An Investigation of Reading Ability and Visual Function with Eccentric Visual Field

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This study investigated the detrimental effect of central field loss (CFL) on reading ability and general visual function. The aim was to improve the understanding of reading with eccentric retina in order that reading performances of individuals with CFL may be maximised.

To improve visual ability of individuals with CFL, it is important to be able to accurately measure the outcome of any intervention. Various methods for determining visual function were therefore compared with perceived visual performance (as measured with a quality of life questionnaire) before and after surgical removal of choroidal new vessels (CNV) in macular disease patients. The results highlight the importance of low contrast measures (low contrast visual acuity and contrast sensitivity) when investigating perceived reading performance. Reading speed was found to be important for reflecting changes in general visual quality of life.

Potential causes for reduced peripheral reading ability were investigated using both normally sighted and CFL subjects. For normally sighted subjects reading eccentrically with rapid serial visual presentation (RSVP) text, the inferior visual field was a better position (in terms of reading speed) for the presentation of the text. The size of the visual span was found to reduce with increasing eccentricity of fixation, providing a potential reason for reduced peripheral reading performances. The investigation of the ability to use context when reading with peripheral retina resulted in conflicting results. Studies in this thesis found both a reduction and no reduction in the ability of the peripheral retina to utilise context compared to the fovea. Individuals with long-term CFL showed no improvement in peripheral reading ability over that found for normally sighted subjects reading at the same eccentricity.

context advantage, preferred retinal locus, rapid serial visual presentation, visual span

Dedicated to

Roger

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Chapter 1

INTRODUCTION

Reading is required for full participation in modern society. For people with impaired vision, reading represents a major challenge for daily living. In fact, reading is the most important rehabilitative goal of older low vision patients (Elliott et al., 1997). Loss of central visual field has a particularly detrimental effect on reading performance (Legge et al., 1985; Legge et al., 1992). Even after training and with appropriate magnification to compensate for peripheral viewing, reading speed in individuals with central field loss (CFL) rarely approaches that of normally sighted observers reading with their fovea. In addition, despite magnification, peripheral reading speeds in normal observers have also been found to be reduced compared to when they are using central retina (Turano & Rubin, 1988; Latham & Whitaker, 1996; Chung et al., 1998).

Among the many causes of CFL, age-related macular degeneration (ARMD) is the most common. ARMD makes up 50% of the blind or partially sighted registrations in the United Kingdom each year (Evans & Wormald, 1996) and is the most common cause of vision impairment in the Western World (Lovie-Kitchin & Bowman, 1985; Richer, 1999). As the number of elderly in the general population increases, vision impairment due to CFL is likely to become more widespread. It is therefore of importance to be able to minimise the effect that loss of central visual field has on reading performance. This thesis therefore investigates reading and visual function in individuals with CFL. The aim is to more fully understand the task of reading with non-foveal retina, so that suggestions can be made to maximise peripheral reading performance.

This subject is investigated from two aspects. Firstly, during the process of rehabilitation or management of CFL patients, it is important to accurately measure the outcome success of any intervention. High contrast distance visual acuity (VA) is the most commonly used measurement of vision in clinical practice. Often clinical and surgical decisions are made in the process of patient management and treatment on the basis of this measurement alone. This assumes that the measurement of a patient's ability to see high contrast letters is a good indication of their everyday visual function. However, a high contrast visual acuity measurement can actually be a poor predictor of a number of aspects of visual function (Hess & Woo, 1978; Paulsson & Sjostrand, 1980; Maroon & Bailey, 1982; Owsley & Sloane, 1987; Lennerstrand & Carl-Otto, 1989; Elliott & Hurst, 1990; Elliott et al., 1990; Mangione et al., 1994). Therefore, in Chapters 5 and 6, for a group of macular disease patients, the results of a series of visual function tests were compared with perceived visual performance as measured with a quality of life questionnaire. The aim was to determine without *a priori* assumption, which visual function measures most closely correlated with perceived general visual performance and perceived reading ability. In this way, a more accurate picture of perceived visual performance may be obtained than from the assessment of high contrast distance visual acuity alone.

Secondly, as stated above, reading speed in individuals with CFL is reduced compared to normally sighted observers reading with their fovea. This occurs despite appropriate magnification to account for reduced peripheral sensitivity. Therefore, it appears that print size is not the performance limiting factor when reading with peripheral retina. Chapters 7-10 of this thesis investigate other potential causes for reduced peripheral reading performance. It is considered that a greater understanding of this peripheral deficit will enable suggestions to be made with regards to reading such that an individual's maximum reading performance can be obtained.

The research for this thesis was conducted mainly within the Neurosciences Research Institute, Aston University. The studies described in Chapters 5 and 6 were conducted within the Department of Ophthalmology, Birmingham Heartlands Hospital, Birmingham, and the studies described in Chapters 7 and 8 were conducted within the Lions Vision Centre, The Johns Hopkins University, Baltimore USA. All normally sighted subjects for the studies carried out within the Neurosciences Research Institute, Aston University were recruited from staff and students within the Institute. Central field loss subjects for the study described in Chapter 9 were recruited from the Birmingham and Midlands Eye Centre, Birmingham and the Coventry and Warwick Hospital, Coventry. All studies had approval from appropriate Ethics Committees and all subjects gave informed consent.

Chapter 2

THE READING PROCESS AND VISION IMPAIRMENT

2.1 INTRODUCTION

The concept of 'reading' and the processes involved have fascinated psychologists, educationalists and researchers since the early 1900's. Reading is an integral part of modern living which allows people in developed societies to communicate and socialise, to learn, as well as to educate others. The studies described in this thesis investigate the effect on reading performance when readers are unable to use their central retina. The reading performances of both normally sighted readers and readers with central field loss using their eccentric retina are compared with normal foveal reading. This chapter therefore summarises the research concerned with understanding the reading process and outlines the outcome measures of reading. Characteristics constituting normal reading performance are discussed, as well as those factors that affect reading speed, the most common measurement of reading performance.

2.2 THE READING PROCESS

2.2.1 Definitions of the Reading Process

There are several ways of characterising the reading process. It has been described as a form of communication or responding discriminatively to graphic symbols and speech (Gibson, 1965; Lewis, 1985), and educationalists look at the reading process as an analytical and problem-solving task requiring a number of stages (Robeck & Wilson, 1974; Goodman & Goodman, 1977). Definitions of the reading process have varied through the years as advances in technology have allowed different aspects of this process to be explored. The many definitions available however, all agree that the reading process is complex and multifactorial in nature. They differ only with regards to their detail and the importance attributed to the various factors involved.

2.2.2 Models of Reading

The process of reading involves an array of human functions in which language code is detected through the visual system and processed further. It is obvious that the process involves a number of sub-processes or steps that are interconnected. A number of researchers (Tinker, 1952; Russell, 1956; Rumelhart, 1977; Just & Carpenter, 1980; McClelland & Rumelhart, 1981; Legein & Bouma, 1982; Lewis, 1985) have proposed models of the reading process in an attempt to account for this complex activity. These models have increased in complexity throughout the years as our knowledge of reading has expanded. Although the details of these models differ, they all suggest that skilled reading requires a number of interacting components. Reading problems can arise as a result of failure or abnormality of any of these components. Both sensory and cognitive processes are involved in reading and impairment of either of these results in characteristic reading problems. This thesis investigates the effect of sensory deficit on reading performance, in particular central visual field loss.

Reading research has been concerned to a large extent with the role of vision in the reading process. In particular, studies proposing reading models have attempted to explain the role of vision in providing a representation of a word as a list of letters in a particular order. The level at which visual processing provides these representations of words has been the main aim of research in the processes of reading. Over the years, studies have provided different suggestions within this argument, none of which can be considered entirely satisfactory. The following is a summary of the three main views as a whole that have been used to explain the reading process.

The first theory is that visual processing makes available whole word information including word length as well as shape (formed by positions of ascending, descending and small letters). This whole word information can then be used to facilitate the recognition of letters in the word that will allow the word itself to be recognised (Haber, 1981; Rayner & Pollatsek, 1989).

The second theory is that visual processing is concerned initially with the representation of letter features. Detectors for visual features excite detectors for letters consistent with the active features and in turn detectors for consistent words are excited. Finally, active word detectors can mutually affect each other and send feedback to letter detectors, thus reinforcing the perceptibility of the constituent letters in the word. In addition, higher levels of processing can interact to determine letter representation and word representation (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982; Lewis, 1985; McClelland, 1987). The 'interactive reading models' described by a number of authors, are examples of this type of processing (Rumelhart, 1977; McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982; Lewis, 1985). For these models visual processing must always provide a representation of letter features before letters. However, the different levels of visual processing can also feed back into lower levels. This suggests that reading is a two-way process with processing that occurs at one level able to affect the processing of adjacent levels either above or below (Figure 2.1).

Each theory of visual processing is supported by the findings of a number of different studies. Studies based on different methodologies, including the use of single words, eye-movements, proof-reading and various psychophysical methods have been unable to agree on which theory is correct. Consequently, the conclusion that early visual processing is wholly responsible for providing an appropriate or suitable representation of the information in text is being questioned by a number of researchers. Instead, the separate mechanism of 'attention' as an additional step in the reading process has therefore been proposed as a possible means of resolving and explaining the conflicting data (Duncan, 1987; McConkie & Zola, 1987; Bock et al., 1993). This 'attention' mechanism is cognitive (compared with a *visual* process) and is applied either to whole words (Bock et al., 1993), letter features and letters (Treisman & Souther, 1986), or both (McConkie & Zola, 1987). Vision is then able to provide a representation of the orthography of the word in order that it can be identified.

Nevertheless, research has still not been able to agree on an adequate explanation of the complex and multi-factorial task that is reading. Reasons have been proposed however, to explain why this is the case. The first explanation concerns methodology. None of the different methodologies employed in reading research (e.g. measures of reading speed, eye-movements, lexical decision and psychophysical procedures) have been able to separate the effects of the various visual and linguistic cues available. As such, it is not possible to identify which factor is responsible for the behaviour observed. A second explanation is that studies have been primarily concerned with determining if visual processing initially provides whole word information or only information about letter features as a means of providing orthographic representation of the text. This emphasis on words implies that the visual context in which a word appears does not affect its visual processing. In fact, in the models referenced above, isolated words are treated no differently from words situated within text. These techniques are therefore unable to determine the effect of the visual context in which words appear, on the visual processing they receive.

Both these reasons highlight some of the assumptions that are made about what reading actually involves as well as what vision is capable of delivering in the visual processing of reading. Considering the complex nature of the reading task, an experimental technique that can identify and isolate the various visual from non-visual (i.e. linguistic) aspects of the reading process would be necessary to provide adequate explanations. Such a task however, would unarguably be an extremely difficult one.

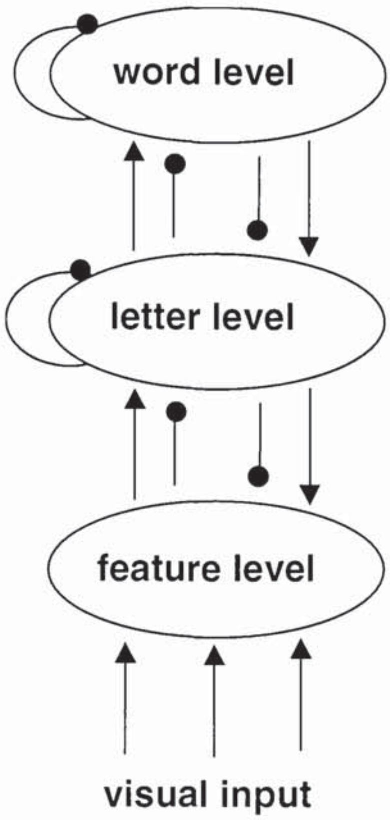


Figure 2.1. The interactive model of word recognition. Visual processing is only able to deliver a representation of letter features. 'Higher-level' stored representation of words can interact in an excitatory (arrows) or inhibitory (circles) manner to determine letter and word representations. Adapted from McClelland & Rumelhart, 1981.

2.3 OUTCOME MEASURES OF READING

Reading performance can be measured in a number of ways; by the recording of eye movement patterns, or the measurement of reading speed or comprehension. Reading studies investigate the reading process by investigating the effect of varying ocular factors (visual acuity, visual field status, contrast sensitivity etc) or text factors (print size, font type, colour etc) on the different outcome measures of reading performance. The following sections look at these different outcome measures in order to understand what exactly reading performance can be.

2.3.1 Reading Speed

In studies of reading, the most common, and in fact the easiest measure of reading performance is reading speed. It is measured as the number of words read per unit time, or words per minute (wpm), and may or may not take into consideration the number of errors made. This method also does not take into account the fact that easier reading material consists of shorter words than more difficult material. Therefore easy text will consist of less material (in terms of characters) than more difficult text of the same number of words in length. One solution that has been suggested to enable comparisons between text of different difficulties is to count syllables and measure reading speed in syllables per minute. However, syllables are difficult to count accurately, therefore, alternatively character spaces can be counted, using six character spaces as a *standard length word* (Carver, 1990). Reading speeds measured in standard words per minute are denoted by the capitalised 'Wpm'. As any comparisons between absolute values of reading speeds made within the studies described in this thesis are made between passages or sentences of equal difficulty, reading speeds were measured in words per minute (wpm). This is also the most common method of measuring reading speed, and as such, using wpm enables easy comparison with other studies.

Both these measures of reading speed assume that a faster reading speed reflects better and more efficient reading ability. In fact, the speed-determining components of the reading process in normally sighted readers have been assumed to be linguistic processing and comprehension (Rayner, 1978). However, factors such as the presentation characteristics of the text will also affect reading speeds. A normally sighted reader, reading standard book-sized print can read 250-300 wpm (Krischer & Meissen, 1980). Similarly, maximum reading speeds measured with a single horizontal line of gliding text are 200-250 wpm (Buettner et al., 1985). In contrast however, values of up to 1600 wpm (Rubin & Turano, 1992) have been measured using rapid serial visual presentation (RSVP), a method of text presentation that minimises the need for eye movements (Chapter 2.4.3). Reading speeds of vision impaired readers are also affected by the characteristics of any low vision aids which can affect the presentation of the text. Other determinants of reading speed such as ocular factors and other types of text variables are detailed in Chapter 2.5.

