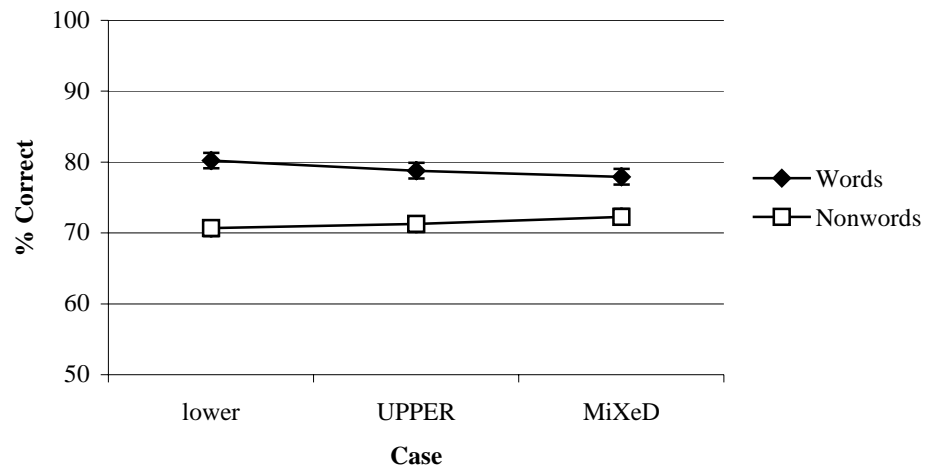


Figure 6.3. Mean percentage of correct responses for different Case types for words and illegal nonwords.

Analysis was also carried out on the magnitude of the performance differences, in terms of the percentage of correct responses, between words and nonwords. An analysis of variance was carried out with three within-subjects variables (Case, Critical Letter Position and Target Luminance) and one between-groups variable (Target Colour). The results of the ANOVA showed significant main effects of Case, $F(2,44) = 4.970$, $MSE = 221.139$, $p < 0.05$, and Critical Letter Position, $F(3,66) = 8.520$, $MSE = 137.224$, $p < 0.001$. No other main effects or interactions were significant ($p > 0.05$). Analysis of the main effect of Case using Newman-Keuls tests indicated that the performance difference between words and nonwords was significantly larger for lowercase stimuli ($M = 9.55\%$) than for mixedcase stimuli ($M = 5.64\%$, $p < 0.01$). Neither of these differed significantly from the mean performance difference for uppercase stimuli ($M = 7.54\%$, both $ps > 0.10$). The Newman-Keuls tests conducted on the main effect of Critical Letter Position revealed that the mean performance difference for Position 1 ($M = 4.21\%$) was

significantly smaller than that for Position 2 ($\underline{M} = 9.07\%$), Position 3 ($\underline{M} = 9.18\%$) and Position 4 ($\underline{M} = 7.85\%$, all p s < 0.01), which did not differ significantly from each other (p s > 0.20).

In order to ensure that the effects described above were not due to a speed-accuracy trade-off, an analysis of variance was carried out on the response time data. The results of the analysis showed main effects of Case, $\underline{F}(2,44) = 3.427$, $\underline{MSE} = 570635.7$, $p < 0.05$, Stimulus Type, $\underline{F}(1,22) = 80.331$, $\underline{MSE} = 69069.9$, $p < 0.001$ and Critical Letter Position, $\underline{F}(3,66) = 6.511$, $\underline{MSE} = 70910.0$, $p < 0.001$ and interactions between Case and Stimulus Type, $\underline{F}(2,44) = 3.675$, $\underline{MSE} = 27684.6$, $p < 0.05$, Stimulus Type and Critical Letter Position, $\underline{F}(3,66) = 16.437$, $\underline{MSE} = 9291.1$, $p < 0.001$, and Stimulus Type and Target Luminance, $\underline{F}(2,44) = 5.623$, $\underline{MSE} = 27058.6$, $p < 0.01$. None of the other main effects or interactions were significant. Newman-Keuls tests were carried out on the interaction between Stimulus Type and Target Luminance (Figure 6.4) and showed that for words, the mean response time for Isoluminant stimuli ($\underline{M} = 1538\text{ms}$) was significantly longer than for both Darker ($\underline{M} = 1495\text{ms}$) and Lighter stimuli ($\underline{M} = 1494\text{ms}$, p s < 0.01). The mean response times for the Darker and Lighter conditions did not differ significantly from each other ($p > 0.20$). For nonwords, no significant differences in response time were found between Isoluminant ($\underline{M} = 1615\text{ms}$), Darker ($\underline{M} = 1635\text{ms}$) and Lighter stimuli ($\underline{M} = 1616\text{ms}$, all p s > 0.10).

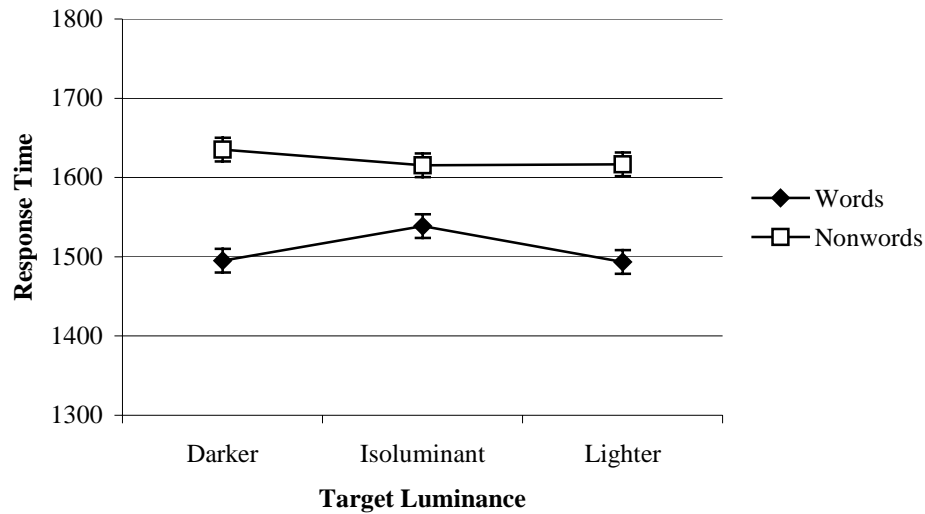


Figure 6.4. Mean response times for different Target Luminances for words and illegal nonwords.

The interaction between Stimulus Type and Critical Letter Position was also examined using Newman-Keuls tests (Figure 6.5). The tests showed that for words, mean response times for Position 1 ($\underline{M} = 1486\text{ms}$) were significantly shorter than those for Positions 2 ($\underline{M} = 1506\text{ms}$), 3 ($\underline{M} = 1525\text{ms}$) and 4 ($\underline{M} = 1519\text{ms}$, all $p\text{s} < 0.05$), which did not differ significantly from each other ($p\text{s} > 0.05$). For nonwords, mean response times for Position 1 ($\underline{M} = 1555\text{ms}$) were significantly shorter than those for Position 4 ($\underline{M} = 1615\text{ms}$, $p < 0.001$), and both of these had shorter mean response times than Position 2 ($\underline{M} = 1651\text{ms}$) and Position 3 ($\underline{M} = 1669\text{ms}$, $p\text{s} < 0.001$). No significant differences in mean response time were found between Positions 2 and 3 ($p > 0.05$). Response times for words were significantly shorter than for nonwords in all critical letter positions (all $p\text{s} < 0.001$).

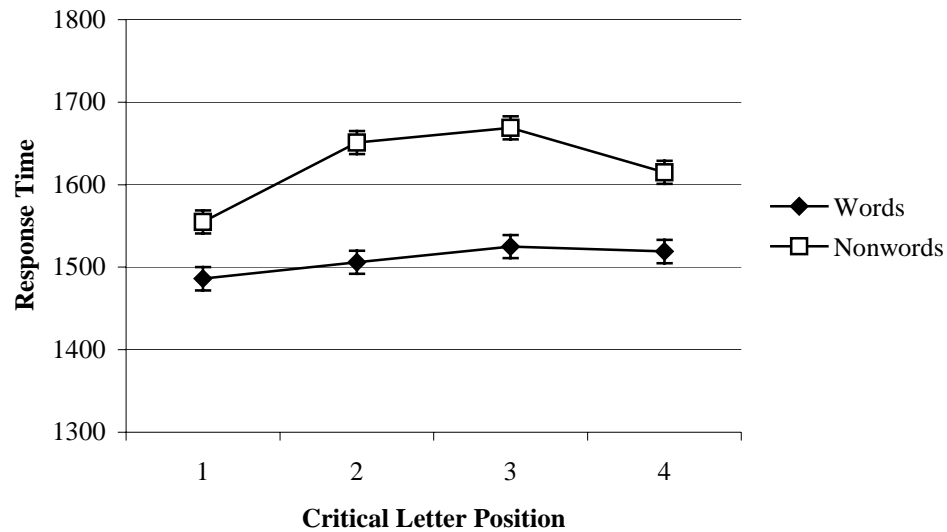


Figure 6.5. Mean response times for different Critical Letter Positions for words and illegal nonwords.

Further Newman-Keuls post-hoc tests were carried out to investigate the interaction between Case and Stimulus Type (Figure 6.6). The results showed that for words, mean response times for lowercase stimuli ($M = 1444\text{ms}$) were significantly shorter than for either uppercase ($M = 1499\text{ms}$) or mixedcase stimuli ($M = 1585\text{ms}$, both $p < 0.001$). Response times for uppercase stimuli were also shorter than those for mixedcase stimuli ($p < 0.001$). Similarly, with nonwords, mean response times for lowercase stimuli ($M = 1576\text{ms}$) were significantly shorter than those for uppercase stimuli ($M = 1623$, $p < 0.001$), and both of these had shorter times than mixed case stimuli ($M = 1668\text{ms}$, both $p < 0.001$). Response times were shorter for words than for nonwords for all case types (all $p < 0.001$).

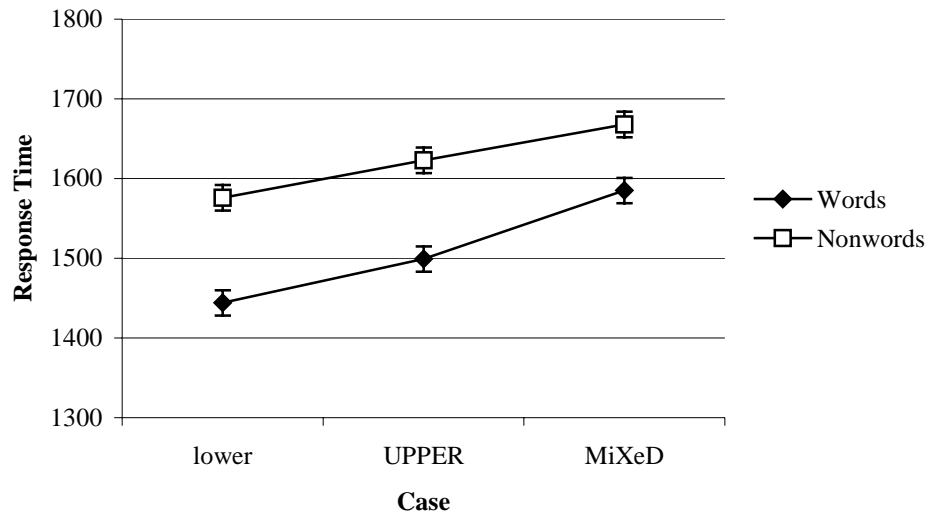


Figure 6.6. Mean response times for different Case types for words and illegal nonwords.

5. Discussion

Analysis of the luminance values obtained in the HFP task revealed that despite the small differences between the stimuli used, the isoluminance points obtained in the three different calibration sessions did not differ significantly from each other for either red on green or green on red stimuli. All of the mean standard deviations were relatively small, with no significant differences between them, indicating that participants responded relatively consistently both between and within calibration sessions. This consistency across sessions suggests that the values obtained for red on green and green on red isoluminance for individuals tend to be stable over time.

The key finding from this experiment is that performance, measured by accuracy in the Reicher-Wheeler task, was significantly lower at isoluminance than in either the Darker or Lighter conditions, and that this effect of Target Luminance

occurred for lower, upper and mixedcase stimuli. Analysis of the magnitude of the performance difference between words and nonwords produced neither a main effect of Target Luminance nor an interaction between Target Luminance and Case, confirming that the size of the isoluminance disadvantage was the same for both words and nonwords, and that this was the situation with all three case conditions. There was no evidence of any speed-accuracy trade off, with longer response times for Isoluminant words compared with those for the words presented under Darker or Lighter conditions for all three case conditions. For nonwords, there was no difference in response times for the different Target Luminance conditions and again this was the case for lower, upper and mixedcase stimuli.

The reduced performance at isoluminance for lowercase words and nonwords is consistent with the findings of Experiment 3, and provides strong support for the view that the M pathway plays a role in written word recognition. However, the absence of any interaction between Target Luminance and Case or Stimulus Type is inconsistent with the view that the isoluminance deficit occurs due to an inability to use holistic word shape information at isoluminance. If, as suggested by the Holistically Biased Hybrid model (Allen et al., 1995), the M pathway is used for processing word level information, whereas the P pathway is used for processing letter level information, it should be expected that any reduction in performance at isoluminance that occurred with mixedcase stimuli should be smaller than that obtained with stimuli presented under other case conditions. This is because the word shape information obtained with mixedcase stimuli should not be familiar enough to allow holistic processing, meaning that the recognition of both words and nonwords

should rely solely on the letter level information provided by the P pathway, regardless of luminance contrast.

As with earlier experiments, the accuracy data showed an interaction between Critical Letter Position and Stimulus Type. For both words and nonwords, accuracy in the exterior letter positions was superior to that in the interior letter positions, a finding that analysis of the response time data revealed not to be due to a speed-accuracy trade-off. As mentioned before, the fact that these typical U-shaped functions are obtained with Isoluminant stimuli as well as Darker and Lighter stimuli indicates that although isoluminance produces a general impairment in word recognition, it may not affect the way in which they are recognised, with “outside in” processing occurring even when only P pathway information is available.