With respect to vision impaired readers, Whittaker & Lovie-Kitchin (1993) and Whittaker & Lovie-Kitchen (1994) have proposed the importance of measuring reading speed by suggesting it will determine what a vision impaired reader is able to do with their reading ability. More specifically, from a review of the literature, they said that to read a novel, a reader needed 'high fluent' reading speeds of at least 160 wpm. However, for 'spot' or 'survival' reading (e.g. price tags), the reader only needed to be able to achieve 40 wpm. From their summary of studies that have investigated the change in reading speed with stimulus parameters, Whittaker & Lovie-Kitchin (1993) made the point that reading was slow when the stimulus was close to threshold, but increased as the print size and contrast became progressively suprathreshold. This can be seen from the reading speed-text size curves described in Chapter 2.5.1.

2.3.2 Comprehension

Comprehension of text is considered to be the true goal of reading. As such, some researchers have used this as a measure of reading performance in both normally sighted and vision impaired readers as an alternative to reading speed (Stroud, 1942; Carlson, 1949; Legge et al., 1989; Dickinson & Rabbitt, 1991; Watson et al., 1992). Comprehension is measured as a percentage score obtained by answering questions about the text, or by simply measuring the amount of the text able to be recalled by the reader. Traditionally, studies using reading speed as a measure of reading performance have assumed that poor comprehension of text results in reduced reading speeds. Studies that have investigated this relationship however, have found conflicting results. Carlson (1949) studied 330 fifth-grade pupils and found that the correlation between comprehension and reading speed varied with the intelligence of the readers, difficulty of the text, style of comprehension test and continuity of the text. All of the correlations however, were low. In contrast, Carver (1990) found that reading speed and comprehension in normally sighted subjects were positively correlated even when they normalised the text for difficulty. Similarly, Stanovich (1980) showed that a slow speed of reading among normally sighted subjects was highly correlated with difficulties in comprehension.

Studies have also investigated comprehension with regards to vision impaired readers. To simulate the effects of vision impairment on reading, researchers have observed the effects on comprehension of less visible or manipulated text. Duchnicky & Kolers (1983) used multiple choice questions to test the comprehension of subjects reading text of different window heights, line lengths and character densities. Manipulating the text reduced the reading speed, but readers were able to maintain a constant level of comprehension. Similarly Menz & Groner (1985) also found that comprehension, as measured with a multiple choice test, remained unchanged as the spacing and vertical placement of letters was varied, even though reading speed was slowed. Legge et al. (1989b) compared comprehension levels of normally sighted and vision impaired subjects using a multiple choice test. They found that 21 out of 24 of their vision impaired readers maintained comprehension levels within one standard deviation of the mean of the comprehension levels of normally sighted subjects, when reading text of the same drift rate.

Authors have suggested that the variable results found between different studies with regards to the relationship between comprehension and reading speed are due to differences in experimental design (Anderson & Tinker, 1936; Carlson, 1949; Dickinson & Rabbitt, 1991). Dickinson & Rabbitt (1991) compared the measurement of comprehension using prompted questions about the text, with asking the reader to recall as much detail as possible (called 'free recall'). The measurement of comprehension using these two methods was also compared when subjects read visually distorted text and undistorted text. The results showed that when the free recall method was used, comprehension of distorted text reduced along with reading speeds, more so than when reading undistorted text. When comprehension was measured with prompted questions, comprehension levels remained the same even though reading speeds dropped. The results of this study indicate that the experimental method must be considered when drawing conclusions about comprehension levels of vision impaired as well as normally sighted readers.

In conclusion, the studies suggest that measurement of comprehension may be useful for vision impaired readers as well as the normally sighted. Although a slow reading speed is a useful indicator of the difficulty that an individual patient is experiencing with a task (Bailey & Lovie, 1980), given the opportunity, a reader will reduce their reading speed to maintain a constant comprehension level. Therefore, one cannot assume that a vision impairment that reduces reading speed will also impede comprehension. Dickinson & Rabbitt (1991) have also suggested that stress and fatigue could accumulate in the vision impaired reader due to the need for an increased concentration and processing effort. Therefore, a vision impaired reader may perform a short task as well as a normally sighted reader, but may decline in comprehension ability over a longer (e.g. one hour) period.

Unfortunately, evidence with regards to the correlation between reading speed and comprehension is inconclusive, and few recognised clinically based tests exist. One such test however is the Low Vision Reading Comprehension Assessment (LVRCA) (Watson et al., 1996). It was designed specifically for readers with macular degeneration and intended for use as the reading-comprehension component of a battery of reading tests that would assess accuracy, speed and duration of reading. The test consists of 18 sentences in two equal formats. Each sentence is a 'cloze task'. That is, each sentence has a word missing that the reader must be able to provide as evidence of understanding the sentence. The sentences are arranged such that there are six steps of increasing difficulty with three sentences at each level. The authors suggest that the LVRCA is a tool by which clinicians can advise people with macular degeneration of their comprehension levels relative to normal, and to evaluate interventions to increase their comprehension. This test holds potential for use on subject groups other than those with specifically macular disease.

2.3.3 Eye movements

Tinker (1966) proposed that eye movement behaviour reflected the nature of the central processes of perception and efficiency of comprehension. He also believed that reading test performance could be predicted from eye movement records for that text material. A number of studies have investigated whether eye movements determine reading proficiency, yet there is only indirect evidence to show that this is the case. We know that central processes affect eye movements, and numerous studies have indicated that variations in the central processes of reading affect the subsequent reading performance.

Anderson (1937) evaluated the importance of eye movements as measures of reading ability, specifically in relation to good and poor readers. He varied the difficulty of the vocabulary, the length of sentences and the complexity of meaning and measured the effect of these variations on various eye movement parameters as well as reading speed. He concluded that the difficulty of the reading material, the purpose for reading and general intelligence of the reader, all affected eye movement patterns. This variation in eye movement patterns that followed changes in the central processes of recognition and comprehension, indicated the dependence of eye movement behaviour on reading ability. An increase in difficulty was reflected by an increase in the number of fixations, the duration of fixations and the number of regressions. In addition, an increase in standard deviation of fixation duration and significant reduction in the reading speed were observed.

More recent studies have found similar links between cognitive processes and eye movements. Authors have shown the effects of difficulty or familiarity of the text on eye movements (Just & Carpenter, 1980; Ehrlich & Keith, 1981). Rayner & Duffy (1982), Hogaboam (1983) and Inhoff & Rayner (1986), all found that fixation time was affected by word frequency, even when they controlled for word length and predictability. Henderson & Ferreira (1990) investigated reading performance and the size of the perceptual span, or the region of the visual field from which useful information can be acquired during a given fixation. They found that the size of the perceptual span (and hence the eye movement patterns) depended on difficulties of the foveal and parafoveal words. The results of a study by Hogaboam (1983) also suggested that the pattern of fixations was sensitive to the types of mental processes used during reading. He investigated the types of eye movement patterns and discovered that a large number of different patterns occurred. Many of these patterns occurred infrequently and Hogaboam believed that none occurred with sufficient frequency to be characterised as the dominant pattern. These results suggest that the eye guidance system is therefore quite sensitive to the various language and comprehension processes occurring during reading.

In summary, there is no ideal method of measuring reading performance, as all methods have their advantages and disadvantages. Eye movement recording is ideal for silent reading, however it can be fraught with technical difficulties and artefacts. Comprehension is the true aim of reading, and therefore could be considered to be the most pertinent measure. However, as described above, measurements are highly variable depending on the particular method used. Reading speed is perhaps the simplest method to employ, even so, when measuring silent reading, it is dependent on the subject's reliability to completely read all the text. Whatever method is used, care must be taken when comparing data so that the numerous text and reader variables that can affect performance are considered. These variables are described in the following sections of this chapter.

2.4 TEXT FORMATS FOR EVALUATING READING

Reading can be evaluated using a number of different text formats, which place different demands on the reader in terms of eye movements and visual processing. When comparing the results of studies investigating reading performance and speed, it is important to consider the method of text presentation employed. The reading performance results will vary depending on whether the text is of standard page format, single line scrolled text or rapid serial visual presentation (RSVP). These formats are described in the following sections.

2.4.1 Standard Page Format

Most of the reading required of us in day-to-day life involves text consisting of lines of meaningful and related sentences. When we read, our subjective impression is that our eyes move smoothly across the page. In fact, this is an illusion. In English, reading standard page format text involves a series of left to right saccadic eye movements separated by fixational pauses that last about 200-250 msec each (Rayner, 1978). Average reading speeds for standard page reading are approximately 250-300 words/min (Tinker, 1966; Rayner, 1978), although values of more than 500 wpm have been reported for single sentences (Legge et al., 1989a). It has been suggested that the programming and execution of reading eye movements impose an upper limit on these speeds (Rubin & Turano, 1992). Figure 2.2 is a diagram of a line recording showing various aspects of horizontal eye movements during reading page format text.

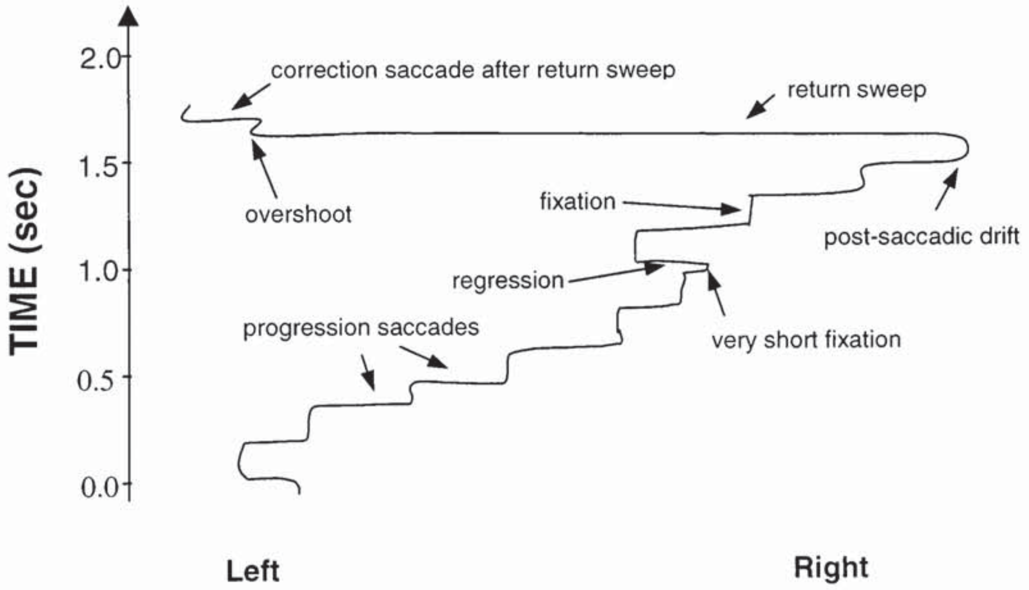


Figure 2.2. A line recording showing various aspects of horizontal eye movements during reading. Adapted from (O'Regan, 1990).

Tinker (1947) and subsequent authors (Coltheart, 1987) reported that fixation pauses take up to 92-94% of the total reading time. Fixation pauses are periods of clear vision during which all new information is extracted from the text. Saccadic eye movements are so rapid that no clear vision is possible during the saccade. The function of saccades is to bring a new region of the text onto the fovea where clear detail can be extracted from the stimulus. The mean saccade length is 8 characters, with its duration being a function of the distance covered (Rayner, 1978). One important aspect of eye movement characteristics in reading is the large variability that exists both within and between subjects. Thus saccade lengths can vary from between 2 and 18 characters or more, and fixation duration values range from 100 to over 500 msec for a single reader within a single passage.

Another type of eye movement characteristic is the regression. For readers of English, these are right-to-left movements, which in skilled readers occur 10-20% of the time (Rayner, 1978). Regressions are assumed to occur when readers misinterpret or have difficulty understanding the text, or when they overshoot the target. A return sweep of the eyes is seen when the reader reaches the end of the line and returns to the beginning of the next. This is another type of right-to-left movement, although it can be distinguished easily from a regression.

With regards to vision impaired readers, in particular those with central field loss, studies have shown variations from the normal fixation patterns during reading of text or words or a scanning task. Abnormal eye movements in scanning and reading tasks for central field loss patients were demonstrated by Cummings et al. (1985) and Whittaker et al. (1988). They suggested that there was an important relationship between reading, eye movement control and scotoma size in patients with macular scotoma. In a scanning task of rows of letters, subjects exhibited about twice as many saccadic eye movements as necessary, with a frequent need for corrective eye movements. Similar findings of increased numbers of corrective eye movements have also been reported by Trauzettel-Klosinski et al. (1994)

when their subjects read cards of meaningful text. In addition, Rayner & Bertera (1979) tested normally sighted subjects reading sentences with artificial scotoma. They found an increase in inaccurate saccades, a decrease in fixation stability and an increase in the frequency of saccades (forward saccades and regressions) as mask size increased.

Bullimore & Bailey (1990) measured the reading rates and eye movements of age-related macular degeneration patients when reading word and text charts of different print sizes. They recorded slower than normal reading speeds, which were most strongly associated with a decrease in the average number of letters per forward saccade as well as an increased number of regressions. Trauzettel-Klosinski et al. (1994) also found a decrease in the number of characters spanned per forward saccade by their maculopathy patients. This finding was more marked for the patients with more advanced maculopathy.

Studies have also found changes from the characteristic 'staircase' pattern of fixation pauses separated by forward or regressive saccades (Figure 2.2) when subjects used low vision aids. Fotinakis & Dickinson (1994) reported a 'saw-tooth' pattern when normally sighted observers read with hand magnifiers. That is, smooth leftward eye movements were found to replace fixation pauses (Figure 2.3). In addition, with increase in magnification, saccades became shorter in terms of character spaces. A similar pattern described as an 'opto-kinetic nystagmus' type of movement was reported by Bowers & Ackerly (1994) when their normally sighted subjects read hand-held or spectacle-mounted magnifiers. Vision impaired observers have also displayed a similar pattern of eye movements when reading with spectacle-mounted magnifiers (Cummings et al., 1989).

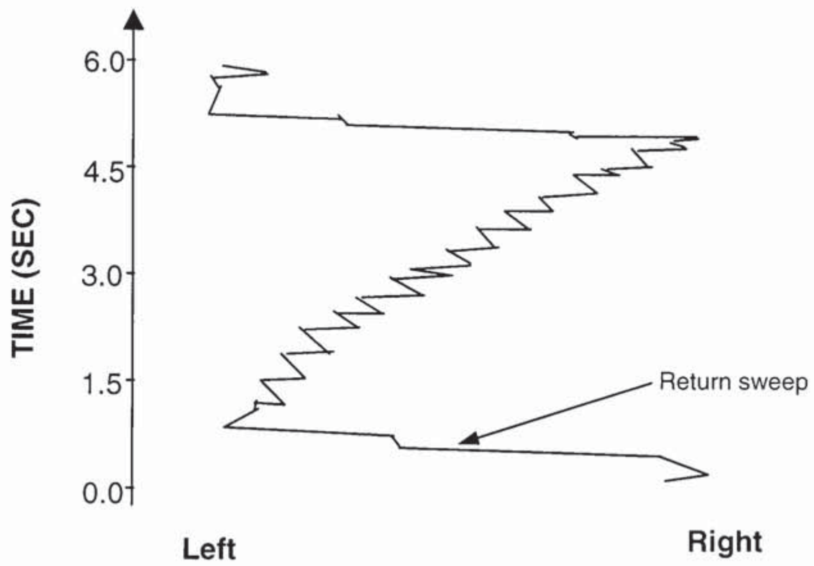


Figure 2.3. A line recording showing the 'saw-tooth' or 'opto-kinetic nystagmus' type of pattern when normal observers read with a hand magnifier. Adapted from Bowers & Ackerly (1994).

2.4.2 Scroll Display

Another method used in reading studies is a scroll display. This method involves a single line of words moving across the screen continuously from right to left (Figure 2.4). It has been shown to affect reading speed, as well as the pattern of eye movements compared with that of standard page format. Average maximum reading speeds when reading from a scrolled display have been measured up to approximately 360 wpm for single sentences (Legge et al., 1989a; Fine & Peli, 1995) and approximately 165 wpm for multiple sentence text (Buettner et al, 1985). However, reading speeds for normally sighted subjects reading from scrolled displays have been found to be between 15 and 44% slower than those from similar length standard page text (Buettner et al., 1985; Legge et al., 1989a). When reading from a scrolled display, optokinetic nystagmus (OKN) is elicited with the fast phase of OKN behaving like a saccade (Whittaker et al., 1991). For normally sighted readers, when compared to standard page reading, Buettner et al. (1985) found average fixations were longer and saccade length was shorter when reading from a scrolled display. In contrast, vision impaired readers have been shown to read slightly faster from a scrolled display than from a standard page of text (Legge et al., 1989a). Authors have attributed the lack of need for a return sweep as one reason vision impaired observers benefit from scrolled displays. If reading large print text, a vision impaired reader must make substantially more return sweeps than a normally sighted reader reading the same text but of standard book sized print. Also, vision impaired subjects, in particular those with central field loss, have reduced accuracy and velocity of eye movements (McMahon et al., 1991; Whittaker et al., 1991). This would result in an increase in the time required for the return eye movement at the end of each line. Therefore, the time saved by eliminating the need for a return sweep would be substantially greater for the vision impaired readers compared to the normally sighted readers. In addition, scrolling text does not allow a reader to plan their eye movements relative to the linguistic content of the text in the same way they can with standard page text. This may be a detriment to reading for a normally sighted reader who is able to actively plan where their next saccade will land, but is restricted by the stimulus-driven pattern of the OKN eye movement (Fine & Peli, 1995). In contrast, a vision impaired observer who has problems with eye movement control (Peli, 1986; Timberlake et al., 1987; Rubin & Turano, 1994), would benefit from the lack of saccade control required for the fast phase of OKN compared with normal saccades (Fine & Peli, 1995).

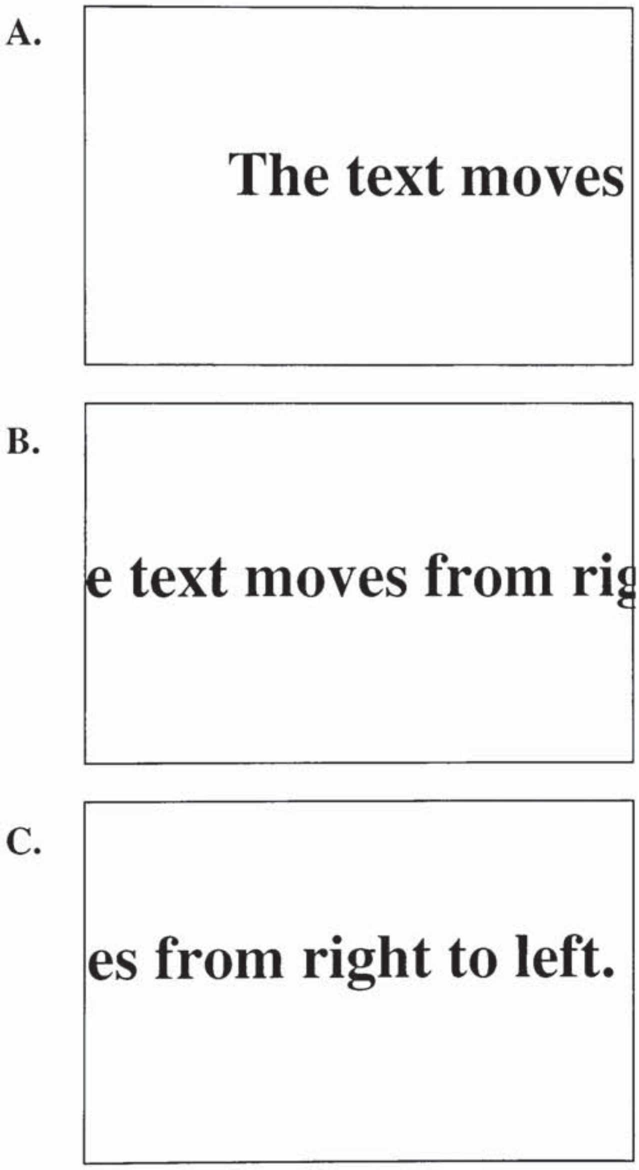


Figure 2.4. A figure of scrolled text, depicting the movement of text from right to left. A, B, and C show the text position at three consecutive moments in time.

2.4.3 Rapid Serial Visual Presentation (RSVP)

RSVP is a display format in which each word is displayed sequentially at the same place on a computer screen (Forster, 1970) (Figure 2.5). The 'standard' RSVP method introduced by Forster (1970) (and the method used in the studies described in this thesis) is where each word is presented for an equal duration. However, presentation times can be varied for each word, can be adjusted by the reader (Arditi, 1999), or inter-stimulus intervals or masks can be used (Potter, 1984). The need to plan and execute eye movements during reading has the potential for limiting reading speed (Rubin & Turano, 1994). RSVP however, is a method of reading that is able to minimise the need for eye movements.

Reading speeds for RSVP reading are substantially faster than standard page reading, for both normally sighted (Forster, 1970; Rubin & Turano, 1992) and vision impaired readers (Rubin & Turano, 1994). Reading speeds upwards of 1000 wpm have been recorded for normally sighted readers reading single sentences (Forster, 1970; Turano & Rubin, 1988; Rubin & Turano, 1992; Latham & Whitaker, 1996). For the vision impaired, Rubin & Turano (1994) found that the benefit of RSVP over page text reading speeds for vision impaired readers without central field loss (CFL) (200% increase), was greater than that found for readers with CFL (50% increase). The difference between the two groups could be due to the fact that the CFL readers used small intra-word eye movements, the execution of which would be expected to slow reading.

Fine & Peli (1995) compared reading speeds for normally sighted and vision impaired observers when reading scrolled and RSVP text. They found that normally sighted subjects obtained faster reading speeds with RSVP than with scroll text. However, their vision impaired subjects read from the RSVP display and the scroll text display at similar speeds. Eleven of their 16 subjects had CFL, and Fine & Peli (1995) suggested that the small intra-word saccades made by the CFL subjects when reading with RSVP would reduce reading speeds. They also state that the lack of control required for the eye movements elicited by the scroll display (Whittaker et al., 1991), may increase scroll reading speeds relative to those for RSVP.

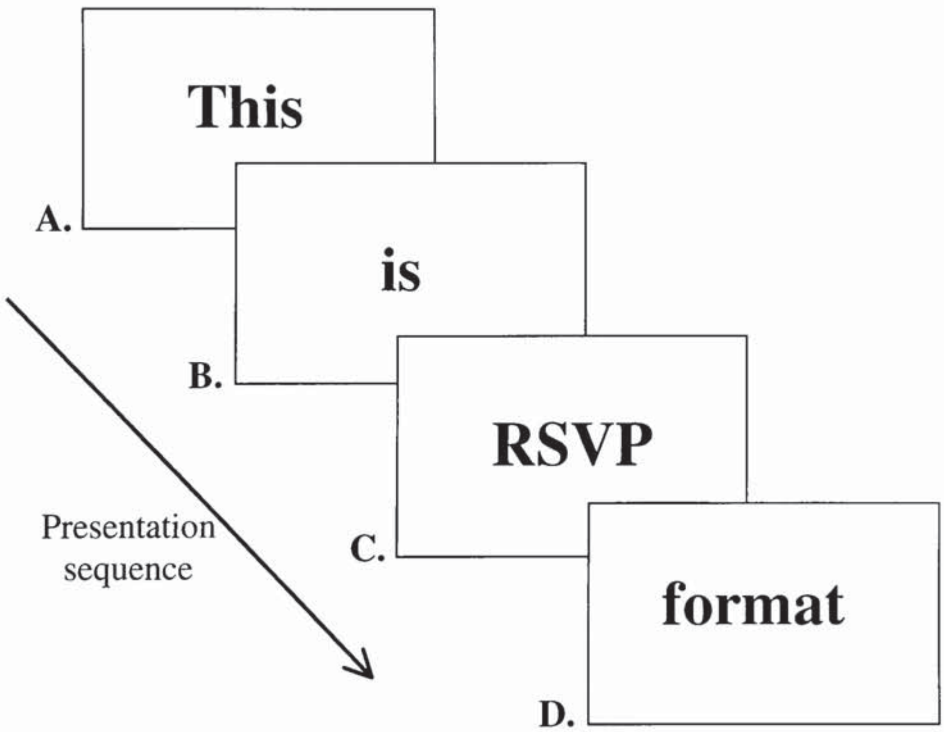


Figure 2.5. Representation of rapid serial visual presentation (RSVP) as it appears to the reader over consecutive frames. Each word is displayed sequentially at the same place on a computer screen.

2.5 FACTORS AFFECTING READING PERFORMANCE

It is common for most vision impaired people to have more difficulties reading and consequently slower reading speeds than normally sighted observers. Inappropriate imaging on the retina or retinal pathology both result in poor resolution of detail (due to reduced visual acuity or contrast sensitivity) or restricted field of view (Krischer & Meissen, 1983). A number of studies have investigated the specific factors influencing reading performance of the vision impaired as a means to either predict and/or maximise potential reading performance in vision impaired patients. This question has been investigated in different ways. Some studies have looked at the effect of physical text variables such as print size or contrast. on reading speed, whilst other studies have investigated the effect of visual variables such as visual acuity, contrast sensitivity, the presence of scotomata and the field of view. For clinicians however, it is also of interest to know whether there are any clinical predictors of reading speed. such as visual factors, age or low vision aid use. Studies have therefore also investigated groups of factors to determine if any of these factors in particular are more important in determining reading speed than others. Any resulting factors could therefore be considered more carefully in a low vision assessment. The following sections look at the different studies that have investigated the factors affecting reading performance.

2.5.1 The Effect of Physical Text Variables on Reading Speed

Reading speed in vision impaired subjects (as well as normally sighted subjects) is sensitive to variations in physical properties of the text such as size and contrast (Prince, 1957; Legge et al., 1985; Lovie-Kitchin & Woo, 1987; Lowe & Drasdo, 1990; Beckmann & Legge, 1991; Raasch et al., 1991). The effect on reading speed of changing print size and print contrast can be recorded as characteristic functions. These functions are described below.

Print Size

The variation of reading speed with size of print can be depicted by a reading speed plot similar to that shown in Figure 2.6. Figure 2.6 reveals that at smaller print sizes, reading speeds decrease with reducing text size, until a threshold text size makes reading impossible. At the larger print sizes, reading speeds remain reasonably constant, forming a 'plateau' of values. If the character size is increased further however (not shown in Figure 2.6), reading speeds have been found to reduce again (Legge et al., 1985), thus indicating a limit to the benefit of magnification on reading performance. None of the studies described in this thesis used character sizes large enough to reduce reading speeds to below the maximum plateau reading speed. Inspection of the reading-speed plot will enable both the maximum reading speed (in wpm), and the smallest print size that could be read close to the maximum reading speed (critical print size or CPS) to be estimated. Alternative methods of determining reading speed variables, include fitting the data with a curve fit (Latham & Whitaker, 1996), 2-line fit (Legge et al., 1985; Chung et al., 1998) or plateau fit (Mansfield et al., 1996).