As accuracy was kept the same for each of the case conditions through adjustments in exposure duration, no differences in performance were found between the conditions. However, it was clear that participants found the task harder with mixedcase stimuli than with lowercase stimuli. The mean exposure duration required to keep accuracy at 75% for mixed case stimuli was significantly longer than that for either lower or uppercase stimuli. Similarly, response times for mixedcase stimuli were significantly longer than for both lowercase and uppercase stimuli. As predicted, the times for uppercase stimuli were in between those for lowercase and mixedcase stimuli. Furthermore, the analysis of the size of the Word Superiority Effect showed that this was smaller for mixedcase stimuli than for lowercase stimuli. This is consistent with the studies discussed at the start of this chapter (Allen et al., 1995; McClelland, 1976), which found larger mixedcase disadvantages for words than for nonwords. Following on from these findings, it might therefore be expected that

in the current experiment, when stimuli were presented in mixedcase, levels of performance with words should be closer to those obtained with nonwords than in the lowercase conditions, as was indeed shown by this result.

Chapter 7

Experiments 6 and 7

1. The use of nonletter characters

Experiments 3-5 have provided strong support for the view that the M pathway is involved in written word recognition. These studies have shown that accuracy in the Reicher-Wheeler task is reduced under isoluminant conditions for both words and nonwords (pseudowords and illegal nonwords) and under all case conditions (lowercase, uppercase and mixedcase). However, it is not clear whether this performance deficit at isoluminance is exclusive to letter strings or whether it would occur with strings of other non-letter characters.

There is experimental evidence to suggest that letter strings are initially processed differently to other multi-contoured linear arrays. For example, Mason and Katz (1976) presented participants with strings of Greek symbols, from which participants were required to identify a target character. They found that participants were slower at detecting targets at the ends of the strings. This finding was repeated by Mason (1982) who showed that the curve obtained with Greek symbols differed from the M or inverted U-shaped serial position curves obtained with strings of letters or digits, a finding which provided strong evidence against the argument discussed in Chapter 3 that the typical serial position curves obtained with letter strings are a result of lateral inhibition. However, it should be noted that it is doubtful that the characters used in these studies should be thought of as true nonletters. Although the familiarity of Greek characters is reduced compared to normal letters, characters such as Ω or λ are recognisable and do have meanings associated with them for a number of readers.

Hammond and Green (1982) carried out a similar experiment in which participants were required to identify whether a target character was presented within a string of five characters. Unlike the Greek letters used in the above studies (Mason & Katz, 1976; Mason, 1982), the nonletter characters used by Hammond and Green (1982) were unrecognisable characters created by selectively intensifying a group of dots in a matrix 7 rows deep by 5 columns wide. As with the study by Mason (1982), it was found that serial position curves differed for letter and nonletter strings. For letter strings, an M-shaped curve was obtained, with reaction times for both exterior letters and the middle letter shorter than those for other positions. For nonletter strings, a U-shaped function occurred, with the longest reaction times occurring for the exterior character positions. A subsequent experiment produced a similar U-shaped functions for strings of pictures, further highlighting the differences between the initial processing of words and other non-letter character arrays.

2. The creation of nonletters

A study by Pelli, Farell and Moore (2003) found that the efficiency of letter recognition is inversely proportional to the complexity of the stimulus, where complexity is defined as perimeter squared over 'ink' area. It is therefore important that in any study using nonletter stimuli, the complexity of these characters should be comparable to the complexity of the letters used so that any comparisons are valid. It is likely that the number of features in a letter is proportional to its complexity. This represents a key limitation of all the studies described above (Hammond & Green, 1982; Mason & Katz, 1976; Mason, 1982). However, this is compatible with the approach used in a study carried out by Johnston and McClelland (1980). They used nonletter characters that were matched to the set of letters used in terms of the number

and type of letter features present, whilst at the same time minimizing the extent to which any particular nonletter character resembled any particular letter.

Figure 7.1 shows the letter and nonletter ‘alphabets’ that were designed for use in Experiments 6 and 7. Each nonletter character was created by rearranging the features of the corresponding letter, whilst attempting to minimise the visual similarity between the two characters. This process of identifying the features of the letter and rearranging them was necessarily carried out manually. Whilst this approach could be viewed as subjective, it was vital to guarantee that the characters created by rearranging the letter features did not resemble any other letter. When arranging the features, it was ensured that the nonletter characters were the same height and width as the corresponding letters and that both were made up from the same number of pixels when presented at 12 points. This guaranteed that the complexity of the nonletters, as defined by Pelli et al. (2003), was the same as that for the letters, therefore removing any potential confounds. In employing these tight controls, the stimuli used in these experiments represent a significant advance over those used by previous research that has examined the recognition of strings of nonletter characters (Hammond, 1980; Hammond & Green, 1982; Mason & Katz, 1976; Mason, 1982).

Appendix B provides an example of the creation of these nonletters, showing one of the original letters, the letter broken down into its component features and the new nonletter character created from these features.

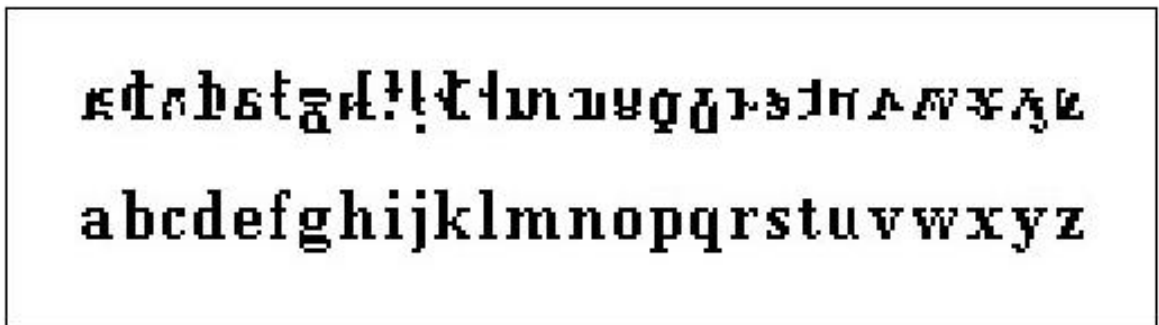


Figure 7.1. Nonletter Font and Adapted Times New Roman Bold font used in Experiments 6 and 7.

3. Experiment 6

This experiment involved the presentation of four-character strings of letters and nonletters in a Reicher-Wheeler task under isoluminant and non-isoluminant (Darker, Lighter) conditions. Participants took part in four sessions, of which two involved the presentation of letter strings (illegal nonwords) and the other two involved the presentation of nonletter strings. For each stimulus type, one session contained red character strings on a green background and the other contained green character strings on a red background. As with Experiment 5, this experiment used a blocked design, in which the different stimulus conditions were kept separate instead of intermixed, in order to keep performance at 75% for letter and nonletter strings and also ensure that the stimuli used in calibration were always appropriate to those used in the experiment proper.

If accuracy in the Reicher-Wheeler task were reduced at isoluminance for letter strings but not for nonletter strings, this would provide support for the view that letter strings are a special class of stimulus and that whilst the M pathway is involved

in the perception of briefly presented letter strings, the processing of strings of nonletter characters relies solely on information provided by the P pathway (as suggested by Livingstone & Hubel, 1987). If, however, performance were reduced at isoluminance for both letter and nonletter strings, then this would indicate that the initial visual processing of letter strings occurs in the same manner as that of other character strings. With regards to the effect of stimulus type on the serial position curve, it was predicted that typical U-shaped curves should be obtained for letter strings. However, based on the findings of previous research using nonletter strings (Hammond & Green, 1982; Mason & Katz, 1976; Mason, 1982) it was expected that the shape of the curve should be different for these stimuli, possibly with higher accuracy in the interior letter positions than in the exterior letter positions.

4. Method – Experiment 6

4.1 Participants

Sixteen participants, from the population described in the General Methods section in Chapter 3, took part in four 45-minute sessions for which they were paid.

4.2 Stimuli

The stimuli used in this experiment were the illegal nonword stimuli described in the General Methods section. These stimuli were presented under two different stimulus type conditions: in an adapted version of the Times New Roman Bold (12pt) font, and as nonletter characters. The nonletter alphabet was created by rearranging the features of the letters of the adapted Times New Roman Bold font. Each character in the nonletter font had the same dimensions and the same number of pixels as its letter equivalent. The two fonts used in this experiment are shown in Figure 7.1.

4.3 Visual conditions

The two forced-choice alternatives were presented in black on a small grey rectangular background so that the choices were equally visible for all conditions. Only the critical characters of the two alternatives were displayed, with the other letter positions being replaced by dashes. For example, the target xbqe would be followed by the two alternatives ---e and ---h. The presentation of the alternatives in the same case as the target stimulus was necessary due to the nature of this experiment, as it was not possible to alter the ‘case’ of the nonletter characters.

The luminance of the red and green used for the character strings in the Isoluminant condition was 16.5cd/m^2 and the CIE(x,y) coordinates were (0.62, 0.34) and (0.28, 0.61) respectively. The stimuli in the Lighter condition were 50% brighter (24.8cd/m^2), and the stimuli in the Darker condition were 50% darker (8.3cd/m^2). The luminance of the background was calculated for each participant at the beginning of each session using the calibration procedure detailed below. The grey rectangle that the choices were presented on was the same luminance as the coloured background.

4.4 Design

Participants were presented each character string once in each of the Target Luminance, Target Colour, and Stimulus Type conditions. Thus there were 1152 experimental trials in total. These were split across four sessions with 288 experimental trials in each one. A blocked design was used in which participants carried out the task under one of the Target Colour and Stimulus Type conditions in each session. In the first two sessions participants were shown character strings in one Colour condition (either Red on Green, or Green on Red), and in the other Colour

condition in the final two sessions. Half the participants were presented stimuli in the Red on Green condition first, and the remaining half, the Green on Red condition first. The order of the Stimulus Type condition (letter strings, nonletter strings) sessions within each Colour condition was counterbalanced across participants. Within each session, cycles of 12 stimulus items were created by randomly selecting one pair from each possible combination of Target Luminance condition and Critical Letter Position.

4.5 Calibration

10 HFP trials were carried out at the start of each session and the average luminance obtained was used for the backgrounds of the stimuli in the Reicher-Wheeler task. The stimuli used in HFP were either Red on Green or Green on Red, depending on which session it was. They consisted of a string of four x's presented against a background of the other colour. The x's were presented in the appropriate font for that session (either the adapted Times New Roman Bold font or the nonletter font). Participants were required to adjust the luminance of the background until they perceived the flicker as being minimal.

4.6 Procedure

The procedure, and all remaining aspects of this experiment are identical to those specified in the General Methods section.

5. Results – Experiment 6

Six of the initial participants were replaced because they failed to achieve 65% correct on at least one session.

The calibration data were examined using a repeated measures analysis of variance with two within-subjects variables, Stimulus Type [letters, nonletters] and

Colour Adjusted [red, green]. Neither of the main effects nor the interaction between Colour Adjusted and Stimulus Type was significant ($p_s > 0.05$). The mean background luminance required to obtain minimal flicker in green adjustment trials was 17.2cd/m^2 for letters and 16.6cd/m^2 for nonletters. For red adjustment trials, the mean luminance required for minimal flicker was 15.2cd/m^2 for letters and 16.4cd/m^2 for nonletters. A 2×2 within subjects ANOVA, featuring the same variables, was also carried out on the standard deviations of each participant's 10 responses in order to give a measure of consistency. Again, neither of the main effects nor the interaction reached significance ($p_s > 0.20$). For green adjustment trials the mean standard deviations were 2.267cd/m^2 for letters and 2.391cd/m^2 for nonletters, and for red adjustment trials, the mean standard deviations were 2.135cd/m^2 for letters and 2.406cd/m^2 for nonletters.

In the Reicher-Wheeler task, the mean percentage correct was 75.23% for letter strings and 71.86% for nonletter strings indicating that the exposure duration adjustments were reasonably effective in keeping performance in the mid range. An analysis of variance was carried out on the mean exposure duration necessary to achieve 75% performance for the different stimulus types. There was a main effect of Stimulus Type $F(1,15) = 44.643$, $\text{MSE} = 449.142$, $p < 0.001$, with the mean exposure duration required for letter strings ($\underline{M} = 13.31\text{ms}$) significantly shorter than that required for nonletter strings ($\underline{M} = 48.71\text{ms}$). Neither the main effect of Target Colour nor the interaction between Target Colour and Stimulus Type reached significance ($p > 0.20$).

The accuracy data were examined using a repeated measures analysis of variance with four within-subjects variables (Target Colour [red, green], Stimulus

Type [letter strings, nonletter strings], Critical Letter Position, and Target Luminance [Darker, Isoluminant, and Lighter]). The results of the ANOVA showed significant main effects of Stimulus Type, $F(1,15) = 22.996$, $MSE = 94.467$, $p < 0.001$, Critical Letter Position $F(3,45) = 4.134$, $MSE = 441.177$, $p < 0.05$, and Target Luminance $F(2,30) = 14.000$, $MSE = 160.862$, $p < 0.001$, and interactions between Stimulus Type and Critical Letter Position, $F(3,45) = 3.256$, $MSE = 169.462$, $p > 0.05$, and between Stimulus Type and Target Luminance $F(2,30) = 6.662$, $MSE = 133.241$, $p > 0.01$. No other main effects or interactions were significant ($p > 0.10$). Newman-Keuls tests were used to examine the interactions more closely. With regards to the interaction between Target Luminance and Stimulus Type (Figure 7.2), the only meaningful comparisons among the six conditions are the comparisons across Target Luminance, within the same stimulus type, as different exposure durations were used for the letter and nonletter strings. For letter strings, performance with Isoluminant stimuli ($M = 70.35\%$) was lower than performance with either Darker ($M = 79.95\%$, $p < 0.001$) or Lighter stimuli ($M = 75.39\%$, $p < 0.05$). Performance in the Darker condition was also higher than in the Lighter condition ($p < 0.01$). However, with nonletter strings, performance in the Isoluminant condition ($M = 71.00\%$) was not significantly different from performance in either the Darker ($M = 73.24\%$) or Lighter conditions ($M = 71.35\%$) and these did not differ from each other (all $ps > 0.20$).