A 'curve fit' method, as used by Latham & Whitaker (1996), fits a curve of the following form to the data.

$$\text{Reading rate (wpm)} = k_1 \times (1 + ((k_2 - k_3)/(\text{text size} - k_3)))^{-1} \qquad \text{Equation 2.1.}$$

where:

k_1 = maximum reading speed

k_2 = the text size at which reading rate is half its maximum

k_3 = the text size at which reading rate tends to zero

It is shown in Figure 2.7.

The 'two-line fit' consists of a raising straight line and a second straight line with the slope fixed as zero (Figure 2.8). It has the form:

$y = a + bx$ if $x <$ critical print size.

$y = c$ if $x >$ critical print size.

The co-ordinates of the intersection of these two lines determine the maximum reading speed (Y-co-ordinate) and the critical print size (X-co-ordinate) (Legge et al., 1985: Chung et al., 1998).

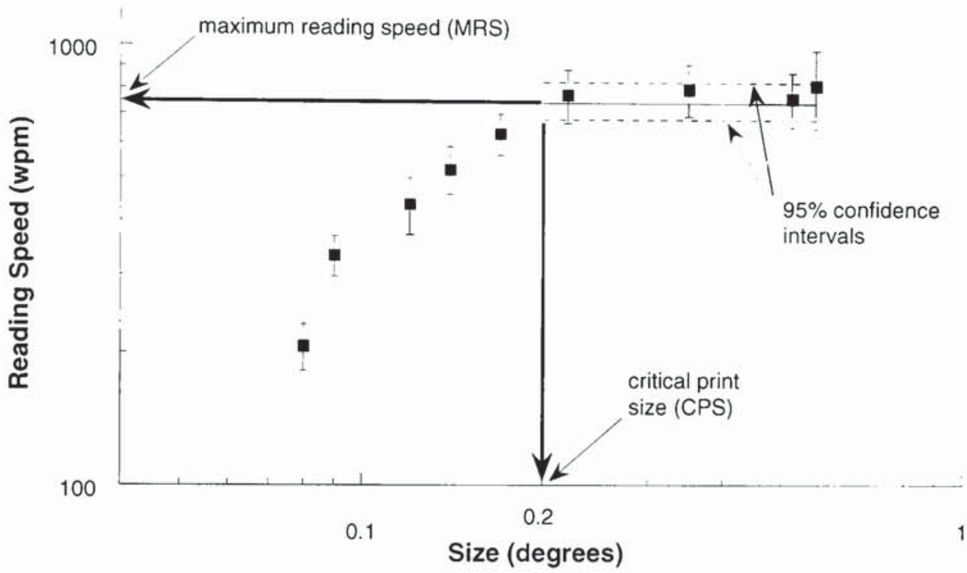


Figure 2.6. Reading speed (wpm) as a function of print size (degrees). The solid line is the maximum reading speed calculated using the algorithm by Mansfield et al. (1996). The dotted lines are the 95% confidence intervals for the maximum reading speed. The critical print size is the smallest print size along the maximum reading speed line.

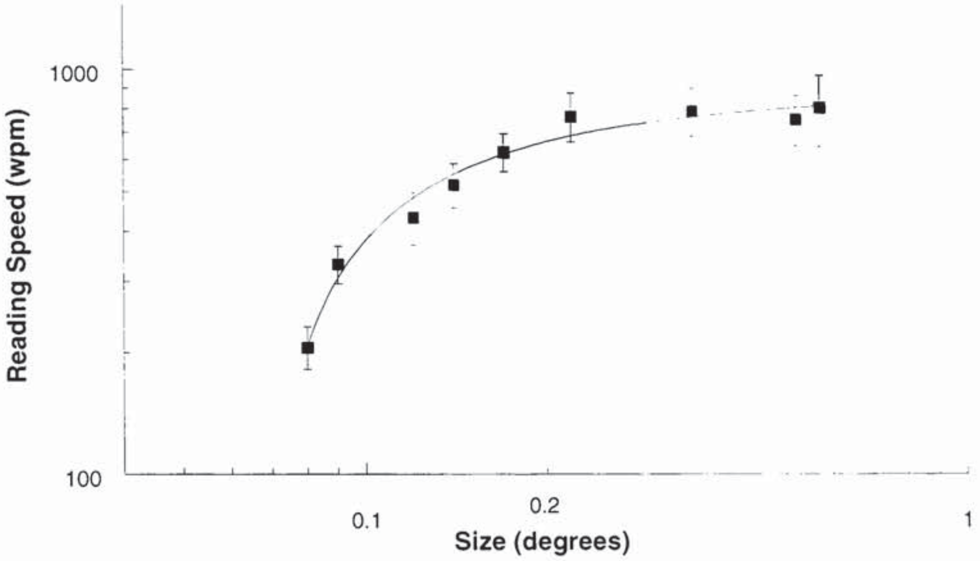


Figure 2.7. The same data as in Figure 2.6 plotted with the 'curve fit' method as used by (Latham & Whitaker, 1996). The plot is reading speed (wpm) as a function of print size (degrees).

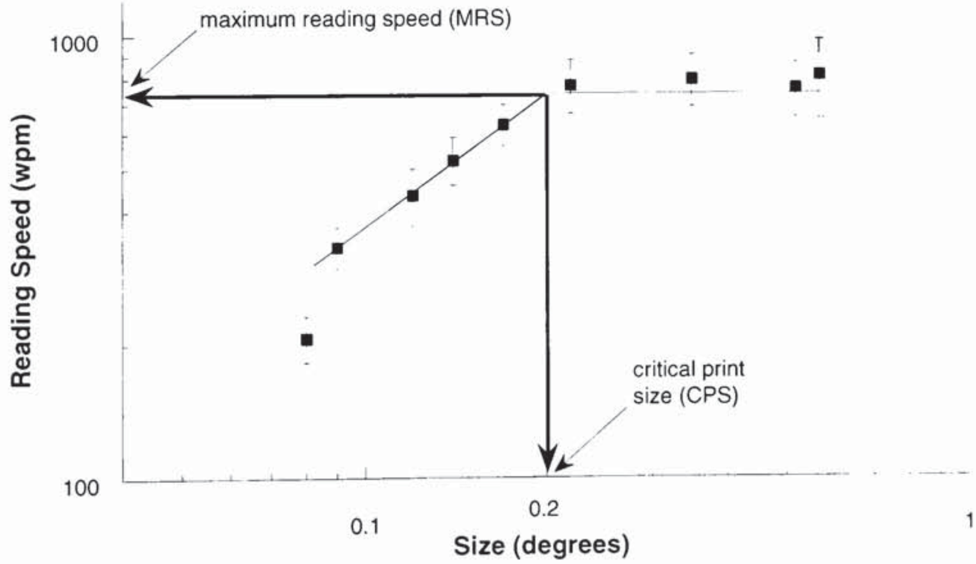


Figure 2.8. The same data as in Figure 2.6 plotted with the 'two-line fit' as used by Legge et al. (1985) and Chung et al. (1998). The plot is reading speed (wpm) against print size (degrees).

Reading–speed plots similar to that shown in Figure 2.6 are presented in Chapters 7, 9 and 10 of this thesis. The data in these chapters has been analysed using an algorithm developed by Mansfield et al. (1996), which fits a single plateau line to the data (i.e. a plateau fit). The algorithm identifies the reading speed plateau by comparing the mean reading speed of a range of character sizes to the maximum reading speed in that range. The range is extended until it contains a reading speed that differs from the maximum by 1.96 standard deviations or more. The largest range not including such a value is taken as the range of character sizes for which is found a maximum reading speed (MRS). The maximum reading speed is the geometric mean of the reading speeds in the selected range, and is shown by the solid line in Figure 2.6. The smallest print size included in the maximum reading speed range is the critical print size (CPS), or the size below which reading speed falls below the maximum. The critical print size is dependent on the sampling density of the character sizes used. In the studies described in Chapters 7, 9 and 10 of this thesis we used print sizes in 0.1 log unit steps. A non-parametric bootstrapping procedure determines 95% confidence intervals for the value of maximum reading speed and critical print size (Mansfield et al., 1996). The dotted lines in Figure 2.6 show the 95% confidence intervals for the maximum reading speed.

The plateau fit method described above was chosen for the analyses of the data in this thesis because it has its advantages over the curve fit and two-line fit methods of fitting reading speed versus print size data. Even though the plateau fit method uses all the data from smaller print sizes in the calculation of the position of the CPS, it does not put as much emphasis on this data as the 2-line fit and the single curve fit do. This is an advantage, as the CPS value in the plateau fit method is therefore less dependent on the variable results of reading speed that occur close to the acuity limit. Small variations in reading speed at print sizes near the acuity threshold have great influence over the CPS value in the 2-line fit method. They also influence both the CPS and MRS values in the single curve fit method (Mansfield et al., 1996).

Text Contrast

The effect of text contrast on reading speed can be shown with a reading speed-text contrast plot of a similar form as the reading speed-text size plots described above (Legge et al., 1987; Rubin & Legge, 1989). Legge et al. (1987) measured reading speeds for both static and drifting text of varying contrasts. For each contrast, the maximum reading speed was determined when the subject first began to make errors. Subjects read drifting text at 3 character sizes (0.25, 1 and 12 degree letters), and static text at 0.5 degree. As a separate experiment, when reading text of similar character sizes, data for drifting and static text of two subjects was found to be similar. Figure 2.9 shows reading speed as a function of contrast for two subjects reading three different character sizes. At high contrasts, there is little if any reduction in reading speed with reduction of contrast. The data for the 1 degree characters forms a plateau of reading speeds at these higher text contrasts. At lower contrasts, there is a sharp drop in reading speed with reduction in letter contrast. The contrast at which reading speed has dropped to one half of the maximum value is referred to as the *critical contrast*. It is an indication of the observer's tolerance to contrast reduction. The data also shows that character size interacts with contrast in their effect on reading. Reading speeds for the smaller characters (0.5 degrees), and also the larger characters (12 degrees), are more affected by reductions in contrast than the 1 degree characters. Legge et al. (1987) suggested that this would provide a reason to expect that contrast may play a more critical role for the vision impaired who require large characters to read.

In a later study, Rubin & Legge (1989) measured the effect of contrast on reading speeds for 19 low-vision observers with a wide range of visual disorders and degrees of vision loss. Figure 2.10 shows the data for four vision impaired observers reading text of 6 degree characters. From the data, the dependence of reading speed on contrast appears to vary widely across vision impaired observers. For large text (6 degree letters), some vision impaired subjects were as tolerant to contrast reduction as normal subjects (Observer R). Others are highly sensitive to even a slight reduction in contrast (Observer D). Rubin &

Legge (1989) reported that the degree of sensitivity was not determined by the eye disease nor the type of vision loss. In fact, the effects of contrast on low vision reading were found to be closely related to contrast sensitivities of vision impaired observers. Rubin & Legge (1989) suggested that practical implications of this finding were that determining the benefit a vision impaired observer will gain from contrast-enhancing low vision aids could be determined simply by measuring their peak contrast sensitivity. Conversely, the same measurement would be able to predict which observers would suffer most under poor contrast conditions.

Figure 2.9. Oral reading speed of drifting text as a function of contrast for three character widths. Solid symbols refer to dark letters on a light background and open symbols refer to light letters on a darker background. Letter contrasts are given in Michelson contrast. Taken from Legge et al. (1987).

Figure 2.10. Reading speed as a function of contrast for four normal observers. Observer D: Optic neuropathy; Observer F: Age-related maculopathy; Observer L: Optic nerve hypoplasia; Observer R: Congenital cataract. The solid line represents the average data for three normal observers. Letter contrasts are given in Michelson contrast. Taken from Rubin & Legge (1989).

2.5.2 Visual Factors and their Effect on Reading Speed

The section above describes how text characteristics can be varied in terms of size and contrast, in order to see the effect of these changes on reading speed. In the following section, it is shown how reading ability can vary with clinically measured visual function.

Whittaker & Lovie-Kitchin (1993) defined the significant visual factors most likely to cause a problem for patients with regards to reading speed. From a review of the published literature, the visual factors chosen were: 1. Acuity reserve; 2. Field of view; 3. Central scotoma size; 4. Contrast reserve. Understanding how these factors affect reading enables manipulation of the text to ensure optimum performance. Clinically, it suggests visual function tests that should be emphasised within the scope of an eye examination in order that optimum reading performance be predicted. These four factors are discussed in turn below.

Visual Acuity (and Acuity Reserve)

The clinical low vision examination emphasises the measurement of visual acuity. Visual acuity provides an estimate of the smallest characters that can be read, usually at high contrast (Chapter 4). However, maximum reading speed usually occurs for characters much larger than the acuity limit (Legge et al., 1985). A number of studies have shown either no link (Goodrich et al., 1977; Brown, 1981; Legge et al., 1989b), or a weak link (Sloan & Habel, 1973; Krischer & Meissen, 1983; McMahon et al., 1991; Legge, 1991; Legge et al., 1992) between reading speed and distance or near visual acuity.

All of the authors cited above agreed that the low correlation between visual acuity and reading speed could be explained by the multifactorial nature of reading speed determination. The visual demands of a single letter acuity task also differ in a number of ways from those of fluent reading (Legge et al., 1985). In addition, from the reading speed-text size plots discussed above (Chapter 2.5.1), it can be seen that speed and size are distinct modalities since the slope and length of the initial response to magnification are not fixed. It is therefore unlikely that speed and acuity would be strongly related.

As visual acuity is a poor predictor of reading speed, Whittaker et al. (1988) investigated the effects of the print size relative to visual acuity; i.e. acuity reserve. Although considerable variation in optimum acuity reserve was seen, generally decreasing acuity reserve below 3:1 significantly depressed reading speeds, and maximum speeds were achieved between acuity reserves of 6:1 to 18:1. Legge (1991), Beckmann & Legge (1991) and Raasch et al. (1991) found similar results.