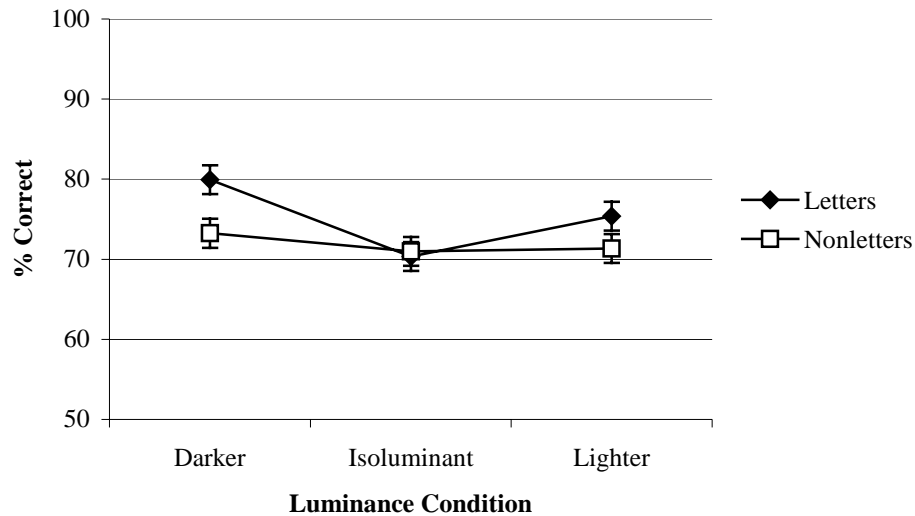


Figure 7.2. Mean percentage of correct responses for different Target Luminances for letter and nonletter strings.

Newman-Keuls tests were also used to examine the interaction between Critical Letter Position and Stimulus Type (Figure 7.3). The results of the analysis showed that for letter strings, performance in Position 1 ($\underline{M} = 77.95\%$) and Position 4 ($\underline{M} = 77.21\%$) was better than in both Position 2 ($\underline{M} = 73.22\%$) and Position 3 ($\underline{M} = 72.53\%$; $ps < 0.05$). There were no significant differences between Positions 1 and 4 or between Positions 2 and 3 ($ps < 0.50$). For nonletter strings, performance in Position 4 ($\underline{M} = 78.04\%$) was better than performance in Positions 1 ($\underline{M} = 70.49\%$), 2 ($\underline{M} = 69.57\%$) and 3 ($\underline{M} = 69.36\%$; $ps < 0.01$), none of which differed significantly from each other ($ps > 0.5$).

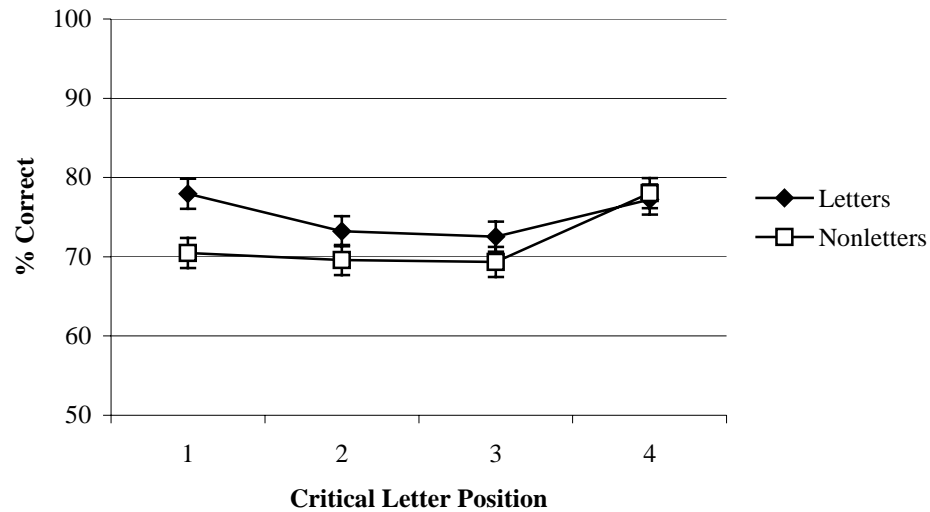


Figure 7.3. Mean percentage of correct responses for different Critical Letter Positions for letter and nonletter strings.

In order to ensure that the effects found above were not due to a speed-accuracy trade-off, an analysis of variance was also carried out on the response time data. The results of the analysis showed a main effect of Stimulus Type, $F(1,15) = 7.922$, $MSE = 242720.6$, $p < 0.05$, with response times for letter strings ($M = 1738\text{ms}$) being shorter than those for nonletter strings ($M = 1838\text{ms}$; Figure 7.4). No other main effect or interaction was significant ($ps > 0.05$).

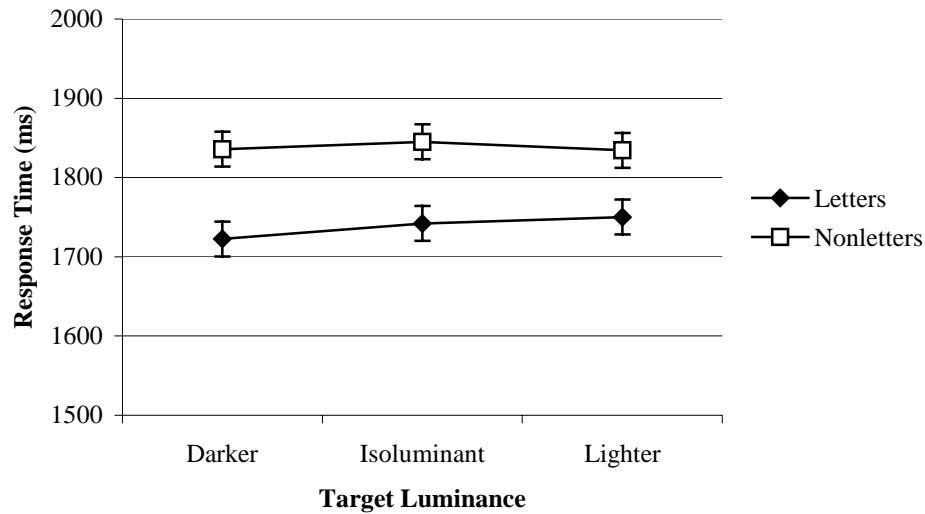


Figure 7.4. Mean Response Times for different Target Luminances for letter and nonletter strings.

6. Discussion – Experiment 6

The analysis of the calibration data indicated that the background luminance required to obtain isoluminant stimuli was not affected by whether the target was a letter string or a nonletter string. This is consistent with the results of Experiment 5, and would be expected in this instance, given that both stimulus types were of the same size. As with previous experiments, the mean standard deviations were relatively small for both stimulus types for red on green and green on red stimuli, with no significant differences, indicating that participants responded consistently in the HFP task both between and within sessions.

Unlike the analyses of the other experiments described earlier in this thesis, analysis of the data for Experiment 6 indicated that there was an interaction between Target Luminance and Stimulus Type. Whilst for letter strings, accuracy was significantly lower in the Isoluminant condition compared to the Darker and Lighter

conditions, there was no such performance deficit at isoluminance for nonletter strings with equivalent performance in all Target Luminance conditions. The absence of any effects of Target Luminance in the response time data means that a speed-accuracy trade-off can be ruled out as a potential explanation for these findings. Performance with nonletter strings was above 70% for each of the Target luminance conditions, which, along with the fact that the two curves overlap (Loftus, 1978) and the absence of any skew in the data, clearly rules out the argument that this finding occurred due to floor effects.

There are two main potential explanations for the above finding. The first of these is that the lower levels of accuracy at isoluminance for letter strings reflect the use of M pathway information in the recognition process. However, the absence of any performance reduction at isoluminance for nonletter strings reflects the fact that this M pathway involvement is specific to the processing of letter strings, and the recognition of other multi-contoured linear arrays is carried out using solely P pathway information, as with other object recognition (Livingstone & Hubel, 1987). The second explanation is that the absence of any reduction in performance for nonletter strings is due to the increased exposure duration required to keep performance for such stimuli at approximately 75%. Whilst an average exposure duration for nonletter strings of approximately 48ms still appears to be relatively brief, it was considerably longer than the average exposure for letter strings in this experiment. It could be argued that with such increased exposure to the target stimulus, participants were no longer limited by data availability, but by processing resources. Given that previous research has shown that under resource-limited rather than data-limited conditions, accuracy tasks are more sensitive to post-perceptual

factors (Santee & Egeth, 1982), it could be argued that the absence of an effect of Target luminance for nonletter strings was due to the task not being sensitive to perceptual factors. In order to rule out this possibility, Experiment 7 replicated Experiment 6 almost exactly, the only difference being that the exposure duration for nonletter strings was identical to that for letter strings and was fixed throughout the experiment.

One further finding from Experiment 6 was that the shape of the serial position curve differed for nonletter strings. With letter strings, the typical U-shaped serial position curve was obtained (e.g. Jordan & Bevan, 1996; Jordan et al., 1995; Rumelhart & McClelland, 1982). However, with nonletters, accuracy was highest in Position 1, but roughly equivalent across the other positions. Although the shape of this curve was not the same as those obtained in previous research examining the recognition of nonletter strings (Hammond & Green, 1982; Mason & Katz, 1976; Mason 1982), it is still consistent with the finding obtained in these experiments that the serial position curves obtained with non-letter stimuli are significantly different to those obtained with words and nonwords, and further supports the view that letter strings are processed differently from other character arrays.

7. Experiment 7

The aim of Experiment 7 was to rule out the possibility that the interaction between Stimulus Type and Target Luminance obtained in Experiment 6 was caused by the increased exposure duration needed for nonletter strings in order to keep performance in the midrange. In order to address this issue, Experiment 7 was a replication of Experiment 6 in which the same exposure duration was used for both letter and nonletter strings.

8. Method – Experiment 7

8.1 Participants

Sixteen participants, from the population specified in the General Methods section, took part in four 45-minute sessions for which they were paid.

8.2 Design

The design of Experiment 7 was the same as for Experiment 6 except that exposure durations were not reassessed at the end of each cycle of 12 stimuli. Instead, exposure duration was set at 31.25ms throughout the practice and experimental sections for all four sessions. All remaining aspects of this experiment were the same as in Experiment 6.

9. Results – Experiment 7

As with Experiment 6, the HFP data were examined using an analysis of variance with two within-subjects variables, Colour Adjusted [red, green] and Stimulus Type [letters, nonletters]. There was a main effect of Colour Adjusted, $F(1,15) = 20.423$, $MSE = 13.191$, $p < 0.001$, with the background luminance required for minimal flicker significantly higher for green adjustment trials ($M = 18.6 \text{ cd/m}^2$) than for red adjustment trials ($M = 14.5 \text{ cd/m}^2$). Neither the main effect of Stimulus Type nor the interaction between Colour Adjusted and Stimulus Type was significant ($ps > 0.2$). The mean background luminance required to obtain minimal flicker in green adjustment trials was 18.7 cd/m^2 for letters and 18.6 cd/m^2 for nonletters. For red adjustment trials, the mean luminance required for minimal flicker was 14.7 cd/m^2 for letters and 14.4 cd/m^2 for nonletters. A within-subjects ANOVA, featuring the same variables, was also carried out on the standard deviations of each participant's 10 responses in order to give a measure of consistency. Neither the main effects nor the

interaction between the two reached significance ($p > 0.10$). For green adjustment trials the mean standard deviations were 1.971cd/m^2 for letters and 1.859cd/m^2 for nonletters, and for red adjustment trials, the mean standard deviations were 1.460cd/m^2 for letters and 1.355cd/m^2 for nonletters.

The accuracy data were examined using a repeated measures analysis of variance with four within-subjects variables (Target Colour [red, green], Stimulus Type [letter strings, nonletter strings], Critical Letter Position, and Target Luminance [Darker, Isoluminant, and Lighter]). Examination of the data revealed that some conditions were significantly negatively skewed ($z < -1.96$), as would be expected from the varying levels of performance obtained for the different conditions as a result of using a fixed exposure duration. As a result of this, the data were transformed using a square root transformation in order to meet the assumptions of the ANOVA.

Using the transformed data, there was a significant main effect of Stimulus Type, $F(1,15) = 117.779$, $MSE = 8.974$, $p < 0.001$, and interactions between Stimulus Type and Critical Letter Position $F(3,45) = 11.929$, $MSE = 1.656$, $p < 0.001$, and between Stimulus Type and Target Luminance $F(2,30) = 12.926$, $MSE = 0.760$, $p < 0.001$. No other main effects or interactions were significant. Newman-Keuls tests carried out on the interaction between Stimulus Type and Target Luminance showed that for letter strings, performance with Isoluminant stimuli ($M = 87.73\%$) was lower than performance with either Darker ($M = 91.67\%$, $p < 0.001$) or Lighter stimuli ($M = 89.62\%$, $p < 0.05$). Performance in the Darker condition was also higher than in the Lighter condition ($p < 0.01$). However, with nonletter strings, performance in the Isoluminant condition ($M = 72.23\%$) was not significantly different from performance

in either the Darker ($\underline{M} = 70.28\%$) or Lighter conditions ($\underline{M} = 70.15\%$) and these did not differ from each other (all $ps > 0.05$). In all Target Luminance conditions, performance with letter strings was higher than with nonletter strings ($ps < 0.001$). This interaction is illustrated in Figure 7.5.

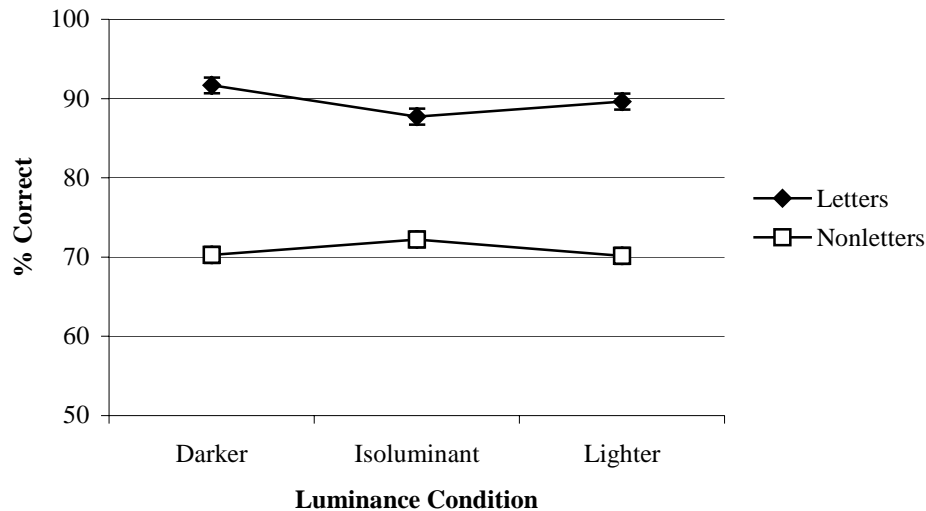


Figure 7.5. Mean percentage of correct responses for different Target Luminances for letter and nonletter strings.

Newman-Keuls tests were also used to examine the interaction between Critical Letter Position and Stimulus Type (Figure 7.6). The results showed that for letter strings, there was no significant difference in performance between Positions 1 ($\underline{M} = 90.58\%$), 2 ($\underline{M} = 89.71\%$), 3 ($\underline{M} = 90.10\%$) and 4 ($\underline{M} = 88.28\%$; all $ps > 0.05$). For nonletter strings, performance in Position 4 ($\underline{M} = 77.52\%$) was better than performance in Positions 1 ($\underline{M} = 67.19\%$), 2 ($\underline{M} = 68.79\%$) and 3 ($\underline{M} = 69.79\%$; $ps < 0.01$), which did not differ significantly from each other ($ps > 0.20$). Performance with letter strings was significantly better than performance with nonletter strings for all serial positions (all $ps < 0.001$).

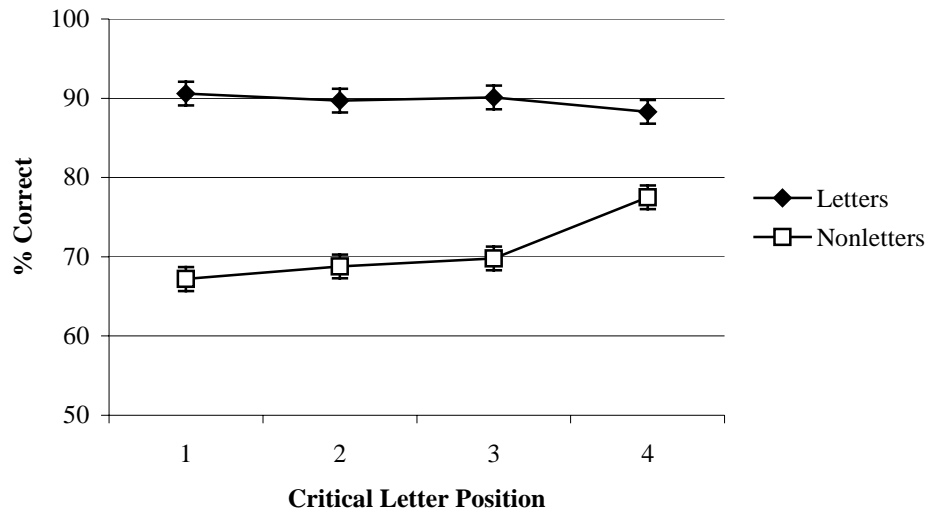


Figure 7.6. Mean percentage of correct responses for different Critical Letter Positions for letter and nonletter strings.

As with previous experiments, an analysis of variance was carried out on the response time data in order to ensure that the effects found above were not due to a speed-accuracy trade-off. The results of this analysis showed main effects for Stimulus Type $F(1,15) = 46.707$, $MSE = 130841.0$, $p < 0.001$, and an interaction between Stimulus Type and Critical Letter Position $F(3,45) = 10.730$, $MSE = 20306.0$, $p < 0.001$. No other main effects or interactions were significant ($ps > 0.10$). Figure 7.7 shows the mean response times for the different Target Luminances for letter and nonletter strings.

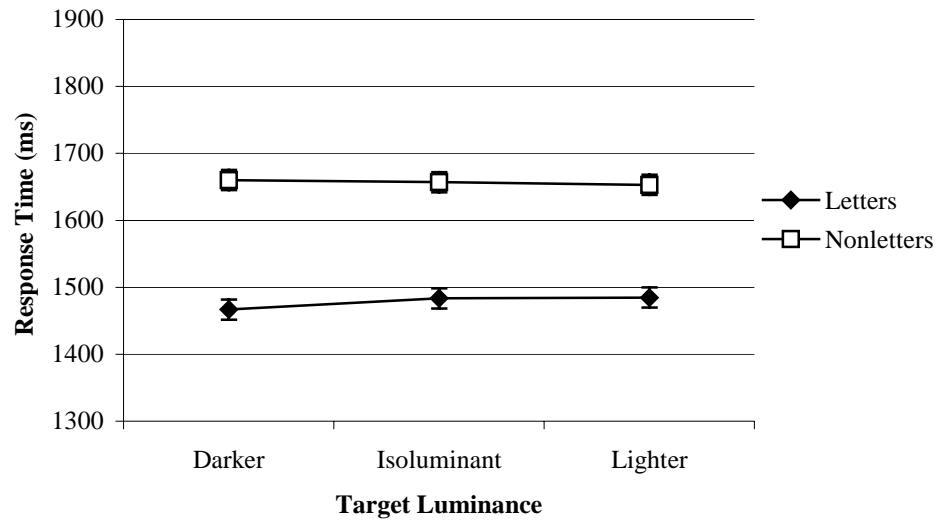


Figure 7.7. Mean response times for different Target Luminances for letter and nonletter strings.

Newman-Keuls tests were carried out on the interaction between Stimulus Type and Critical Letter Position (Figure 7.8). For letter strings, response times for characters in Position 1 ($\underline{M} = 1427\text{ms}$) were significantly shorter than those in either Position 2 ($\underline{M} = 1501\text{ms}$), Position 3 ($\underline{M} = 1477\text{ms}$) or Position 4 ($\underline{M} = 1507\text{ms}$, $p_s < 0.05$), none of which differed significantly from each other ($p_s > 0.2$). For the nonletter strings, response times in Position 1 ($\underline{M} = 1702\text{ms}$) were significantly longer than in Positions 2 ($\underline{M} = 1659\text{ms}$), 3 ($\underline{M} = 1637\text{ms}$) and 4 ($\underline{M} = 1628\text{ms}$, $p_s < 0.05$). There were no significant differences between response times for Positions 2 to 4 ($p_s > 0.20$). Response times were significantly shorter for letter strings than for nonletter strings for all Critical Letter Positions (all $p_s < 0.001$).

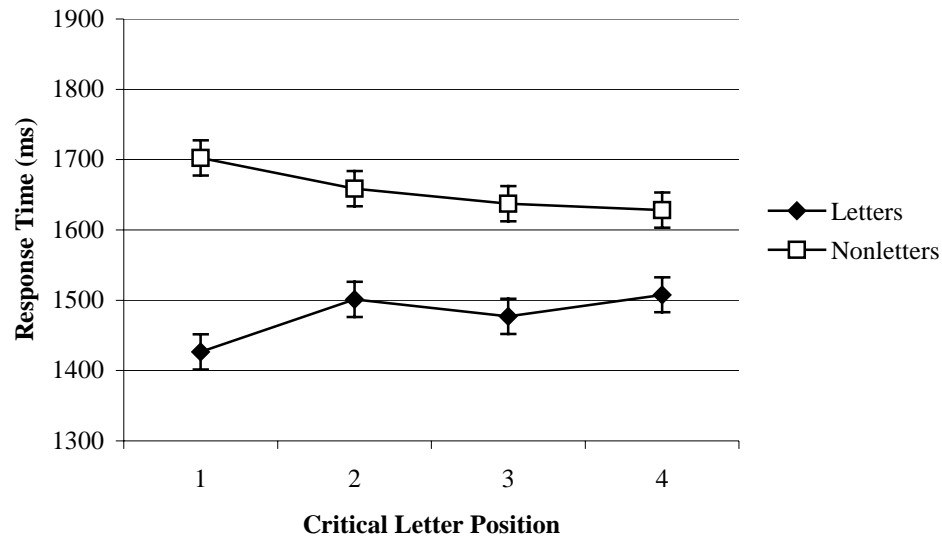


Figure 7.8. Mean response times for different Critical Letter Positions for letter and nonletter strings.

10. Discussion – Experiment 7

Analysis of the data from the HFP task revealed that the luminance of the adjusted colour required to achieve isoluminance was significantly higher for green adjustment trials than for red. This is consistent with the findings of Experiment 1, as well as the findings of previous research (Bilodeau & Faubert, 1997; Dobkins et al., 2000). The fact that such an effect was found in this experiment, but not Experiments 5 or 6 presumably reflects the fact that isoluminance points vary across individuals (Experiment 1; Metha & Mullen, 1996). Examination of the calibration data from these experiments reveals that the size of the difference in mean luminance values obtained for red and green adjustment trials varies considerably across participants. As with previous experiments, the mean standard deviations of participants responses were relatively small for both stimulus types for both red and green adjustment trials,

with no significant differences between them, indicating that participants responded consistently in the calibration task both between and within sessions.

The main finding from this study is that the results of the Reicher-Wheeler task were extremely similar to those obtained in Experiment 6. Once the data had been transformed to deal with the skew caused by the ceiling effect found with letter strings, analysis of the accuracy data revealed a reduction in performance at isoluminance for letter strings (as found in Experiments 3-6), but no such impairment for nonletter strings. This is consistent with the findings of Experiment 6 and rules out the possibility that the absence of any isoluminance deficit for nonletter strings resulted from the differences in exposure duration required to keep accuracy with these stimuli at approximately 75%. As a result, it is possible to conclude with confidence that whilst the processes involved in letter string recognition can exploit information carried by the M pathway, there is no evidence to suggest that the recognition of strings of non-letter characters involves information carried by the M pathway and would appear to rely solely on P pathway information, reinforcing the view that letter strings are a special class of stimuli, that are initially processed quite differently to non-letter character arrays.

The unique nature of letter strings is also reinforced by the finding from both Experiments 6 and 7 that the serial position curves produced in the Reicher-Wheeler task with nonletter strings are quite distinct from those obtained with letter strings, a finding which is consistent with previous research using strings of non-letter characters (Hammond & Green, 1982; Mason & Katz, 1976; Mason 1982). However, Experiments 6 and 7 represent an important step forward from these studies, by using more precisely controlled conditions in which the nonletter stimuli were matched to

the letters in terms of height, width and the number of pixels, the key aspects complexity (Pelli et al., 2003), an significant influence on the efficiency of recognition. This tighter control over therefore means that greater confidence can be placed in the conclusions drawn from these experiments.

Chapter 8

Experiment 8

1. The recognition of isolated letters

The experiments described in the previous chapters have given a clear indication that information carried by the M pathway is used in the recognition of written words. However, despite some previous research in this area (Omtzigt et al., 2002), it is still not clear whether the M pathway is involved in the recognition of isolated letters. Research comparing the recognition of words and isolated letters under data-limited conditions has provided a number of interesting and influential findings for word recognition research. The Word-Letter Effect (Johnston & McClelland, 1973) in particular, has had a considerable impact on theories of word recognition over the past 30 years. The aim of Experiment 8 was to extend investigation in this area to cover presentation under isoluminant conditions, with the objective of furthering our understanding of written word recognition, and the role of the M pathway in particular.

1.1 The Word-Letter Effect

The Word-Letter Effect is the finding that in the Reicher-Wheeler task, letters in words are reported more accurately than individual letters when followed by a pattern mask. As mentioned above, this is a key finding in word recognition research, and one that has been explained in a number of different ways. The Interactive-Activation Model of word recognition (McClelland & Rumelhart, 1981) accounts for this phenomenon in terms of the pattern mask adding noise to the network, replacing activation at the letter level. As activation at the word level is far less susceptible to replacement by this noise, accuracy in the Reicher-Wheeler task is greater for words

than for isolated letters, when stimuli are followed by a mask. However, a model such as the Holistically Biased Hybrid Model (Allen et al., 1995) might account for such a finding in terms of the different channels, with words being processed by the faster word-level channel. A further layer of complexity in explaining this phenomenon has been added by findings by Jordan and Bevan (1994, 1996), which showed that the Word-Letter Effect occurs with forward as well as backward masking, and that the size of the mask is critical in determining whether effects are obtained. Jordan and de Bruijn (1993) advocate the Integration Discrimination Hypothesis as an alternative explanation of the effect. According to this theory, when words and letters are presented under backward (or forward) masked conditions, composite percepts of the target and mask are formed. As isolated letters are smaller, they are less easily discriminated from the pattern mask, hence causing the performance advantage for words.

1.2 The recognition of isolated letters under isoluminant conditions

A recent study by Omtzigt et al. (2002) has compared the identification of isolated letters at isoluminance with letters flanked by a pair of distractors. In this study, participants were required to name briefly presented stimuli which were either isoluminant or isochromatic (i.e. the target and background differed only with respect to their luminance values). It was found that whilst performance with isoluminant stimuli was equivalent to that with isochromatic stimuli for isolated letters, with flanked letters both accuracy and response times were significantly poorer for isoluminant stimuli than for isochromatic stimuli. This would indicate that M pathway information is not used in the identification of isolated letters, but is used in the identification of flanked letters, as might be expected from the findings with

illegal nonwords from Experiments 3-7 in this thesis. This conclusion is further backed up by the findings of Lehky (2000). However, the findings of Omtzigt et al. (2002) also suggest that only the Parvocellular system is involved in the identification of isolated letters.

Unfortunately, there are a couple of methodological issues with this study that make it impossible to draw strong conclusions about the findings. The first of these is the nature of the HFP task used to achieve isoluminance. The stimulus used for the HFP task was a disc occupying approximately 2.5 deg of visual angle. Given that each letter in the identification task subtended approximately 0.4 deg of visual angle, it is not clear that the stimulus used in the HFP task was appropriate. The second issue relates to the experimental task itself. Target stimuli were presented for 105ms, over 8 times the typical exposure duration used for words and nonwords for the experiments described in this thesis. It is therefore doubtful that the recognition conditions in that study could be described as data-limited. Given that the principal dependent variable in the task was participants' reaction time, it is possible that the task was not sufficiently sensitive to perceptual factors to identify any effect of isoluminance on isolated letters (see Santee & Egeth, 1982).

2. The present study

In order to examine the effect of isoluminance on the recognition of isolated letters, Experiment 8 involved the presentation of words and isolated letters in the Reicher-Wheeler task under the same three Target Luminance conditions used in Experiments 2-7 (Isoluminant, Darker, Lighter). Participants took part in four sessions, of which two involved the presentation of four letter words and the other two involved the presentation of isolated letters. For each stimulus type, one session

contained red target stimuli presented on a green background and the other contained green stimuli on a red background. As with Experiments 5-7, a blocked design, in which the different stimulus types were presented in different sessions, was used in order to both allow the independent adjustment of exposure duration and to allow the use of appropriate stimuli in the HFP task.