Field of View

Whittaker & Lovie-Kitchin (1993) defined the field of view as the number of characters visible at a single fixation. Also called the 'visual span', it can be described as the number of characters visible on either side of the point of fixation (O'Regan, 1990). It is determined by interactions of print size, low vision aid characteristics, and the presence of visual field defects (Whittaker & Lovie-Kitchin, 1993). It is a measurement that can be investigated by varying physical window sizes (horizontal field) and noting the effect on reading performance (Duchnicky & Kolers, 1983: Lovie-Kitchin & Woo, 1988). It is important to note however, that this view of the visual span differs from the concept of the 'perceptual span' (McConkie & Rayner, 1975; Rayner & McConkie, 1976). The 'perceptual span' takes into consideration the functional demands of reading, including detection of word length and spacing, in addition to letter recognition. It is therefore bigger than the visual span and is the area used to plan the next saccade. As such, a comparison of perceptual span with visual span or field of view cannot be made, however, the results of studies looking at both types of measure are described in the sections below. Studies that require the subject to read static text using page navigation can be considered to be measuring perceptual span, whilst studies using scrolled or RSVP format text or letter strings are measuring visual span.

Studies investigating the size of the visual span have done so by determining the window width (the horizontal width of characters visible) that results in maximum reading speeds. Legge and co-workers (Legge et al., 1985: Legge et al., 1985) found that for scanned text, increasing the field size above 4 characters did not increase the reading speed regardless of character size. Legge et al. (1997a) used the RSVP method and random word strings of 4 words to determine the size of the visual span to be 10 letters for 1 degree characters and five letters for 6 degree characters.

From their investigations of the size of the perceptual span, Rayner et al. (1980) found that 3-4 characters were needed to the left of fixation and 15 characters to the right of fixation to achieve best reading performance. Rayner et al. (1981), using variable window sizes and static text, found that reading performance improved with increasing window size. When the field was 29 characters, reading speed was similar to that when the entire line was visible. In contrast, Beckmann & Legge (1991) found that a minimum field of 5 characters was necessary for 75% maximum reading speed, when page navigation was required of their CCTV readers.

In studies where readers moved a magnifier across text (Lovie-Kitchin & Woo, 1988; Lowe & Drasdo, 1990), reading speeds of normally sighted subjects increased until the field of view reached between 15 and 24 characters. However, Lovie-Kitchin & Woo (1988) found a wide variability in results for their vision impaired subjects depending on reading skill, eye pathologies, and the subject's ages. Varying the field size (number of characters) had an effect on the reading speed of some of their vision impaired observers but not others. Their results led them to suggest that minimum magnification and maximum field size allowed vision impaired patients who were good readers to achieve maximum reading speeds; whereas slower vision impaired readers would improve at higher magnifications despite reduced field sizes. Nevertheless, these findings reveal a large discrepancy in the suggested field of view requirements for maximum reading speeds. Whittaker & Lovie-Kitchin (1993) suggested that these differences depended on whether or not the reader controlled the speed of presentation of the text. As well, these alternatives were complicated by different navigational demands. In order to rationalise these differences Beckmann & Legge (1996) compared optimum window widths for three criterion reading speeds using CCTV and drifting-text. They found that the drifting text reading speeds were higher at all window widths than the CCTV speeds. For CCTV reading, normal subjects had window requirements that were more than 3 times larger than for drifting text, and for vision impaired subjects, this factor was 1.5-2. The effect of page navigation was therefore not only to slow down reading, but also to introduce a stronger dependence on window width. Beckmann & Legge (1996) also compared these results with the CCTV data reported by Lowe & Drasdo (1990) and Lovie-Kitchin & Woo (1988). When the distinctions between these studies were taken into account, Beckmann & Legge (1996) found that the results were remarkably similar. The results suggested that for a CCTV magnifier, reading speed increased approximately as the square root of the window width up to 20 characters and then levelled out.

Therefore, the large discrepancy between studies with regards to optimal window sizes can mostly be explained by the type of reading task. Factors such as page navigation and whether or not the reader can manually control text speed will greatly affect the results. In addition to this, experimental designs do not always state clearly whether the reading task enables measurement of the visual or perceptual span, two distinctly different measurements. The wide spectrum of abilities and characteristics of vision impaired readers would also be expected to contribute to the variability in the low vision data.

Central Scotoma

A number of studies have investigated the effect of a central scotoma on reading performance. The effect of a central scotoma is not only to force the reader to use more peripheral areas of retina, but to also restrict the field of view (Whittaker & Cummings, 1990).

Whittaker & Cummings (1990) found that the state of the central field was the best predictor of the reading speed of vision impaired patients. Similarly, a retrospective study by Cummings et al. (1991) found reduced performance from patients with macular pathologies. Analysis revealed that restrictions in the field of view and eccentricity of fixation (related to the size of the central scotoma) accounted for 72% of the variance in reading speed.

All studies agree that average reading speeds of patients with maculopathies are lower than those of normally sighted patients. Cummings et al. (1985) found that using the Pepper Visual Skills for Reading test, reading speeds of subjects with maculopathies (0-60 wpm) were lower than those of normally sighted subjects (80-120 wpm), even though character size was increased to compensate for subjects' losses in visual acuity.

As well as the presence of a central scotoma, increasing the eccentricity of the retinal locus used for fixation results in a progressive reduction in reading speed (Rayner & Bertera, 1979; Cummings et al., 1985; Cummings et al., 1990; Cummings et al., 1991; Legge et al., 1992; see also Whittaker & Lovie-Kitchin, 1993). Cummings et al. (1990) measured the reading speed and accuracy of patients with central field restrictions. They found that the variance in reading speed was mostly explained ($r^2 = 0.76$) by the integrity of the right reading field and the eccentricity of fixation.

Studies that have simulated a scotoma in normally sighted subjects have shown similar results. Rayner and co-workers (Rayner & Bertera, 1979; Rayner et al., 1981) obliterated foveal vision using a mask that moved in synchrony with the eye. They found that reading speeds slowed and there were fewer correctly reported words as masked size increased from 1 to 17 characters in size. In addition, after considering the work of Rayner and co-workers (Rayner & Bertera, 1979; Rayner et al., 1981), Fine & Rubin (1998) matched the number of letters masked across several mask sizes, and compensated for reduced peripheral acuity. They found that the number of letters masked accounted for more of the variance in reading speed than the size of the mask in degrees. Cummings & Rubin (1991) compared the effect on reading speed of a central scotoma with that of a scotoma located elsewhere in the visual field. They simulated a 6 degree scotoma in normally sighted subjects and found a scotoma centred on the fovea slowed reading speeds more than a scotoma displaced either horizontally or vertically from fixation.

A central scotoma forces patients to develop different strategies for reading. Studies have shown that the majority of patients with a central scotoma use one eccentric retinal locus where they position characters of interest onto the retina (von Noorden & Mackensen, 1962; Cummings et al., 1985; Timberlake et al., 1986; Timberlake et al., 1987; Guez et al., 1993). This area of retina is known as the 'preferred retinal locus' or PRL (Cummings et al., 1985), and there is evidence that a PRL can be trained (Nilsson et al., 1998). Studies have shown however that some patients use more than one PRL for fixation (Cummings et al., 1985; Whittaker et al., 1988; McMahon et al., 1991; Trauzettel-Klosinski et al., 1994; Lei & Schuchard, 1997). More specifically, different loci can be used to identify two different targets (Guez et al., 1993; Trauzettel-Klosinski et al., 1995) or even under different stimulus luminances (Lei & Schuchard, 1997). In addition to the eccentricity of the PRL, its location with respect to the scotoma can affect the reading performance (Cummings & Rubin, 1992; Duret et al., 1999) (see also Chapter 7). It has also been suggested that patients do not always choose an optimal PRL (Timberlake et al., 1987) with regards to achieving optimal reading performance. The effect of PRL location within the visual field on reading performance is investigated in the study described in Chapter 7 of this thesis.

Contrast (and Contrast Reserve)

The effects of print contrast on reading speed will depend on the subject's contrast threshold. Therefore, Whittaker & Lovie-Kitchin (1993) suggested *contrast reserve* as the relevant visual factor. Contrast reserve is calculated as the ratio of print contrast to a person's contrast threshold. Vision impairment can result in poor overall contrast sensitivity. As well as degrading visual acuity, media opacities and several retinal diseases also reduce contrast sensitivity over a range of spatial frequencies (Brown, 1981; Rubin & Legge, 1989). Also, central scotomata force the use of more peripheral retinal areas, which are known to have poorer contrast sensitivity (Chapter 4). When contrast sensitivity is reduced, for a set print contrast, contrast reserve decreases. As a result, if the contrast reserve is reduced below a critical level, small reductions in letter contrast can significantly reduce reading performance (Brown, 1981; Rubin & Legge, 1989; De Luca et al., 1995). From their review of the literature, Whittaker & Lovie-Kitchin (1993) suggested a letter contrast of less than 10 times contrast threshold (contrast reserve of 10) would reduce fluent reading speed. For spot reading tasks, a contrast reserve of at least 3 was recommended.

Rubin & Legge (1989) measured reading speeds as a function of contrast in 19 vision impaired observers. They recorded the contrast at which reading speeds declined to half their maximum values (referred to as the *critical contrast*) and found them to be approximately 3.9 times higher than results obtained in a similar experiment Legge et al. (1987) using normally sighted subjects. Whittaker & Lovie-Kitchin (1993) normalised the letter contrasts used by Rubin & Legge (1989) for the critical contrast condition and the maximum reading rate condition to contrast reserve, and compared them with average performance of normally sighted observers in the study of Legge et al. (1987). The results showed that under the critical contrast condition, a few vision impaired subjects actually had faster reading speeds than normally sighted subjects reading with comparable contrast reserve. However, the performance of most vision impaired subjects was well below normally sighted subjects, especially with higher contrast reserves. Similarly, using lines of common words, Brown (1981) found that even small reductions of contrast caused slower CCTV reading speeds for most of his vision impaired observers. However, to some extent, he observed that reduced performance due to reduced contrast could be offset by increased magnification. This observation needs to be tested quantitatively, however, it stands to reason when considering the contrast sensitivity function as dividing size x contrast space into visible and invisible stimuli (Figure 2.11).

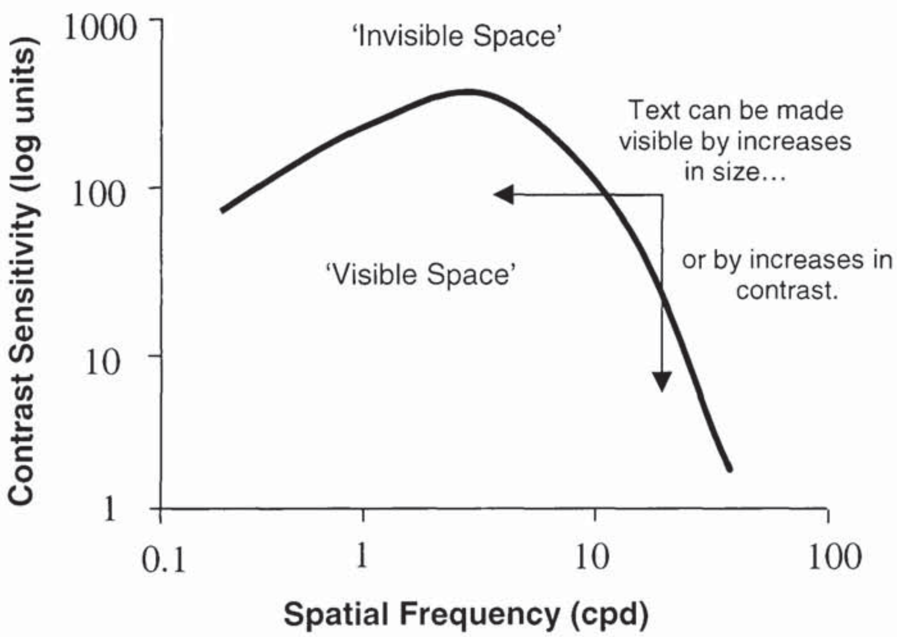


Figure 2.11. The contrast sensitivity function delineates an 'area' of contrast and object size (spatial frequency) in which objects are visible – 'visible space'. An object outside this area can be made visible by increasing the contrast or increasing object size (angular subtense) or both, to move it into 'visible space'. Adapted from Wolfe (1990).

Rubin & Legge (1989) observed that the degree of sensitivity (in terms of changes in reading speed) was not determined by the type of vision loss but instead appeared highly predictable from the measures of contrast sensitivity for letters. Hence, contrast effects on vision impaired reading were closely related to contrast sensitivities of vision impaired observers. They concluded that the dependence of reading on contrast had the same form as normal observers if scaled appropriately for the contrast attenuation caused by optical factors such as intra-ocular scatter, or a reduction in the effective contrast in eyes with field loss. They also concluded that an overall reduction in an observer's contrast sensitivity had a greater effect on reading performance than small depressions in sensitivity at particular spatial frequencies. This suggests that a simple measure of peak contrast sensitivity is all that is required to predict reading performance.

Contrast polarity is also an aspect of contrast that is important to vision impaired readers. The use of CCTV systems enables the reversal of contrast polarity from positive (black letters on white background), to negative (white letters on black background). High positive contrast may cause halation and thus reduce letter stroke width, while negative contrast reduces flicker and glare. Legge et al. (1985) found that vision impaired subjects with cloudy media usually read print with negative contrast better than with positive contrast. Also, when shown the difference between contrast polarity, subjects usually preferred negative contrast rather than positive contrast Lovie-Kitchin & Woo (1988).