Based on the findings of Omtzigt et al. (2000) and the findings of earlier experiments in this thesis, it was expected that whilst participants would respond less accurately at isoluminance when compared to performance in the Darker or Lighter conditions with words, no such performance deficit should occur with isolated letters at isoluminance. This finding would provide strong evidence to support the hypothesis that whilst the Magnocellular system plays an important role in the identification of written words and nonwords, it is not involved in the identification of isolated letters. As the design of this experiment meant that performance would be equivalent for both words and isolated letters, it was not possible to directly examine the impact of isoluminance on any Word-Letter Effect. However, the length of the exposure durations required to keep performance at approximately 75% should give an indication of the relative perceptability of the different stimulus types. As there was no pattern mask used in this experiment, it was predicted on the basis of previous research (e.g. Johnston & McClelland, 1973; Juola, Leavitt & Choe, 1974; Marchetti & Mewhort, 1986; Massaro & Klitzke, 1979) that the exposure durations for words and isolated letters should be roughly equivalent. However, it was unclear whether presenting stimuli at isoluminance would have any effect on the magnitude of a potential Word-Letter Effect.

3. Method

3.1 Participants

Sixteen participants, from the population specified in the General Methods section in Chapter 3, took part in four 45-minute sessions for which they were paid.

3.2 Stimuli

This experiment used four-letter words and isolated letters as stimuli. The word stimuli used were those described in the General Methods section. Forty-eight pairs of isolated letter stimuli were formed by deleting the three noncritical letters from each word pair, leaving each isolated letter in exactly the same screen position as it appeared within the word. A further 24 additional pairs of isolated letters stimuli were used as practice stimuli at the beginning of each session, and these were created in the same manner (using the practice word pairs). The stimuli were either red on a green background or green on a red background, and were either isoluminant with the background, lighter, or darker than the background.

3.3 Visual conditions

Target words and isolated letters were presented on the computer screen in a proportionally spaced, lowercase font (12pt Times New Roman Bold). The two forced-choice alternatives were presented in uppercase Arial, and in black, within a small grey rectangle. In the word condition only the critical letters of the two alternatives were displayed with the other letter positions being replaced by dashes. These dashes were also used for isolated letters so that the same testing procedure was used for both types of target stimulus. For example, the target aces (or the target c) would be followed by the two alternatives -C-- and -X--.

The luminance of the red and green used for the character strings in the Isoluminant condition was 16.5cd/m^2 and the CIE(x,y) coordinates were (0.62, 0.34) and (0.28, 0.61) respectively. The stimuli in the Lighter condition were 50% brighter (24.8cd/m^2), and the stimuli in the Darker condition were 50% darker (8.3cd/m^2). The luminance of the backgrounds was calculated for each participant at the beginning of each session using the calibration procedure detailed below. The grey rectangle that the choices were presented on was the same luminance as the coloured background.

3.4 Design

Participants were presented each character string once in each of the Target Luminance, Target Colour, and Stimulus Type conditions. Thus there were 1152 experimental trials in total. These were split across four sessions with 288 experimental trials in each one. A blocked design was used in which participants carried out the task under one of the Target Colour and Stimulus Type conditions in each session. In the first two sessions participants were shown character strings in one Colour condition (either Red on Green, or Green on Red), and in the other Colour condition in the final two sessions. Half the participants were presented stimuli in the Red on Green condition first, and the remaining half, the Green on Red condition first. The order of the Stimulus Type condition (words, isolated letters) sessions within each colour condition was counterbalanced across participants. Within each session, cycles of 12 stimulus items were created by randomly selecting one pair from each possible combination of Target Luminance condition and Critical Letter Position.

3.5 Calibration

10 HFP trials were carried out in each session, and the average luminance obtained was used for the backgrounds of the stimuli in the Reicher-Wheeler task. The stimuli used in HFP were either Red on Green, or Green on Red depending on which session it was. For the word condition they consisted of a letter string, 'xxxx', presented against a background of the other colour, whilst for the isolated letters condition, the string of x's was replaced by a single 'x'. Participants were required to adjust the luminance of the background until they perceived the flicker as being minimal.

3.6 Procedure

The procedure, and all remaining aspects of this experiment are identical to those specified in the General Methods section.

4. Results

The HFP data were examined using a repeated-measures analysis of variance with two within-subjects variables, Colour Adjusted [red, green] and Stimulus Type [words, isolated letters]. Neither of the main effects nor the interaction between Colour Adjusted and Stimulus Type was significant ($p_s > 0.05$). The mean background luminance required to obtain minimal flicker in green adjustment trials was 17.1cd/m^2 for words and 17.0cd/m^2 for isolated letters. For red adjustment trials, the mean luminance required for minimal flicker was 15.6cd/m^2 for words and 15.5cd/m^2 for isolated letters. As with previous experiments, a second ANOVA including the same variables was carried out on the standard deviations of each participant's 10 responses in order to give a measure of consistency. Again, neither of the main effects nor the interaction reached significance ($p_s > 0.10$). For green

adjustment trials the mean standard deviations were 2.783cd/m^2 for words and 1.923cd/m^2 for isolated letters and for red adjustment trials, the mean standard deviations were 2.374cd/m^2 for words and 1.963cd/m^2 for isolated letters.

In the Reicher-Wheeler task, the mean percentage correct was 74.58% for words and 76.03% for isolated letters, indicating that the exposure duration adjustments were effective in keeping performance in the mid range. An analysis of variance was carried out on the exposure duration necessary to achieve these levels of performance for words and isolated letters in both the Red on Green and Green on Red colour conditions. There was a main effect of Target Colour, $F(1,15) = 5.711$, $MSE = 28.948$, $p < 0.05$, with exposure durations needed for 75% performance being longer for Green on Red stimuli ($M = 13.40\text{ms}$) than for Red on Green stimuli ($M = 10.19\text{ms}$). However, there was no evidence of a difference between the exposure durations needed for words ($M = 11.52\text{ms}$) and isolated letters ($M = 12.07\text{ms}$, $F(1,15) = 0.520$, $p > 0.20$), or an interaction between Stimulus Type and Colour condition (Figure 8.1).

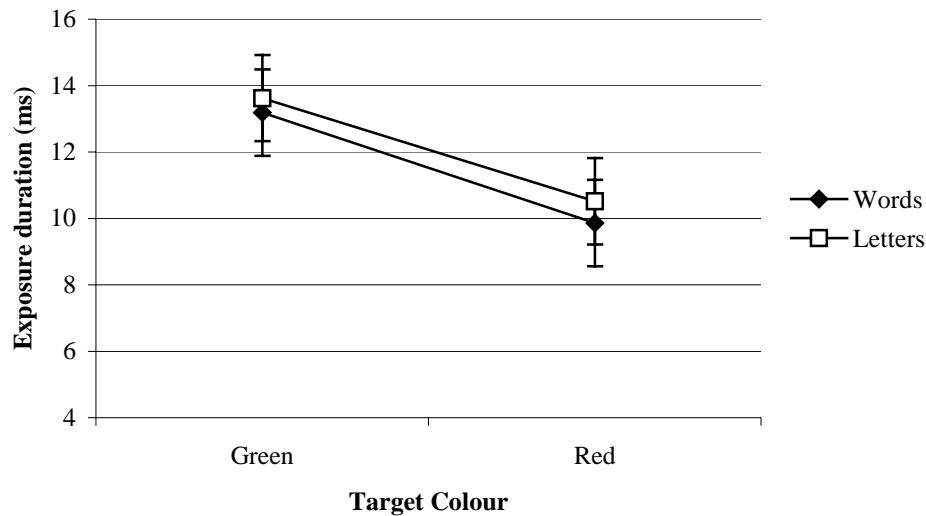


Figure 8.1. Mean exposure duration required 75% overall performance for words and isolated letters under Green on Red and Red on Green colour conditions.

The accuracy data were examined using a repeated measures ANOVA with four within-subjects variables (Target Colour [red, green], Stimulus Type [words, isolated letters], Critical Letter Position and Target Luminance [Darker, Isoluminant, and Lighter]). There were significant main effects of Stimulus Type, $F(1,15) = 9.200$, $MSE = 44.120$, $p < 0.01$, Critical Letter Position, $F(3,45) = 21.517$, $MSE = 156.576$, $p < 0.001$, and Target Luminance, $F(2,30) = 7.918$, $MSE = 348.429$, $p < 0.01$, and an interaction between Stimulus Type and Critical Letter Position, $F(3, 45) = 3.838$, $MSE = 97.333$, $p < 0.05$. Neither the main effect of Target Colour nor any other interaction was significant. To examine the main effect of Target Luminance, Newman-Keuls tests were used (Figure 8.2). These showed that performance was significantly lower in the Isoluminant condition ($M = 71.94\%$) than in either the Darker ($M = 78.50\%$, $p < 0.01$) or Lighter ($M = 75.47\%$, $p < 0.05$) conditions, which did not differ significantly from each other ($p > 0.05$).

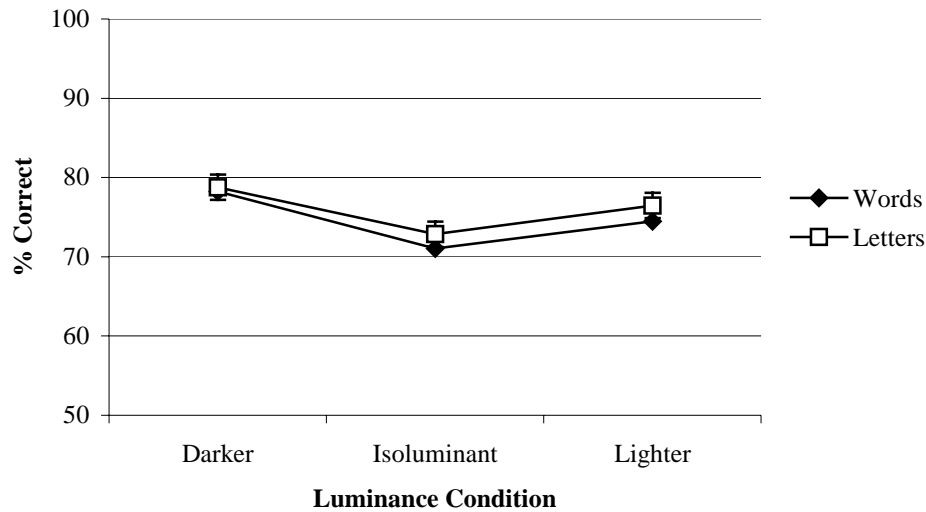


Figure 8.2. Mean percentage of correct responses for different Target Luminances for words and isolated letters.

Newman-Keuls tests were also used to examine the interaction between Critical Letter Position and Stimulus Type (Figure 8.3). The results of the analysis showed that for words, performance was significantly higher in both Positions 1 ($\underline{M} = 78.99\%$) and 4 ($\underline{M} = 79.51\%$) than in Positions 2 ($\underline{M} = 70.49\%$) and 3 ($\underline{M} = 69.31\%$; all p s > 0.001). Neither the difference in performance between Positions 1 and 4 or between Positions 2 and 3 was significant (p s < 0.20). For isolated letters, performance in Position 1 ($\underline{M} = 79.77\%$) and Position 4 ($\underline{M} = 77.30\%$) was better than in both Position 2 ($\underline{M} = 74.00\%$) and Position 3 ($\underline{M} = 73.05\%$; p s < 0.05). There were no significant differences between Positions 1 and 4 or between Positions 2 and 3 (p s < 0.20). There was no difference in performance between words and isolated letters for Positions 1 and 4 (p s > 0.20), although performance was higher in Positions 2 and 3 for isolated letters than for words (p s < 0.05).

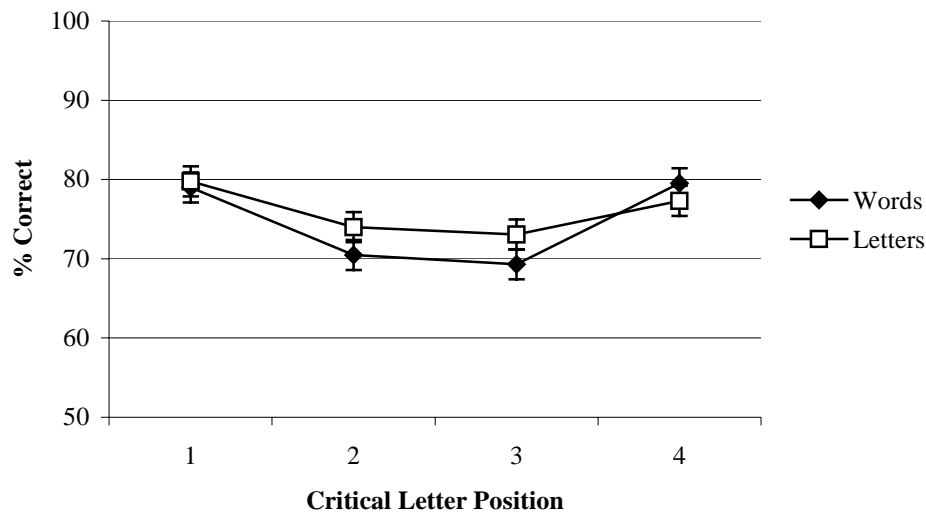


Figure 8.3. Mean percentage of correct responses for different Critical Letter Positions for words and isolated letters.

In order to ensure that the effects found above were not due to a speed-accuracy trade-off, an analysis of variance was also carried out on the response time data. The results of the analysis showed main effects of Stimulus Type, $F(1,15) = 38.899$, $MSE = 198537.4$, $p < 0.001$, Critical Letter Position, $F(3,45) = 4.966$, $MSE = 27527.4$, $p < 0.005$, and Target Luminance, $F(2,30) = 4.361$, $MSE = 46979.0$, $p < 0.05$, and interactions between Stimulus Type and Critical Letter Position, $F(3,45) = 3.818$, $MSE = 18865.4$, $p < 0.05$, and Stimulus Type and Target Luminance, $F(2,30) = 4.261$, $MSE = 13373.2$, $p < 0.05$. Neither the main effect of Target Colour nor any of the other interactions were significant ($ps > 0.05$).

The interaction between Stimulus Type and Target Luminance was examined using Newman-Keuls tests (Figure 8.4). For words, response times for Isoluminant stimuli ($M = 1599ms$) were longer than those for both Darker ($M = 1556ms$) and Lighter stimuli ($M = 1551ms$, $ps < 0.01$), which did not differ significantly from each

other ($p > 0.20$). For isolated letters, response times for Isoluminant stimuli ($M = 1397\text{ms}$) were longer than for Darker stimuli ($M = 1327\text{ms}$, $p < 0.001$), although they were not significantly different from response times for Lighter stimuli ($M = 1381\text{ms}$, $p > 0.20$). Response times for Darker stimuli were longer than for Lighter stimuli ($p < 0.001$). For all target luminances, response times were longer for words than for isolated letters ($p < 0.001$).