In summary, studies suggest that vision impaired observers are highly sensitive to reductions in text contrast. However, contrast sensitivity needs to be considered in relation to the print contrast as well as print size in order to correlate with reading performance.

2.5.3 Clinical Predictors of Reading Speed

The previous section described how changes in different visual functions affect reading speed. Clinically, it is of benefit to understand if any of these factors have a greater effect on reading performance than others. It is clear that vision impaired readers, due to the nature of their visual loss and the need for any special low vision aids, show individual reading characteristics and need to adopt specific reading strategies. The numerous types of vision defects and their effects on vision adds to the impracticality of attempting to predict the reading characteristics of vision impaired people as a whole. Studies have investigated, however, whether any particular visual function characteristics are better at predicting reading performance than others. If particular visual functions exist, it is possible that links could be made between reading performance and the nature of the underlying ocular problem; i.e. refractive anomalies, macular degeneration or other diseases.

Krischer & Meissen (1980) suggested that the quality of the functioning retina was an important variable that influenced speed. Their results were supported by Krischer et al. (1985), who investigated reading speed with scrolled text as a function of an opto-kinetic nystagmus measure of acuity. As cited previously, a number of studies have shown little or no link between reading speed and visual acuity (Chapter 2.5.2). However, Krischer et al. (1985) found that for their vision impaired subjects as a whole, a linear relation was demonstrated between their measure of visual acuity and reading speed for subjects with visual acuities below 15% of normal (less than approximately 6/40). When subdivided into diagnoses, the slopes of regression lines relating reading speeds to acuity were termed *reading expectance factors*. Higher values (steeper slopes) corresponded to better reading performance for a given visual acuity. These factors were found to have different values for different diagnoses suggesting the ability to predict reading performance from visual acuity and diagnosis. For example, refractive anomalies, retinal diseases and glaucoma had high expectance factors of 4.7 to 5.5, suggesting relatively large increases in reading speeds for small increases in visual acuities. In contrast, macular disease had a lower reading expectance factor of 3.3. Only the reading performance of cataract patients appeared to show no dependence on visual acuity.

Legge et al. (1985) found two principal factors that affected vision impaired reading. These were whether or not the central visual fields were intact and the degree of optical clarity of the ocular media. Using scrolled text, they determined that these two variables accounted for 64% of the variance between peak reading speeds in vision impaired readers.

More recently however, Legge et al. (1992) carried out a large-sample study (N = 141) to test whether or not a set of clinical measures (Snellen acuity, status of central visual fields and ocular media, diagnosis, and age) could be used in a clinical setting to predict reading speed of static text presented on a computer screen. In contrast to the earlier study by Legge et al. (1985), the set of clinical predictors accounted for only about 30% of the variance in low vision reading speeds. Snellen visual acuity accounted for only 8% of the variance on reading speeds overall, but played a more important role for subjects with central visual field loss. Even so, for a given visual acuity, there was a large variability in reading speeds.

To explain the discrepancy between the two studies, the authors suggested that the clinical and research opinion that central loss is prognostic of poor reading may have been a result of self selection. People with small scotomata are unlikely to seek help from a clinician and thus do not tend to become part of research studies. Also, characterising scotomata as merely present or absent may be over simplifying the situation. Factors such as the eccentricity of fixation (Chapter 9) or the location of fixation within the visual field and with respect to the scotoma (Chapter 7) are also important.

To further explain the differences between the two studies, Legge et al. (1992) suggested that the results of Legge et al. (1985) may not be applicable to the clinical prediction of reading speeds. Non-visual factors such as motivation and cognitive skills will contribute more variance in a clinical study of reading performance than in their laboratory study that attempted to minimise these factors. Also, the subject sample in the original study was small (n = 16) with many of the subjects under 30 years old which is unrepresentative of the vision impaired population at large.

In view of the fact that their clinical predictors were unable to significantly predict vision impaired reading speed, Legge et al. (1992) suggested that a standardised clinical measure of reading speed may be necessary to accurately predict real-world reading function. This was tested in a study by Ahn & Legge (1995). They investigated a set of clinical parameters to see how well they could predict reading performance of vision impaired subjects when reading with their own magnifiers. They found that the score on a standardised test of reading speed (Minnesota Low-vision Reading Test (MNREAD)) was the best predictor of magnifier-aided reading speed of a variety of tests, and accounted for 79.7% of the variance. Age accounted for 43.7% of the variance, and magnifier type accounted for 42.3%. Similar to the results of Legge et al. (1992), Snellen acuity, central visual field status and ocular media status were not significantly correlated with magnifier-aided reading speed.

After investigating the effect of magnification and field of view on reading speed using CCTV, Lovie-Kitchin & Woo (1988) concluded that reading speed was an individual characteristic of vision impaired patients. It must be noted however, that reading speed is also an individual characteristic for normally sighted readers independent of visual acuity. It is clear therefore that numerous factors contribute to the overall performance attained.

The inconclusive results reflect the variable nature of visual function in vision impaired patients. Although some results do suggest a link between reading performance and diagnosis, the degree to which various factors are affected is still unclear. It is difficult to compare results between studies due to the various methods (e.g. scrolled text, page text, RSVP) of reading employed, which make different demands on the visual system and have been shown in the previous section to produce different reading performances (Rubin & Turano, 1994; Fine & Peli, 1996). The broad spectrum of abilities and characteristics of vision impaired patients as a whole can also make the choice of an optimum sample population difficult. Moreover, the use of an atypical sample population will ultimately bias the results obtained. It is clear that many factors could be considered to affect the results, thus contributing towards the inconsistencies in these findings.

2.6 SUMMARY

Research studies agree that reading is a complex and multifactorial process, involving both sensory and cognitive skills. Deficits or problems in either of these areas can cause difficulties in reading performance. This thesis is concerned with the effects of sensory deficit on reading performance, in particular the effect of central field loss. Reading performance can be affected by the readability of the text directly, through text characteristics such as size, contrast and field of view. In addition, the appearance of the text, and therefore its readability can also be affected by ocular factors induced by eye disease and degeneration. Hence the effect of text factors and ocular factors combine to determine reading performance which can be defined in terms of reading speed, comprehension and/or eye movement patterns.

Chapter 3

PERIPHERAL VISUAL STRUCTURE AND FUNCTION

3.1 INTRODUCTION

When foveal vision is compromised as a result of an ocular disorder, the task of reading becomes a difficult and frustrating one (Faye, 1984; Legge et al., 1985). Teaching a person with central field loss to read with peripheral vision is a time consuming and not always successful task. It is well known that even with the use of magnification to compensate for poorer peripheral acuity, reading performance still remains below that achievable with an intact central field (Cummings et al., 1985; Legge et al., 1985; Turano & Rubin, 1988; Whittaker & Lovie-Kitchin, 1993; Higgins et al., 1996). Understanding why reading is slower in the peripheral visual field is important in the rehabilitation of this large number of patients. In order to do this it is necessary to understand the differences between foveal and peripheral vision in terms of their anatomy and physiology as well as their psychophysical performance. The purpose of this chapter is therefore to outline the anatomy of the retina and visual pathway, comparing foveal and peripheral neural arrangement. At the retinal level, the neural arrangement can then be compared to psychophysical observations of foveal and peripheral visual performance.

3.2 ANATOMY OF THE RETINA AND THE VISUAL PATHWAY

3.2.1 The Visual Pathway

The retina is necessary for the formation of images, which are then interpreted by the brain. In the emmetropic eye, light enters the eye through the cornea and pupil and is focussed to a clear image on the retina. Light energy is transformed to a neural signal by the photoreceptors, and this signal passes to the ganglion cells. Travelling out of the eye via the optic nerve, 90% of the fibres carry the light signal through the optic chiasm, on to the lateral geniculate nucleus (LGN) and then up the optic radiation to the striate cortex. The remaining 10 % of the fibres travel to the cortex via the superior colliculus (Perry et al., 1984; Snell & Lemp, 1989).

At the level of the retina, the anatomical differences with eccentricity correlate well with psychophysical and functional observations of vision. These anatomical details are described in the following sections. There are distinct differences in both the relative numbers and arrangements of the cells in the foveal and peripheral retinal areas that define the visual performance obtained. At higher levels of the visual pathway, correlates between anatomical traits and psychophysical observations of central and peripheral vision are less well documented.

3.2.2 Retinal Anatomy

The retina is a delicate tissue, which measures about 0.1 mm in thickness at the ora serrata, 0.2 mm at the equator and 0.56 mm adjacent to the optic nerve head. The internal aspect of the retina is in contact with the vitreous and the external aspect is adjacent to the retinal pigment epithelium. The retina consists of a number of layers of neurons that terminate (except for the nerve fibre layer) at the optic nerve head. The neurons of the retina in the peripheral regions are divided into three main layers, which are shown in Figure 3.1:

1. The most external layer is the **photoreceptor cell layer**, which includes the outer and inner segments and the photoreceptor cell bodies (outer nuclear layer).
2. The layer of intermediate neurons (**inner nuclear layer**).
3. The layer of **ganglion cells**.

In between these layers are the outer and inner plexiform layers which contain the synapses of the neural cells.

The most external layer of the retina is Bruch's membrane which separates the retinal pigment epithelium (RPE) and the sensory retina from the choriocapillaris. It consists of a network of capillaries that supply nutrients to the retina (McDonnell, 1989; Snell & Lemp, 1989). Immediately beneath Bruch's membrane lies the RPE, with its thin processes surrounding the photoreceptor outer segments. The RPE constantly engulfs, digests and regenerates material shed from the outer segments and regulates fluid and nutrient flow to and from the retina. The photoreceptor layer is the most external layer of the sensory retina, and therefore light has to pass through all the preceding layers before stimulating the receptors. The elongated axonal processes of the photoreceptor cells synapse in the outer plexiform layer with the processes of the bipolar cells and horizontal cells, whose cell bodies are located in the inner nuclear layer. The horizontal cells, via their processes, also communicate with the photoreceptors. The bipolar cells synapse with amacrine and/or ganglion cells. The amacrine cells, located in the inner nuclear layer, extend their processes to adjacent amacrine cells or bipolar cells and their axons synapse with ganglion cells. The axons of ganglion cells converge to form the nerve fibre layer and leave the eye as the optic nerve. Enclosing the cell bodies of the retina are the external and internal limiting membranes. The external limiting membrane is created by junctions between cell membranes of the retinal glial cells, the Müller cells and photoreceptor inner segments. The internal limiting membrane is actually a modified surface of the vitreous body and the end processes of the Müller cells.

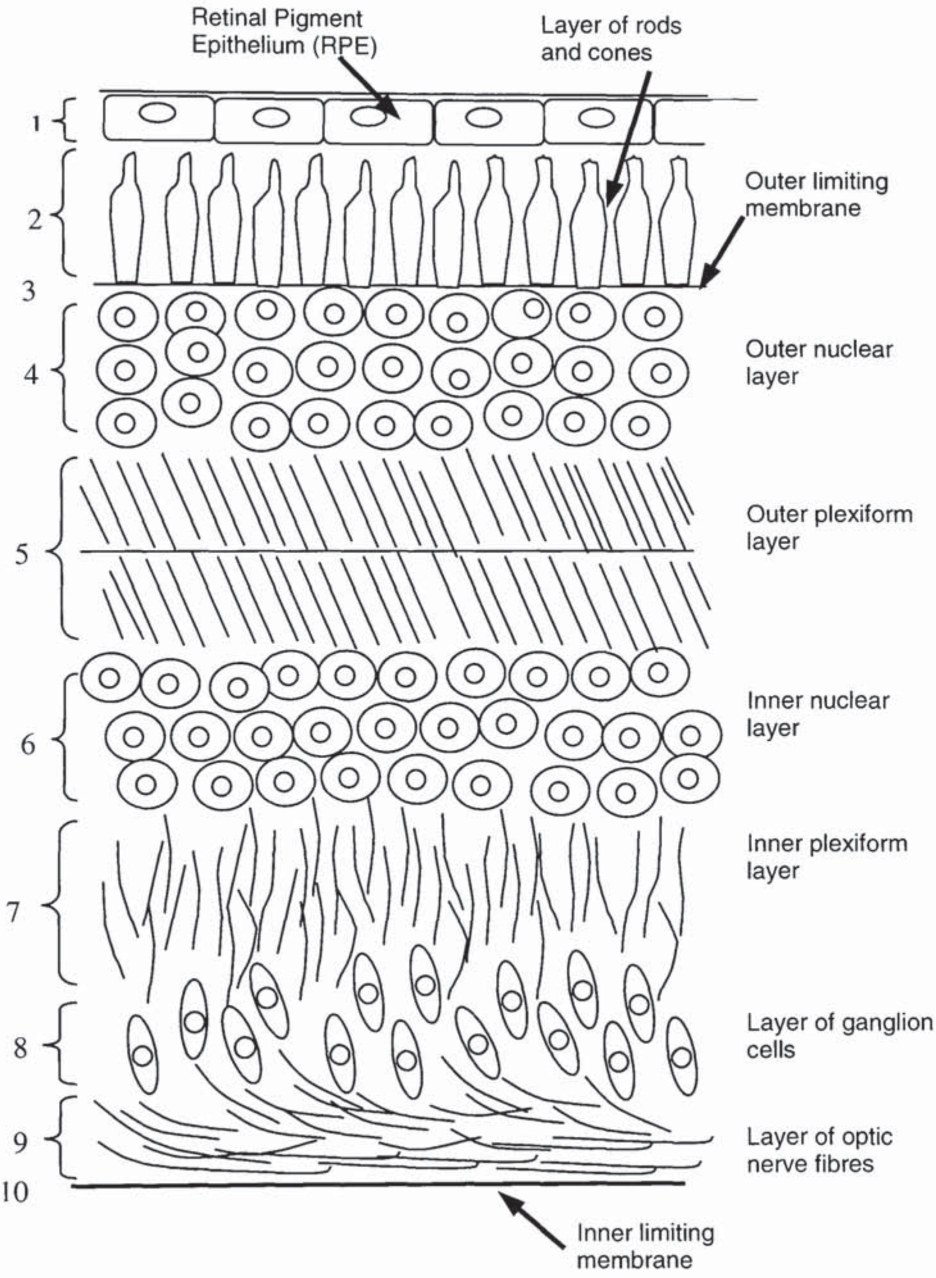


Figure 3.1. A diagram of the ten layers of the retina (including the three main layers of neurons), as seen in an ordinary histologic section. Adapted from Snell & Lemp (1989).

3.2.3 Anatomy of the Macular Region

The macula lutea is a specially differentiated region of retina that lies two disc diameters temporal to the optic nerve head and is approximately 5.5 mm in diameter. Regionally it is divided into four zones: foveola, fovea centralis, parafovea and perifovea (Apple, 1981; McDonnell, 1989) (Figure 3.2).

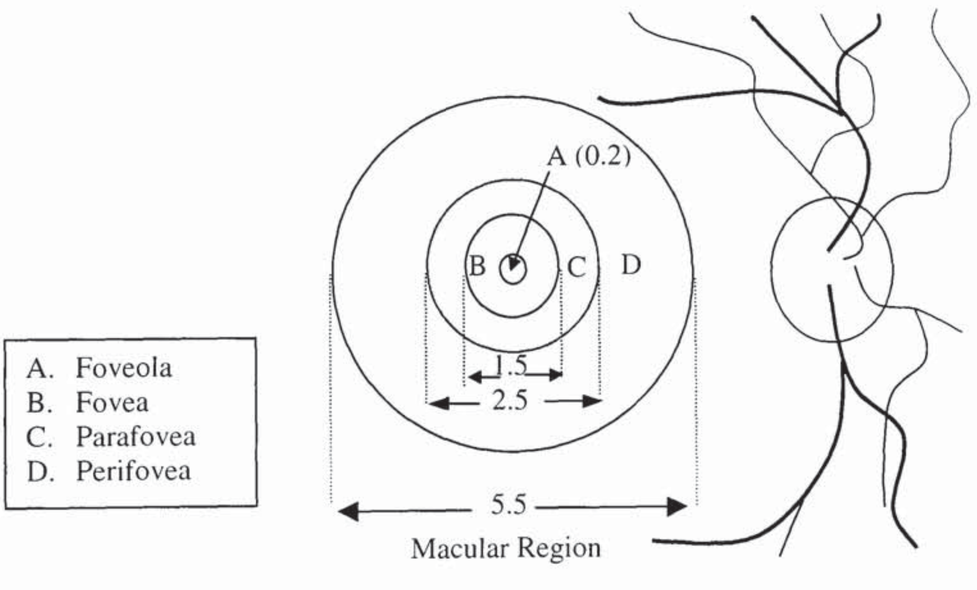


Figure 3.2. A schematic diagram showing the boundaries of the macular region. Measurements in degrees (not to scale).

The central depression of 1.5 mm in diameter contains the foveola and the fovea centralis. The foveola, at the centre of the depression, subtends 0.2 ° Here, the retina is at its thinnest, consisting only of cones and their nuclei. The depression however, is not due to a reduction in the actual number of cells. Instead, the retinal layers from the outer plexiform to the nerve fibre layer are displaced circumferentially from the depression, with only the photoreceptors left centrally. Although the ganglion cells are displaced, they are still linked to the foveal cells, making measurements of cone:ganglion cell ratios difficult. The foveola is responsible for the highest degree of visual acuity (VA) since the obstruction to light caused by the nerve fibres and other layers is reduced to a minimum and the density of cones is greatest.

The foveola is immediately surrounded by the fovea centralis. Its inner border is defined as the site at which the nuclei of the inner nuclear layer and the ganglion cell layers reappear. At the peripheral edge of the fovea, the retina reaches its maximum thickness where the ganglion cells become stratified into six to eight layers. The parafovea and perifovea immediately surround the central foveola depression and extend 2.5 and 5.5 degrees in diameter respectively (Apple, 1981; McDonnell, 1989).

3.3 COMPARISON OF FOVEAL AND PERIPHERAL NEURAL ARRANGEMENT

3.3.1 Photoreceptors

The photoreceptor cells are the light sensitive cells of the retina. The photoreceptor mosaic provides all the spatial information available to higher levels of visual processing and defines the limits of the range of spatial frequencies available to the retina. The human retina contains two types of photoreceptors; rods and cones. Rods are sensitive to very low light levels and are the receptors of scotopic vision, while cones are sensitive to photopic light levels. Structurally both types of photoreceptors are very similar, each consisting of an outer segment containing the light sensitive photopigments, a cell body, an inner segment and a synaptic terminal. In rods, the light sensitive photopigment is called rhodopsin and is maximally sensitive to light of 496 nm wavelength. In cones however, the photopigment is maximally sensitive to either 420, 530, or 565 nm, thus allowing the retina to be spectrally sensitive (Bowmaker, 1991; Rowe, 1991).

The density of rods and cones varies greatly with retinal eccentricity. The average total number of cones in the eye is 4.6 million. In the central fovea, the cone concentration peaks sharply at approximately 199,000 cones/mm^2. Peak cone densities however, have been shown to vary by more than 3 fold between individuals (Curcio & Allen, 1990). Even so, within the central 5 mm, all retinas have approximately the same number of cones, suggesting that it is the distribution of cones that varies between individuals rather than the total numbers. This is thought to result from variations in the rate of migration of cones towards the foveal centre during development, and correlates with the variation in peak psychophysical resolving power of the eye between individuals (Hirsch & Curcio, 1989; Rowe, 1991). Away from the foveal centre, cone density falls off abruptly so that half the maximum density is reached at only 120-150 µm from the foveal centre. At about 10 degrees eccentricity, the density of cones is reduced to approximately 4000-5000 cones/mm^2

and then stays constant at that level across the remaining retina. At the eccentricity of the optic disc, there are more cones in the nasal retina than in temporal retina by a factor of 1.25. Around the mid-line this ratio continues to rise until about 9 mm eccentricity and from that point beyond, there are 40-45% more cones per mm^2 in the nasal retina than corresponding points in the temporal retina. This feature is described as the 'nasal streak' (Curcio et al., 1990; Rowe, 1991). Differences in cone density between superior retina and inferior retina are variable between individuals. Average results therefore show only a weak asymmetry, with inferior retina having slightly higher densities (Curcio et al., 1990).

Rods are absent from the centre of the human fovea, and first appear at 100-200 μm from the foveal centre. The rod concentration peaks (as does the ratio of rods to cones) at 20 degrees from the fovea where the density is about 176,000 rods/mm^2 forming a broad horizontally orientated elliptical ring. The density of rods then falls off gradually to about 30,000 to 40,000 rods/mm^2 at the extreme periphery of the retina (Curcio & Allen, 1990). The rod isodensity contours are roughly circular, but similar to the cone topography, they are displaced towards the nasal and superior retina. The nasal to temporal ratio of rod densities is greater than 1.0 at 5-6 mm and increases to 1.28 at the far edge of the temporal retina (Curcio et al., 1990).

The ratio of total number of rods to the total number of cones is 20:1. Regionally, the rod:cone ratio is minimum near the fovea and increases to a maximum in the mid-periphery. It then decreases slowly with eccentricity. Rod:cone ratios are lowest in nasal retina at all eccentricities. This is because, up to the rod ring, in nasal retina rod densities are at their lowest, and at eccentricities greater than 1 mm, cone densities are relatively high (Curcio et al., 1990).

3.3.2 Ganglion Cells

The number of ganglion cells and the indirect connections they make to photoreceptors also vary with eccentricity. In the macular area, there is a small population of cones connected via intermediate cells to a large supply of displaced ganglion cells. The highest ganglion cell densities are found in a horizontal, elliptical ring that extends from 0.4-2.0 mm from the foveal centre. The ganglion cell density drops off with eccentricity more rapidly along the vertical meridian than along the horizontal meridian. There are more ganglion cells in the nasal than temporal retina by a factor of 1.15 from 0.4-2.0 mm eccentricity. This higher density of ganglion cells along the nasal meridian compared with the temporal meridian is found at all eccentricities exceeding that of the optic disc. These density gradients result in a feature of ganglion cell topography known as the 'visual streak'. From 4 mm eccentricity a superior-inferior asymmetry exists, whereby on average, the superior retina has 60% more ganglion cells than corresponding eccentricities in the inferior retina (Stone & Johnston, 1981; Curcio & Allen, 1990).

The sampling density of retinal ganglion cells in the macula region exceeds that of the cone photoreceptors. Therefore resolution in the macula would be determined by cone density, not by ganglion cell density (Wang et al., 1997). Curcio et al. (1990) predicted the mean acuity from foveal cone density of their retina samples to be 66.3 cycles/degree, with a range of 47.5-86.3 cycles/degree. However, the psychophysical measurement of foveal visual acuity has been found to be highly variable and ranges from 30-60 cycles/degree (Westheimer, 1982; Hirsch & Curcio, 1989; Curcio et al., 1990). Curcio et al. (1990) suggest that this two-fold range in visual acuities is larger than the range in foveal cone densities would predict, even when methodological differences are taken into account. They suggest that factors other than cone spacing are most likely involved in producing the functional variability. Unfortunately, obtaining accurate human data of this type is complicated by the practicalities of obtaining both anatomical and functional information from the same eye.

With increasing eccentricity, there is an increasing ratio of photoreceptors (mainly rods) to ganglion cells. In more peripheral retinal regions, there is a high ratio of photoreceptors to ganglion cells and hence a high sensitivity to detecting light (due to high densities of photoreceptors) but poor discrimination acuity (due to lower densities of ganglion cells). Starting at approximately 10 degrees from the fovea, cones outnumber ganglion cells. It would therefore be expected that the resolution acuity in the periphery should be determined by the relatively low sampling density of the ganglion cell mosaic (Wang et al., 1997).

3.3.3 Magnocellular and Parvocellular Divisions

The discussion of ganglion cells in the previous section has been with regards to ganglion cells as an entire group. There are however several types of ganglion cell, and a number of classification systems have arisen to describe them. Two main types of ganglion cell are known as M and P cells (Shapley & Perry, 1986). M cells project to the magnocellular layers of the lateral genicuate nucleus (LGN) whilst the P cells project to the parvocellular layers. These cells constitute 10% and 80% respectively of the retinal ganglion cells.

M and P cells code for several different aspects of vision. M cells show short latencies and transient responses to stimuli, have large receptive fields and show either linear or non-linear spatial summation (Kaplan & Shapley, 1982; Derrington & Lennie, 1984). Their receptive fields are centre-surround and broadband colour insensitive, with all varieties of cones contributing to centres and surrounds (Livingstone & Hubel, 1988). The major properties of M cells are thus low acuity, high temporal and contrast sensitivity, and lack of wavelength selectivity (De Yoe & Van Essen, 1988; Bassi & Lehmkuhle, 1990). In contrast, P cells show longer latencies and sustained responses to stimuli, have receptive field sizes 2-3 times smaller than M cells and show linear spatial summation. They have low sensitivity to contrast but do not saturate at high contrasts. The centre-surround organisation of P cell receptive fields consist of different cone classes so they are colour opponent (Livingstone & Hubel, 1988). The major properties of P cells are thus high acuity, wavelength selectivity, and low contrast and temporal sensitivity.

There has been much debate in the literature about whether the relative proportions of M and P cells vary with retinal eccentricity. Several studies have found anatomical evidence of higher concentrations of P cells in the fovea, whereas M cells have appeared to be more evenly distributed across the visual field (Daniel & Whitteridge, 1961; Derrington & Lennie, 1984; Schein & de Monasterio, 1987; Drasdo & Thompson, 1989; Drasdo, 1991; Dacey & Petersen, 1992). Psychophysical evidence also points to differences in M and P eccentricity gradients (Harwerth & Levi, 1978; Drasdo & Thompson, 1989; Drasdo, 1991). In contrast, histological studies have cast some doubt on the existence of different gradients for the magnocellular and parvocellular systems at retinal and cortical levels in primates. Livingstone & Hubel (1988) found no evidence that in the cortex there is a large difference between fovea and far periphery in the relative mapping densities of the magnocellular and parvocellular systems. From cell counts throughout the ganglion cell layer, Perry & Silveira (1988) also found that any variation in P:M ratio with eccentricity was not as great as had been suggested. Perry et al. (1984) and Silveira & Perry (1991) also found minimum variation in the gradients between the two systems.

Despite the conflicting findings, most evidence suggests that there is some difference in the relative proportions of M and P cells across the field, with P cells making up a greater proportion of cells in central vision, and M cell distribution being more even across the visual field.

3.3.4 Lateral Geniculate Nucleus

Ganglion cell axons leave the retina and pass up the optic nerve to the optic chiasm. At this point nerve fibres from the temporal retina, representing the nasal visual field, continue to the ipsilateral lateral geniculate nucleus (LGN). Fibres from the nasal retina (representing the temporal visual field) cross at the chiasm and travel to the contralateral LGN. (Figure 3.3) From the geniculate level onwards each cortical hemisphere thus deals with the processing of the contralateral visual field.

The LGN is composed of six distinct layers, four dorsal parvocellular layers and two ventral magnocellular layers. The ventral layers, 1 and 2, receive axons of retinal M cells, while the dorsal layers, 3 to 6, receive input from retinal P cells (Perry et al., 1984). Information is segregated into monocular layers which alternate between ipsilateral and contralateral eyes, so that each eye is represented in the LGN by two parvocellular and one magnocellular layer. Similar to ganglion cells, the receptive fields in the LGN are of the centre-surround type. Information therefore leaves the LGN in the same form as it enters. However, feedback is also received from the cortex and the brainstem reticular formation, and local synapses occur within the LGN, suggesting the some sort of information processing occurs at this level (Hubel, 1988).