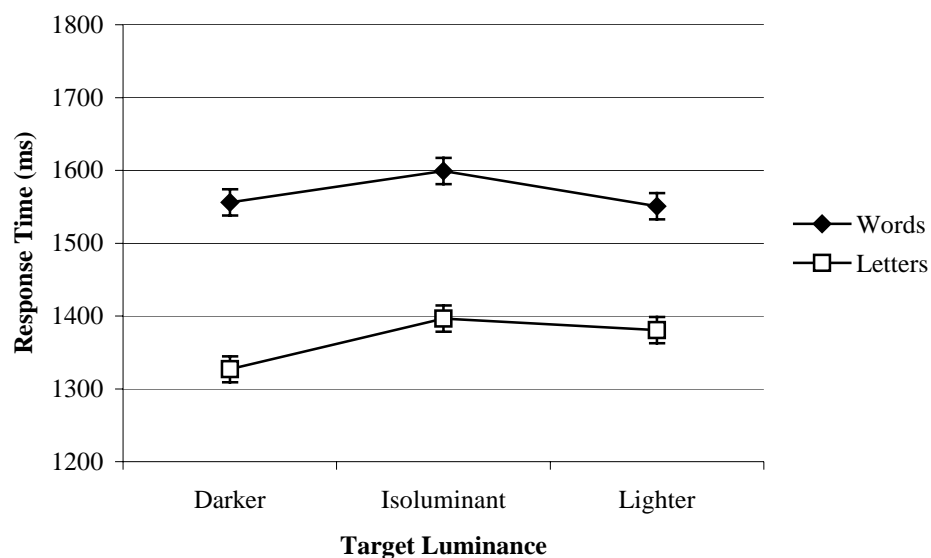


Figure 8.4. Mean response times for different Target Luminances for words and isolated letters.

Newman-Keuls tests were also carried out on the interaction between Stimulus Type and Critical Letter Position (Figure 8.5). For words, mean response times for Position 1 ($M = 1523\text{ms}$) were significantly shorter than those for either Position 2 ($M = 1573\text{ms}$) or Position 3 ($M = 1623\text{ms}$, $ps < 0.05$), but did not differ significantly from Position 4 ($M = 1556\text{ms}$, $p > 0.05$). Mean response times for both Positions 2 and 4 were shorter than for Position 3 ($ps < 0.05$) and did not differ significantly from each other ($ps > 0.2$). There were no significant differences in response times for any

Critical Letter Position for isolated letters (all p s > 0.05). Response times were longer for words than for isolated letters for all Critical Letter Positions ($p < 0.001$)

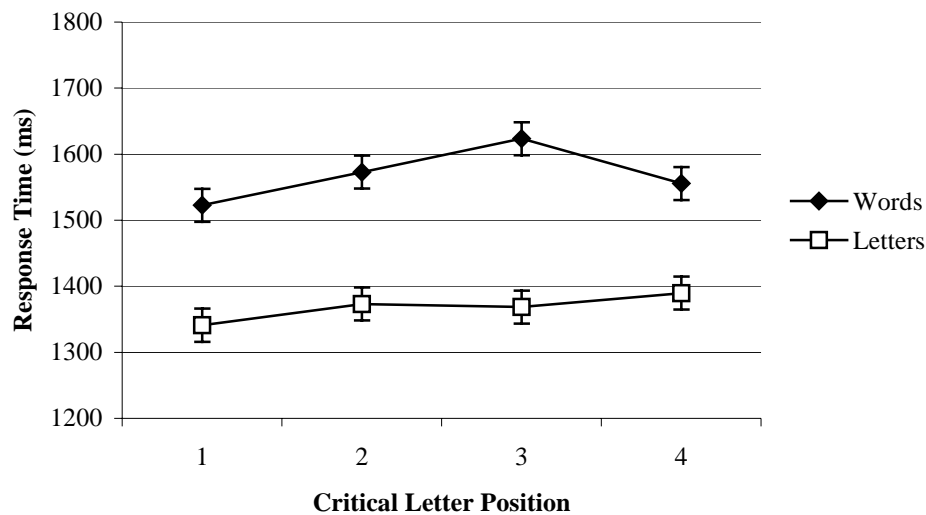


Figure 8.5. Mean response times for different Critical Letter Positions for words and isolated letters.

5. Discussion

Analysis of the data from the calibration section revealed that the background luminance required to obtain isoluminant stimuli was not affected by whether the target was a word or an isolated letter. Similarly, there were no differences between the mean standard deviations of participants responses for words and for isolated letters, for both red on green and green on red stimuli, confirming that participants were responding consistently in this task.

Analysis of the exposure duration data showed that there was no difference between the exposure durations required to achieve approximately 75% performance for words and isolated letters. This fits neatly with previous research, which has shown that when words and isolated letters are presented in the Reicher-Wheeler task,

the Word Letter Effect is observed when targets are followed by pattern masks, but disappears when pattern masks are replaced by blank post-target fields (e.g. Johnson & McClelland, 1973; Juola et al., 1974; Marchetti & Mewhort, 1986; Massaro & Klitzke, 1979). As there was no post-target mask present in the current experiment, it is consistent with this research to expect that the exposure durations required to keep performance in the midrange would not be longer for isolated letters than for words.

The finding that the exposure duration required to achieve performance levels of 75% correct was longer for Green on Red stimuli than Red on Green stimuli fits in with research showing that the presentation of green stimuli on an diffuse red background reduces Magnocellular functioning more than presenting red stimuli on a green background (e.g. Breitmeyer May & Williams, 1989). As mentioned in Chapter 1, this is because the inhibitory surrounds of many M cells are in fact red dominant rather than purely broadband (e.g. De Monasterio, 1978; Livingstone & Hubel, 1984), thus the presentation of a red background should inhibit the responding of these cells. The absence of any interaction between Stimulus Type and Colour Condition suggests that any reduction in Magnocellular functioning caused by the presentation of stimuli on a red background affects the perception of both words and isolated letters equally. It is of interest that despite using both red on green and green on red stimuli in all of the previous experiments, this is the only experiment in which such an effect has been produced, although the (non-significant) differences in exposure duration found in earlier experiments have generally been in the same direction. It is likely that this has happened because exposure duration is not a sensitive enough measure to consistently identify a perceptual factor such as the reduction of M pathway activity with diffuse red backgrounds. A further possibility is that not all individuals are affected by the

presence of red backgrounds, meaning that the differences in exposure duration will only reach significance in a limited number of cases.

The accuracy data show that performance in the Reicher-Wheeler task is reduced when target stimuli are presented at isoluminance, compared to both Darker and Lighter stimuli. Furthermore, this performance deficit occurs for both words and isolated letters. The response time data showed no evidence of any speed-accuracy trade-off, with the longest response times occurring in the Isoluminant condition. These findings are not consistent with those of Omtzigt et al. (2002), who found that whilst performance in a letter naming task was reduced at isoluminance for flanked letters, there was no such performance deficit for isolated letters. The reason for the differences between the findings of these two experiments could be due to the technique used by Omtzigt et al. to assess isoluminance. As mentioned above, whilst HFP was employed, instead of using a stimulus appropriate to the experimental task, a disk, subtending a visual angle of approximately 2.5 deg was flickered against a dark background in order to find participants' isoluminance points. The use of such a stimulus could have led to the use of a luminance contrast which did not accurately reflect the correct contrast needed for isoluminance in the isolated letter condition, although it should be noted that the HFP data from Experiment 8 did not show any difference in the luminance values required for isoluminance for isolated letters and those required for words. Alternatively, Omtzigt et al. (2002) may have failed to find reduced performance for isoluminant isolated letters, relative to that with isochromatic letters due to the exposure durations employed. In Experiment 8, the mean exposure duration for isolated letters was approximately 12ms, compared with 105ms used by Omtzigt et al. As argued in the introduction to this chapter, it is

unlikely that such a long exposure duration would lead to data-limited conditions, especially for isolated letters.

The findings of this experiment have considerable implications for at least two explanations of the role of the M pathway in written word recognition: The view that the M pathway provides word-level information in the recognition process (Allen et al., 1995; Chase, 1996), and the view that the role of the M pathway relates to attentional selection (Omtzigt et al., 2002; Steinman et al., 1997; Vidyasagar, 1999; Vidyasagar & Pammer, 1999). The implications for these theories from this and earlier experiments are discussed in depth in Chapter 9.

Chapter 9

General Discussion

1. Aims of thesis

The principal aim of the experiments reported in this thesis was to ascertain whether information carried by the Magnocellular (M) pathway plays any role in the recognition of written words. Despite claims that the M pathway does play a role of some kind in word recognition and reading by a number of authors (e.g. Allen et al., 1995, 2002; Breitmeyer, 1980, 1993; Chase, 1996; Chase et al. 2003; Cornelissen et al., 1998a, 1998b; Hendricks & Putts, 2000; Omtzigt et al. 2002; Lovegrove & Williams, 1993; Steinman et al., 1997; Vidyasagar, 1999; Vidyasagar & Pammer, 1999), the evidence to support these claims is relatively limited. Out of the different approaches that have been used to investigate this area to date, the use of isoluminance was identified as one of the most promising, despite some debate about the technique (e.g. Breitmeyer, 1992; Logothetis et al., 1990; Schiller, Logothetis & Charles, 1991). This research project was therefore conducted with the objectives of establishing the suitability of presenting stimuli at isoluminance to reduce Magnocellular functioning; of assessing the impact of presenting words and other stimuli at isoluminance in the Reicher-Wheeler task; and of identifying the implications of these findings for the various theoretical explanations of the role of the M pathway in word recognition and reading.

2. The use of isoluminance to identify whether the M pathway is used in written word recognition

Isoluminance has been used to identify whether abilities rely on the M or P pathways across a wide range of areas including depth perception and perspective

(Livingstone & Hubel, 1987), motion perception (Cavanagh & Anstis, 1991), object localisation, (Anderson & Yamagishi, 2000), scene segmentation (Leonards & Singer, 1997) and feature binding (Lehky, 2000). However, the use of isoluminance in this way has not been without criticism, so care was taken in this project to make sure firstly that the isoluminant stimuli were produced in a way that was both effective and appropriate, and secondly, that it could be concluded with confidence that any reduction in accuracy in the Reicher-Wheeler task at isoluminance did reflect reduced functioning of the M pathway.

2.1 The creation of effective and appropriate isoluminant stimuli

The decision was taken to use Heterochromatic Flicker Photometry (HFP) to create isoluminant stimuli, rather than simply rely upon onscreen luminance matching. This decision was taken in the light of previous research which had shown that isoluminance points can vary with spatial frequency (Cavanagh et al., 1987; Dobkins et al., 2000), with spatial location (Bilodeau & Faubert, 1997) and across participants (Metha & Mullen, 1996). HFP was able to deal with these factors and had been shown to be accurate at determining participants' isoluminance points by a number of researchers (e.g. Di Russo et al., 2001; Regan & Lee, 1993).

As previous research into HFP had focussed on gratings rather than “real world” stimuli, Experiment 1 aimed to examine what effect, if any, stimulus type would have on the luminance values obtained from the HFP task, and as a result, what the most appropriate stimulus would be to obtain accurate isoluminance points for use in the subsequent word recognition experiments. Experiment 1 therefore compared the luminance ratios obtained for minimal flicker in HFP for a number of different stimulus types. Examination of the results provided evidence to show that these

values are stimulus dependent, and in particular revealed that the luminance values obtained when the stimulus being flickered is a string of letters presented on a large square background are different to those obtained with other stimuli, such as a large square flickered against another large square of the other colour. Two potential interpretations of this finding were proposed: The first was that the different luminance ratios required for minimal flicker for different stimulus types represented a straightforward relationship between isoluminance points and stimulus type. The second was that the variation in the luminance ratios obtained was influenced by differences in participants' sensitivity to flicker for the different stimulus types. Regardless of which of these interpretations is correct, this finding highlights the importance of both using HFP to create isoluminant stimuli and of selecting stimuli for HFP that are appropriate to those used in the experiment proper. Furthermore, the second interpretation also stresses the need to choose calibration stimuli that are large enough to allow participants to perceive small differences in the amount of flicker and thus respond consistently and accurately in the HFP task.

Analysis of the results of Experiments 2 and 3 confirmed that the second of these interpretations was the correct one. Both of these experiments compared the recognition of words and illegal nonwords under isoluminant and non-isoluminant conditions, and differed only with respect to the stimuli employed in the HFP calibration task. In Experiment 2, which used a letter string flickered on a large square background as the stimulus in HFP, the data from the Reicher-Wheeler task did not indicate that isoluminance had been successfully achieved. With green stimuli presented on a red background, accuracy was lower when targets were darker than the background (Darker condition) than when they were supposedly at isoluminance,

despite the former differing from the background in terms both of luminance and colour. It could be argued that such an effect could occur due to the overall stimulus luminance being lower in the Darker condition than at isoluminance (Berman et al., 1996), but this is extremely unlikely given the very small differences in overall luminance found in this experiment. A much more plausible argument is that as the luminance of green required to obtain minimal flicker in the HFP task in Experiment 2 was over twice the luminance of the red (as with this stimulus type in Experiment 1), and far in excess of the values obtained with other stimuli in Experiment 1, it could be that biases occurring due to participants' poor flicker sensitivity with this stimulus type increased the luminance values reported for minimal flicker, and that the luminance values used in the Darker condition of the Reicher-Wheeler task actually represented a better approximation of isoluminance. This argument was supported by the Reicher-Wheeler data from Experiment 3 in which the same basic stimuli were used in HFP, but it was the large square background, rather than the foreground that was flickered. Analysis of the Reicher-Wheeler data revealed a significant reduction in accuracy at isoluminance for both red on green and green on red stimuli, providing clear evidence that the stimuli used in the calibration section of this experiment were appropriate for the creation of isoluminant stimuli.

As a result, care was taken to ensure that the stimuli used for HFP in the following experiments were both directly appropriate to the stimuli used in the Reicher-Wheeler task and that the area flickered was large enough to allow participants to perceive small differences in the amount of flicker, and thus obtain consistent and accurate luminance values in the HFP task. In order to achieve this objective, Experiments 5-8, which used stimuli other than lowercase letter strings,

employed blocked designs, in which participants carried out the Reicher-Wheeler task under one stimulus condition in each session. This allowed the stimuli used in the HFP calibration task at the start of each session to be directly applicable to those used in the experiment proper. Furthermore, the spread of participants' responses in the 10 calibration trials were analysed to ensure that they were able to respond consistently both within and across sessions.