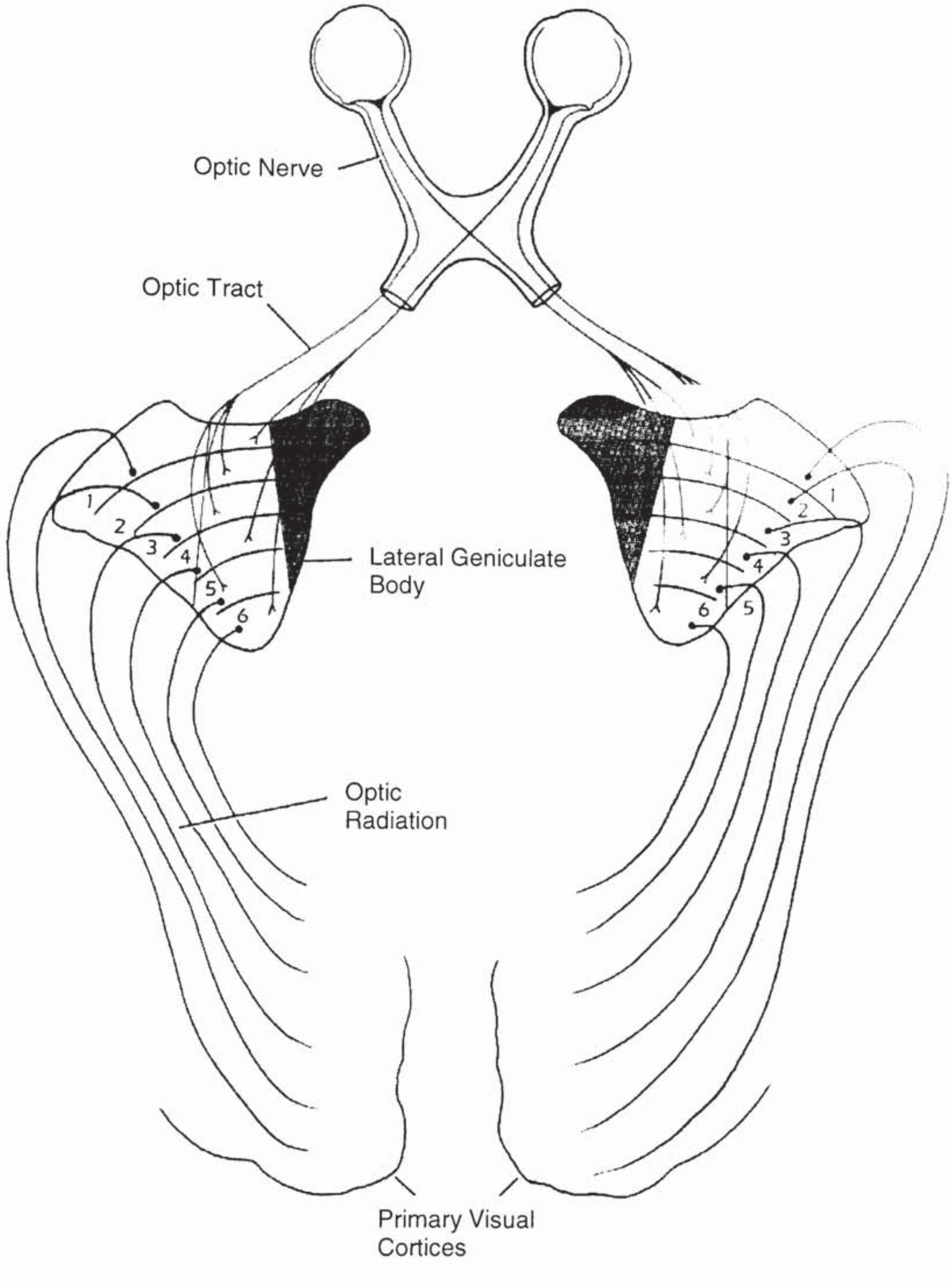


Figure 3.3. Schematic diagram of the visual pathway.

3.3.5 Striate Cortex

Nerve fibres leave the LGN and continue up the optic tract to the striate cortex, also known as visual area 1 (V1), Brodmann's area 17 or the primary visual cortex. The striate cortex occupies most of the occipital lobe and is so named because of its distinct layering. Six main layers are identified, with some subdivision of the layers (Figure 3.4). Axons originating from the two ventral (magnocellular) layers of the LGN synapse primarily in the upper half of layer 4C called 4Cα; those from the four dorsal (parvocellular) layers end in the lower half of 4C (4Cβ). The cells in the entry level of layer 4 have centre-surround receptive fields like those of the retina and LGN, receiving information from only one eye and with no preference for orientation. Beyond this layer, receptive fields become progressively more complicated and are termed simple, complex, and hypercomplex or endstopped cells (Hubel & Wiesel, 1968). It is unlikely that the processing of visual stimuli by the two pathways remains completely segregated as the pathways reach the temporal and parietal regions of the visual cortex (Shapley, 1990; Merigan & Maunsell, 1993; Callaway, 1998). In fact, there is a great deal of reciprocal cross connection between the two streams in the striate cortex and beyond. Felleman & Van Essen (1991) suggest that the amount of connectivity between the cortical visual areas is thought to approach 40% of maximum possible connections. From entry level 4C, projections are first sent to other layers in the primary visual cortex, and then on to other cortical areas or to deep structures in the brain (Hubel, 1988).

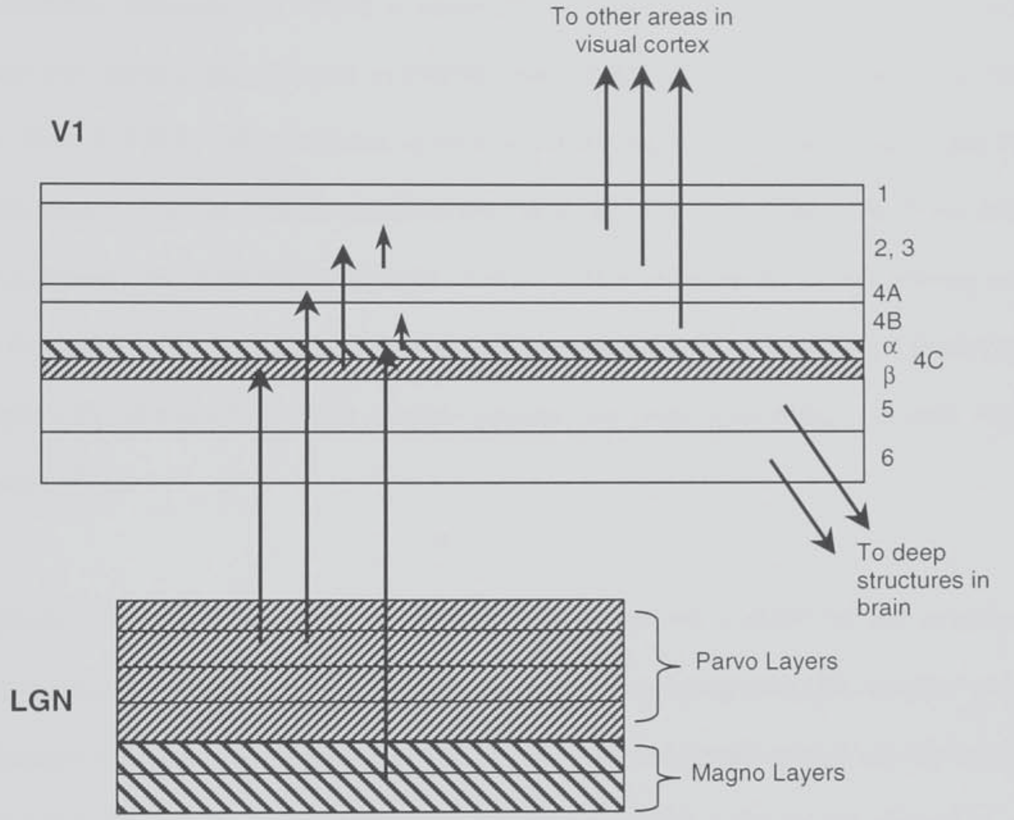


Figure 3.4. Diagram of the Magnocellular and Parvocellular projections between the LGN and primary visual cortex (V1). Information sources: Livingstone & Hubel (1988) and Hubel (1988).

3.4 VISUAL FUNCTION AND THE PERIPHERAL RETINA

3.4.1 Cortical Magnification

From Chapter 3.3.2, we know that at the level of the retina, the variation in ganglion cell density gives emphasis to the fovea. This foveal emphasis is also seen at cortical level, whereby the visual world is projected from the retina and laid out in a topographical map. Post-retinally, although cell density is reasonably constant with eccentricity, there is larger volume and surface area devoted to central visual fields compared with more peripheral areas (Polyak, 1957). This variation in cortical processing with eccentricity of visual field can be quantified by the cortical magnification factor, M. This is defined as the linear extent of visual cortex (in millimetres) devoted to each degree of visual field, and moving away from the fovea, M declines rapidly (Daniel & Whitteridge, 1961). A number of studies have attempted to estimate M in both primate species and man, with highly variable results (Drasdo, 1991).

In general terms, cortical magnification theory claims that the visibility of any stimulus is similar across the whole visual field if the amount of cortex representing the stimulus at each eccentricity is similar. According to the theory of cortical magnification (Virsu & Rovamo, 1979), enlarging peripheral visual stimuli by M_0/M_E (where M_0 is the foveal value of M, and M_E is the value of M at eccentricity E) will equalise the cortical representation of all stimuli. This procedure, known as M-scaling, was introduced by Virsu & Rovamo (1979) as a means by which foveal and peripheral visual performance could be equated. In Virsu & Rovamo's study, contrast thresholds were obtained for detection, orientation discrimination, and discrimination of direction of movement of gratings in the inferior field. Stimulus size was varied by changing the viewing distance, and they used magnification factors previously published by Rovamo et al. (1978). With the magnified stimuli involving equal amounts of cortical area (i.e. M-scaled), contrast sensitivity functions became similar at all eccentricities, with equivalent peak sensitivities. However, there was a shift to lower spatial frequencies at greater eccentricities (Figure 3.5).

Figure 3.5. Contrast sensitivity as a function of retinal spatial frequency and eccentricity in the inferior visual field. A. Retinal image size is constant. B. Calculated cortical projection images were constant for stimuli at each eccentricity. Taken from Virsu & Rovamo (1979).

In a subsequent paper, Rovamo & Virsu (1979) derived equations for application to M-scaling in man. Earlier anatomical evidence had led to the assumption that the frequency of retinal ganglion cells is directly proportional to the striate-cortical magnification factor M. On this basis, Rovamo & Virsu (1979) estimated M across the visual field using previously published data about the total density and number of ganglion cells. For eccentricities beyond 10 degrees, values of M were derived by using ganglion cell densities. At eccentricities less than 10 degrees, cone densities were used, assuming a cone to ganglion cell ratio of 1:1 in the fovea. M_0 was determined to be 7.99 mm/deg. Due to the radial asymmetry of the distribution of primate ganglion cells, Rovamo & Virsu determined four equations (each representing a principle meridian) from which M could be found (Rovamo & Virsu, 1979). These equations are shown in Table 3.1

Meridian	**Equation**	**Eccentricity Range (degrees)**
Nasal	$M_N = (1 + 0.33E + 0.00007E^3)^{-1}M_0$	0 – 60
Superior	$M_S = (1 + 0.42E + 0.00012E^3)^{-1}M_0$	0 – 45
Temporal	$M_T = (1 + 0.29E + 0.000012E^3)^{-1}M_0$	0 – 80
Inferior	$M_I = (1 + 0.42E + 0.000055E^3)^{-1}M_0$	0 – 60

Table 3.1. Cortical magnification equations of Rovamo & Virsu (1979). M_0 is the foveal value of M; E is the eccentricity in degrees.

The publication of Rovamo & Virsu's equations for cortical magnification resulted in a number of studies of peripheral visual performance to which the equations were applied. Some of these studies were successful in being able to equate central and peripheral vision using M-scaled stimuli, whilst others were not (Drasdo, 1991). These latter studies served to highlight the difficulties involved in peripheral scaling according to pre-determined magnification factors. The M-scaling technique assumes that all tasks vary with eccentricity at the same rate. If the chosen magnification factor does not remove eccentricity dependence from the task, it is possible that either the incorrect magnification factor was chosen, or that the task itself is not able to be equated across eccentricities by simple magnification scaling. It must also be remembered that M factors were determined using assumptions based on anatomical and physiological data. These assumptions should be viewed with caution considering the large discrepancies that exist between estimates of M (Drasdo, 1991). In addition, the equations determined by Rovamo & Virsu (1979) assume a ganglion cell: cone cell ratio of 1:1, and a direct relationship between ganglion and cortical cells. In the light of more recent anatomical data both these assumptions have been questioned (Drasdo, 1991). In view of the problems associated with M scaling, it would be considered better to be able to compare performance at different eccentricities without being tied to *a priori* assumptions of cortical magnification factors. Such a procedure is referred to as *spatial scaling*.

3.4.2 Spatial Scaling

As explained in the previous section, there are difficulties in scaling peripheral stimuli according to pre-chosen magnification factors. To avoid the requirement of *a priori* magnification factors, the method of spatial scaling requires that thresholds for a set of stimuli, which are all magnified versions of each other, are measured at the fovea and then at various eccentric locations. The thresholds can then be plotted against stimulus size for each eccentricity. The amount by which the peripheral data is offset from the foveal data can then be determined. This difference or offset is the rate at which the stimulus size must increase in the periphery, in order for thresholds to equate the performance at the fovea, or the local spatial scale at that eccentricity (Johnston, 1987; Watson, 1987). Therefore, there is a number, the local spatial scale, that is associated with each point in the visual field. This process was described by Watson (1987) and is shown in Figure 3.6.