2.2 The reduction of Magnocellular functioning at isoluminance

The validity of using isoluminance to distinguish between processes reliant on the M and P pathways has been questioned previously within the literature for two main reasons. The first of these relies on research calling into question the view that the responses of M cells are nulled at isoluminance (Logothetis et al. 1990; Schiller & Colby, 1983; Schiller et al, 1991). As discussed in Chapter 1, Logothetis et al. (1990) demonstrated that abilities assumed to be carried by the M pathway, whilst impaired, are not completely wiped out at isoluminance. It was also determined through single cell recording that no single luminance ratio can be expected to silence all cells, and thus all activity in the M pathway. However, this might be expected, as Logothetis et al. used a variety of spatiotemporal stimuli to evaluate responses, and as noted in this research (Experiment 1; see also Cavanagh et al., 1987; Dobkins et al., 2000), the spatial pattern of the stimulus can have a significant effect on isoluminance. Even if it is the case that M pathway functioning is not wiped out (other research has shown that M cells do not respond at isoluminance (e.g. Hicks et al., 1983; Lee et al., 1988), there is a strong argument that this does not represent a serious problem for the experiments described in this thesis or any like them as long as there is still a significant reduction in Magnocellular activity.

The second reason for questioning the usefulness of isoluminance as a means of distinguishing between the pathways is evidence suggesting that P cells can also be silenced at isoluminance (Gouras & Kruger, 1979; Logothetis et al., 1990; Schiller & Colby, 1983). Furthermore, Schiller et al. (1991) have shown that following Magnocellular lesions, stereopsis, which is thought to rely upon the P pathway has been reduced at isoluminance. Out of the two issues, this is potentially the most serious concern. If both Magnocellular and Parvocellular functioning can be reduced at isoluminance, it should be expected that performance with all tasks should be impaired at isoluminance, regardless of whether they rely predominantly upon the M or P pathway. However, the finding that P cells are silenced at isoluminance is far from universal, and there is strong empirical support for the view that isoluminance is a suitable technique for specifically impairing M pathway functioning. A number of researchers have found no reduction in Parvocellular functioning at isoluminance (Hicks et al., 1983; Lee, Martin & Valberg, 1989; Shapley et al., 1991). Reid and Shapley (1992) have also shown that P cells are in fact specifically designed to function at isoluminance, a finding difficult to reconcile with those of Logothetis and colleagues. Furthermore, as mentioned in Chapter 1, Shapley (1994) has argued that the conclusion made by Logothetis et al. (1990), that it is not possible to attribute reduced performance at isoluminance to one particular visual pathway, does not follow from their data. There is nothing in their data to suggest that the population response of P cells should experience a disproportionately large reduction at isoluminance. Therefore, at all luminance contrasts, it should be expected that the majority of P cells would be responding, with no exception at isoluminance.

The findings of Experiments 6 and 7 are consistent with this view that isoluminance selectively reduces M pathway functioning. These studies compared the recognition of letter strings (illegal nonwords) and strings of nonletter characters in the Reicher-Wheeler task under isoluminant and non-isoluminant conditions. In both experiments, participants were less accurate with isoluminant letter strings than they were with letter strings presented at a high luminance contrast. However, with nonletter strings, neither experiment showed any reduction in accuracy at isoluminance. If the functioning of both the M and P pathways were impaired at isoluminance, it might be expected that accuracy should be reduced for both stimulus types. Instead, the absence of any reduction in performance at isoluminance for nonletter strings suggests that the visual pathway used in the processing of this stimulus type may not be significantly affected by the absence of luminance differences.

Based on the available evidence, it is clear that the assumption that presenting stimuli at isoluminance causes a specific reduction in the functioning of the M pathway is a reasonable one. Following on from this, it can be concluded that the reduced levels of accuracy at isoluminance found in Experiments 3, 4 and 5 show that M pathway information is used in the recognition of words, pseudowords and illegal nonwords, presented in lower, upper and mixed case. This represents a major new finding, and goes against the view that all object recognition is carried out using only P pathway information, as well as experimental evidence that has shown no reduction in reading performance at isoluminance. For example, Legge et al. (1990) showed that reading rates with isoluminant text are the same as those obtained with high luminance contrast text. The differences between the findings obtained by Legge et

al. and the experiments described in this thesis are likely to have occurred either due to the reading speed measure not being sensitive to perceptual factors (see Santee & Egeth, 1982; Mordkoff & Egeth, 1993), the removal of guesswork in the Reicher-Wheeler task (see e.g. Jordan et al., 2000; Jordan & Thomas, 2002) or the onscreen luminance matching used by Legge et al. not accurately producing isoluminant stimuli.

The comparison between the findings with words and nonwords and those with nonletter strings highlights the view that letter strings represent a special class of stimuli, for which the initial visual processing is different from that carried out with other linear character arrays, a view also supported by work examining the serial position curves obtained in recognition tasks using both accuracy and reaction time measures (Hammond, 1980; Hammond & Green, 1982; Mason & Katz, 1976; Mason 1982). Experiment 8, which compared the recognition of words at isoluminance with that of isolated letters further extended the findings, showing that the recognition of even a single letter is reduced at isoluminance, and thus utilises M pathway information, something not shown by previous research in this area (Omtzigt et al., 2002).

3. Theoretical implications

3.1 The role of the M pathway in holistic processing

The Holistically Biased Hybrid model of written word recognition (Allen et al. 1995) is one of the key models advocating the holistic processing of words. To recap, the Holistically Biased model is a “horse race” framework in which word-level and letter-level (and syllable-level) channels process information independently and in parallel. The basic unit of analysis for each input channel is the spatial frequency

pattern of the relevant piece of information. Whilst the word-level channel has direct access to the lexicon, information processed by the letter-level channel needs to undergo a superposition process to create a word level code in order for recognition to occur. As a result, it is the word-level channel that normally wins the “race” to the lexicon. It is postulated that the letter-level channel is only used in unusual circumstances, when activation in the word-level channel is insufficient to allow a recognition judgement. One of the most interesting aspects of this model is mapping of the word and letter-level channels onto the M and P pathways respectively. A similar interpretation of the role of the Magnocellular system in word recognition was made by Chase (1996), who argued that low spatial frequency shape information, provided by the M pathway, is used to make an initial representation of a word. This representation can be used to carry out recognition if sufficient information is available; if this is not the case then high spatial frequency P pathway information is integrated with the initial representation in order for recognition to occur.

According to the Holistically Biased Hybrid model, when stimuli are presented at very short exposure durations, such as in Experiments 3 and 4, words should be recognised using the faster word-level channel when presented under high luminance contrast conditions. In contrast, pseudowords and illegal nonwords should both be processed by the letter-level channel, as the degraded nature of the input means that the familiarity levels of these letter strings are not sufficient for word-level processing. However, at isoluminance, both words and nonwords should be processed by the letter-level channel, due to the reduced functioning of the M pathway preventing holistic processing by the word-level channel. If this were the case, Experiment 3 should have found an interaction between Target Luminance and

Stimulus type, with a reduction in accuracy at isoluminance for words but not for illegal nonwords, whilst Experiment 4 should have found no effect of Target Luminance, with performance for pseudowords and illegal nonwords being equivalent across all luminance conditions. However, these experiments found a reduction in accuracy in the Reicher-Wheeler task at isoluminance compared to the non-isoluminant conditions for all three stimulus types.

When specifying the model, Allen et al. (1995) claimed that when stimulus presentation times are longer (i.e. under resource-limited conditions) both words and nonwords are processed by the word-level channel. Even though the stimulus durations in Experiments 3 and 4 were very short (typically 10-12 msec), it could be argued that they were still long enough to allow the holistic processing of pseudowords and illegal nonwords. According to the model, under non-degraded presentation conditions, the letter-level channel is used only when stimuli are presented in MiXeD case, as the spatial frequency pattern of the stimulus is not familiar enough to allow processing by the word-level channel. However, Experiment 5 found that for lower, UPPER and MiXeD case stimuli, performance in the Reicher-Wheeler task was lower at isoluminance than in either the lighter or darker conditions. Furthermore, this deficit occurred to the same extent across all case conditions for both words and nonwords. Thus, if the role of the M pathway in written word recognition is to provide word-level shape information, these findings indicate that readers should be able to use shape information even for illegal nonwords presented in mixed case. However, previous research has indicated that this is not the situation (e.g. Dakin & Morgan, 1999; Monk & Hulme, 1983; McClelland, 1976). It is therefore apparent from these findings that it is unlikely that

the word and letter-level channels map onto the M and P pathways in the manner described by Allen and colleagues (1995, 2002).

Even more conclusive evidence against the claim that the role of the M pathway in written word recognition is to provide holistic word shape information comes from Experiment 8. This experiment compared the recognition of lowercase words and isolated letters in the Reicher-Wheeler task under isoluminant and non-isoluminant conditions. A straightforward prediction from the Hybrid model is that whilst, as stated above, the recognition of words will be carried out using the word-level channel, the recognition of isolated letters will always use the letter-level channel, regardless of exposure duration. However, although accuracy with words was reduced at isoluminance as predicted, these lower levels of performance at isoluminance also extended to isolated letters. Therefore, this result suggests that the recognition of isolated letters also utilises M pathway information, meaning that it is extremely improbable that the letter-level channel described in the Hybrid model maps directly onto the P pathway.

The absence of any support from these studies for the claims made by the Holistically Biased Hybrid model (Allen et al., 1995) that the word-level channel maps onto the M pathway does not mean that the model itself has been shown to be invalid by this research. It is possible that in word recognition, readers do use the word and letter-level channels described in the model, but that the mapping of these channels onto the visual system does not occur in the manner postulated by Allen et al. Indeed, given the experimental support for the view that holistic shape information is used in word recognition (e.g. Boden & Giaschi, 2000; Fisher, 1975; Haber et al., 1983; Jordan & Scott-Brown, 1999; Jordan & Patching, 2003; Monk &

Hulme, 1983; Wheeler, 1970), along with the fact that Allen and colleagues (Allen & Emerson, 1991; Allen et al., 1995) have demonstrated that the model is able to explain phenomena not covered by models such as the Interactive Activation Model (McClelland & Rumelhart, 1981) or the Process Model (Besner & Johnston, 1989), it is clear that this model has considerable explanatory power and remains a useful tool. However, the findings described in this thesis do indicate that one of the most interesting aspects of the model, and indeed, one of the model's key strengths: that it maps onto the physiology of the human visual system, is not supported by experimental research.

3.2 The role of the M pathway in attentional selection

The majority of the other explanations for the role of the M pathway in reading and word recognition relate to the allocation of attention (e.g. Cornelissen et al. 1998a, 1998b; Omtzigt et al. 2002; Steinmann, 1998; Vidyasagar, 1999; Vidyasagar & Pammer, 1999). These explanations are particularly plausible given the Magnocellular system forms the predominant visual input into the posterior parietal cortex via area MT, areas associated with attention (Maunsell, 1992; Mishkin et al, 1983; Steinmetz & Constantinidis, 1995; Treue & Maunsell, 1996; Ungerleider & Haxby, 1994). There are at least three different processes involved in reading and word recognition that researchers have linked with attentional processes involving the M pathway. These are the covert identification or targeting of letters, the ordering of letters, and the programming of saccades. As the experiments carried out in this thesis related solely to the recognition of foveally presented single words, rather than lines or passages of text, it was expected that any demonstrated involvement of the M pathway in attentional selection would centre around the first two processes only.

According to Omtzigt et al. (2002), when reading, the spotlight of attention is focussed on the area of interest in order to enhance processing through a mechanism relying on the fast responses of the M pathway (Vidyasagar, 1999). In experiments such as those carried out by Omtzigt et al., which looked at the identification of letters flanked by two distracters, the attentional spotlight is presumably directed towards the central letter either by a pre-attentive mechanism automatically shifting attention towards the letter which differed from the other two, or a voluntary shift in attention due to participants having the knowledge that the target stimulus is always the central letter, or a combination of the two. However, it is not immediately clear where attention is directed when four letter words or illegal nonwords are presented in the Reicher-Wheeler task. In this situation, it is generally the case that all four letters differ from each other, and the target letter can be in any one of the serial positions, so participants do not know which area of the word to focus their attention on.

There is a lot of evidence to suggest that the exterior letters of words combine to form a perceptual unit that is a substantial component of the word recognition process. One source of evidence for this idea is the serial position analyses described in earlier chapters (see also Jordan & Bevan, 1996; Jordan et al., 1995; Prinzmetal, 1992; Prinzmetal & Silvers, 1994; Rumelhart & McClelland, 1982), which show that the exterior letters of letter strings are reported more accurately than letters in the interior positions, with performance levels in both exterior letter positions often very similar to each other. This view is supported by evidence from priming studies (Humphreys et al., 1990; McCusker et al., 1981), by evidence showing that the visual degradation of the exterior letters in words reduces reading speed more than the degradation of either the initial or interior letter pairs (Jordan, Thomas, Patching &

Scott-Brown, 2003), and by the intriguing extension of the Word Letter Effect shown by Jordan (1990): the finding that exterior letter pairs presented in the Reicher-Wheeler task are reported more accurately than single letters. Identifying the positions of these exterior letters presumably requires attentional selection. It is therefore a possibility that the spotlight of attention is directed to the exterior letter positions through a mechanism relying on the M pathway.

Experiments 6 and 7 provide partial support for the link between this “outside-in” processing and the M pathway. As mentioned above, the U-shaped serial position curves typically found with letter strings were not obtained with nonletter strings, indicating that these stimuli are not processed in an outside-in manner. Therefore, no performance deficit should be expected at isoluminance for nonletter strings, as information from the M pathway is not being utilised to direct attention to the exterior positions, and the shape discrimination procedures used to carry out the Reicher-Wheeler task with non-letter stimuli should rely upon information from the Parvocellular system only. The results support this prediction, with both experiments showing no significant differences between performance at isoluminance and in the Darker and Lighter conditions for nonletter strings. However, if the attentional spotlight is guided to the exterior letter positions through M pathway information, it should further be predicted that the U-shaped serial position curves should not be obtained when letter strings (either words or nonwords) are presented at isoluminance. However, the results of Experiments 3-8 show that serial position curves for all stimulus types remain the same, regardless of which Target Luminance condition the stimuli are presented under. This indicates that these U-shaped curves are not dependent on the M pathway guiding attention towards the exterior positions, and

suggests that if the M pathway is involved in the allocation of attention, its function does not relate to the targeting of letters within text, as suggested by Omtzigt et al. (2002).

Further support for this conclusion comes from the findings of Experiment 8. As stated above, this experiment showed that accuracy in the Reicher-Wheeler task is reduced at isoluminance for both words and isolated letters. This is inconsistent with an attentional allocation explanation of the role of the M pathway, as with isolated letters it is not necessary to select letters within the text, as the presentation of an isolated letter should automatically and involuntarily draw attention to itself. Similarly, with isolated letters, the Reicher-Wheeler task obviously does not require the ordering of letters within the stimulus. It must therefore be concluded that M pathway information is being used for some other function.

The experiments presented in this thesis do not rule out the possibility that the M pathway is involved in the planning of saccades; this research focussed on the recognition of individual letter strings, meaning that saccades were minimised. Indeed, given recent experimental evidence using isoluminant stimuli (Hendricks & Puts, 2000), saccade programming may well represent a function of the M pathway in reading. However, it is clear from the present research that it is not the only function; the M pathway is also involved in the recognition of individual letter strings and even isolated letters.

3.3 Other explanations

The research contained within this thesis indicates that the accounts of the role of the M pathway in reading and word recognition described above are either inconsistent with current evidence or not the only valid explanation. One account not

yet dealt with is the saccadic suppression argument, which states that the role of the M pathway is to suppress Parvocellular functioning during saccades. As with the saccade programming argument, the testing of this theory is beyond the scope of this thesis. However, based on research showing that it is M pathway rather than P pathway sensitivity that is reduced during saccadic suppression (e.g. Anand & Bridgeman, 1995; Burr et al., 1994; Shiori & Cavanagh, 1989), it would appear that this theory can no longer be considered a useful one. It is therefore apparent that an alternative explanation of the M pathway's role needs to be proposed.

Taking the available evidence, a logical explanation of the M pathway's role in word recognition is that it could be used to provide shape information not from words, but from individual letters. This is consistent with Experiment 8, which demonstrated that the M pathway is involved in the recognition of isolated letters, as well as the findings with illegal nonwords and pseudowords from Experiments 3 and 4. It is likely that we use this coarse scale letter-level information to carry out initial processing, taking advantage of the faster M pathway to provide information before the P pathway provides fine detail information. It is also a possibility that the M pathway could provide some supra-letter shape information which could be used to help determine the extent of the stimulus and help identify the exterior letter positions in order to facilitate "outside-in" processing (e.g. Jordan, Thomas, et al., 2003; Jordan, Thomas & Patching, 2003).

However, it is apparent from the evidence provided by these experiments that if this M pathway information is not available for some reason, the manner in which word recognition takes place does not change. The magnitude of the Word Superiority and Pseudoword Superiority Effects found in Experiments 3 and 4

respectively were not affected by presenting stimuli at isoluminance. Similarly, analysis of the serial position curves obtained for both words and nonwords in Experiments 3-8 revealed a general performance impairment at isoluminance in all cases, with accuracy reduced by the same amount for all critical letter positions. The unchanging nature of these effects in the absence of luminance differences, indicates that even if M pathway information is used in the manner described above, these processes can also be carried out with Parvocellular information. Therefore, it would appear that the role of the M pathway information in this context is solely to allow faster and more accurate word recognition and the absence of this information does not affect the underlying nature of the recognition process.

This is consistent with a recent study carried out by Patching and Jordan (in press), which showed that word recognition cannot occur with only low spatial frequency (M pathway) information. They presented spatially filtered words and illegal nonwords in a Reicher-Wheeler task. The stimuli were filtered so that each stimulus contained just a relatively narrow band of spatial frequencies. It was found that performance with words and nonwords with a centre frequency of 1.1 cyc/deg was essentially at chance. However, with stimuli centred around higher spatial frequencies, which can be processed by the P pathway, performance was above chance and identification accuracy was higher for words than for nonwords. Consequently, whilst low spatial frequency M pathway information may play an important role in word perception when a broad range of spatial frequency information is processed together (e.g. Boden & Giaschi, 2000; Chase, 1996; Jordan & Patching, 2003; Jordan & Scott-Brown, 1999) the evidence from this study

suggests that higher spatial frequency information (presumably processed by the P pathway) is necessary for word perception to occur.

Combining the findings of the experiments described in this thesis with those of Patching and Jordan (in press) we arrive at a model in which word recognition is predominantly reliant on the P pathway and cannot be carried out using only low spatial frequency (M pathway) information. However, coarse-scale analysis may be sufficient to reveal the horizontal extremities of a word through the provision of low spatial frequency shape information and allow some initial processing of both the exterior and interior letters, thereby speeding up the recognition process, although the findings of Jordan, Thomas et al., (2003) suggest that this M pathway information may be insufficient to reveal the identities of these letters on its own.

4. Future directions

The body of work contained in this thesis represents a significant, original contribution to the written word recognition literature and has helped develop understanding of the initial visual processing of letter strings. In summary, this research has: increased our knowledge regarding the creation of isoluminant “real-world” stimuli; confirmed the suitability of using isoluminance to reduce M pathway functioning; demonstrated that M pathway information is used in written word recognition; shown that this M pathway involvement extends to pseudowords and illegal nonwords, upper and mixedcase stimuli, and isolated letters, but not to nonletter character strings; and aided the evaluation of the various theories surrounding the role of the M pathway in reading and word recognition.

As with all research, these studies have provided further questions that need to be answered and have opened up new avenues of investigation. One area of research

that will clearly benefit from the techniques developed through this project is the investigation of the possibility of a Magnocellular deficit being the cause of developmental dyslexia. A significant number of studies have made such claims (e.g. Cornelissen et al., 1995; Edwards et al., 1996; Lovegrove et al., 1986; Martin & Lovegrove, 1988; Williams & Lecluyse, 1990; Williams et al., 1995), although findings have been somewhat inconsistent (see Skottun, 2000, for a review). In order to evaluate these assertions, it would therefore be useful to repeat some or all of the experiments described in this thesis using participants with dyslexia. If developmental dyslexia does occur as a result of reduced Magnocellular functioning, it might be expected that when compared with a control group, participants with dyslexia might exhibit either a smaller reduction or no reduction in accuracy at all for isoluminant stimuli in the Reicher-Wheeler task. However, one practical problem with such an approach is that an alternative approach to creating isoluminant stimuli may need to be devised. As flicker sensitivity is dependent on the M pathway, at least at higher temporal frequencies (e.g. Dobkins et al., 2000), HFP may not be an appropriate technique to use for such participants.

One approach that was not taken in the present research was to display the two alternatives in the Reicher-Wheeler task at isoluminance. In all experiments they were presented under high luminance contrast conditions. However, presenting these at isoluminance could help further our understanding of the role of the M pathway in word recognition, and in particular, how it could relate to attentional selection. For example, if the M pathway was involved in the targeting of letters within text, it might be expected that when only the critical letters of the two choices are presented, isoluminance should have a relatively small effect (with effect size depending on

whether M pathway information has an additional role), as presumably, attention should automatically be drawn to these characters. However, if the full letter strings are presented as the two alternatives, a larger performance deficit might be expected at isoluminance. It should be noted that one immediate problem with this approach is that in a typical Reicher-Wheeler style task, the two alternatives are normally presented until the participant responds. Following this approach would mean that only response time would represent an appropriate dependent variable, and as noted previously, using a resource-limited response time measure might mean that the study is relatively insensitive to perceptual factors, due to the intermingling of post-perceptual effects (Santee & Egeth, 1982; Mordkoff & Egeth, 1993). A potential solution to this problem could be to use a variant of the standard Reicher-Wheeler task, in which long exposure durations were used for targets, whilst the two alternatives were presented very briefly.

A further development of this research could be to extend it to examining the recognition of sentences presented at isoluminance. There are a number of ways in which this could be done. One approach would be to carry out work using sentences or passages of text presented at isoluminance, possibly using a Reicher-Wheeler style task (see Jordan & Thomas, 2002). Reading speed could be examined and saccades monitored using an eye-tracker to examine claims that saccade programming is impaired at isoluminance. It might be expected that participants make more erratic eye-movements under such conditions, similar to those exhibited by some people with dyslexia (Pavlidis, 1981, 1985; Zangwill & Blakemore, 1972). An additional methodology that could be used is the eye-contingent display change paradigm (McConkie & Rayner, 1975; see also e.g. Balota & Rayner, 1983; Binder, Pollatsek &

Rayner, 1999; Rayner 1975, 1998; Rayner, Well, Pollatsek & Bertera, 1982) in which changes are made to the visual display that the reader is looking at, contingent on when the eyes move. For example, Balota & Rayner (1983) carried out an experiment in which a word that was to be identified and named changed immediately before it was fixated. The target location was originally filled by a nonword and changed to a visually similar or dissimilar word when participants' eyes crossed a boundary. Targets similar to the previews were named faster than dissimilar ones, suggesting that information from the parafovea is available to readers. Using a similar approach, Rayner et al. (1982) confirmed that we are able to obtain supra-letter shape information from the right of fixation. By adopting comparable techniques, in which targets and previews are presented under isoluminant and non-isoluminant conditions, it should be possible to identify whether it is the M pathway that is used to obtain this information from the parafovea.

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Appendix A**Stimuli used in Reicher-Wheeler Task****1. Practice Stimuli****1.1 Words**

bold	fold	dent	bent	fake	take
gown	town	hand	band	tour	four
ages	apes	came	come	fact	fast
held	hold	left	lift	legs	logs
duck	dusk	knew	know	lone	love
oafs	oats	robe	rode	span	spun
clap	clay	file	film	gold	golf
half	halt	tore	torn	trap	tray

1.2 Illegal nonwords

bcmv	dcmv	bqlj	fqlj	dkrj	bkrj
fpbc	npbc	tvsv	fvsz	yxzc	pxzc
cvrz	cxrz	krzu	kvzu	qajs	qejs
wgzv	wpzv	xezc	xuzc	xuhg	xohg
bqgx	bqyx	fvcj	fvsj	jzaq	jzuq
kvcx	kvsx	tqaj	tqnj	xjdk	xjtk
cgjm	cgjn	ihqe	ihqh	xjqe	xjqn
yvbd	yvbf	zcjp	zcjy	zmqa	zmqx

1.3 Pseudowords

corl	dorl	dars	hars	gume	tume
konp	ronp	masi	gasi	tald	cald

bame	bome	boft	buft	erib	evib
kift	keft	pame	pome	tave	tive
bima	bina	knem	knom	nido	nifo
noda	nola	skig	skog	sman	smin
bine	bink	dilk	dilt	glan	glay
hend	hent	kile	kilm	thun	thut

2. Experimental Stimuli

2.1 Words

bang	hang	blue	clue	dive	live
kind	mind	lean	mean	line	wine
meat	seat	most	post	nail	rail
pain	rain	wear	tear	your	pour
aces	axes	blow	brow	glow	grow
open	oven	play	pray	sham	slam
shin	spin	ship	slip	show	snow
slap	snap	slit	spit	slow	stow
bare	base	belt	best	cane	cave
face	fame	hunt	hurt	made	mate
mile	mine	owls	owns	pike	pile
race	rate	rent	rest	ripe	rise
deal	dear	find	fine	hard	harm
leaf	leap	mild	milk	near	neat
paid	pail	park	part	rice	rich
sing	sink	them	they	work	worm

2.2 Illegal nonwords

bcdq	hcdq	bdkw	cdkw	dhecv	lhcv
kgcj	mgecj	lxmc	wxmc	mjtq	sjtq
mqsj	lqsj	nzhc	rzhc	pgcv	mgcv
pjbc	rjbc	pkecv	ykecv	wvrq	tvrq
bhgc	bpgc	gcdq	gxdq	jlqw	jrqw
jlxw	jtxw	jlzf	jrzf	qhjn	qljn
qhzp	qlzp	tpmh	tvmh	vhzw	vnzw
vlxg	vrxg	vnzc	vlzc	vpjk	vljk
aqlz	aqnz	bxrj	bxsj	fjnz	fjrz
gvdk	gvtk	hvlz	hvsz	jwcd	jwmd
kfnm	kfvn	lfnw	lfnw	mkecv	mkcv
rqpv	rqsv	svlz	svnz	txkh	txlh
ihvr	ihvt	iwvk	iwvt	jcpd	jcpm
kcjm	kcjy	oqbf	oqbp	qmvf	qmvv
ujbg	ujbk	ukxd	ukxl	wcpk	wcpm
xbqe	xbqh	xgqd	xgqe	ztdv	ztdk

2.3 Pseudowords

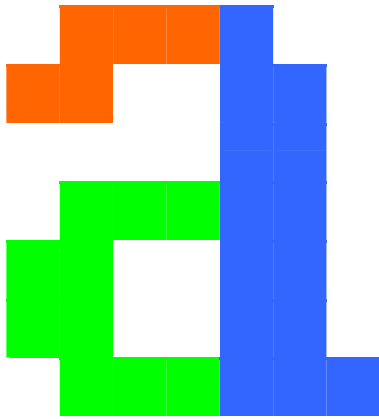
clum	blum	dibe	libe	hulm	bulm
kund	mund	larp	marp	mird	pird
murt	surt	nild	rild	pold	yold
raim	paim	wans	lans	warg	targ
axib	acib	brof	blof	chib	clib
clav	chav	dlom	drom	epin	evin

kleg	kreg	shom	snom	slad	snad
sleb	speb	spib	shib	stoy	sloy
awls	awns	bure	buse	cune	cuve
dila	dina	dist	dilt	hink	hirk
nida	nita	noke	nole	tuci	tumi
vunt	vust	wope	wose	wuce	wute
durf	durp	furk	furt	nace	nach
peld	pelm	reng	renk	shem	shey
sird	sirl	snar	snat	snul	snur
tand	tane	vird	virk	wilk	wilm

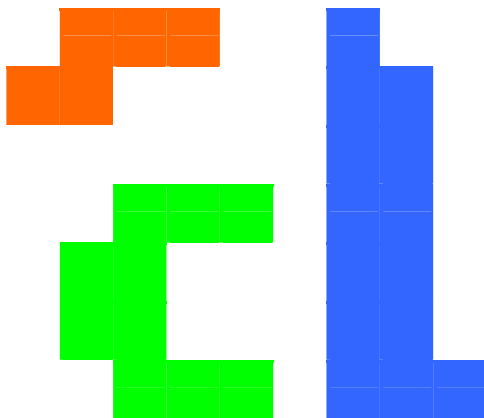
Appendix B

Example of nonletter stimulus design

Original letter 'a' (adapted Times New Roman):



Letter broken down into individual features:



New nonletter character created by rearranging letter features:

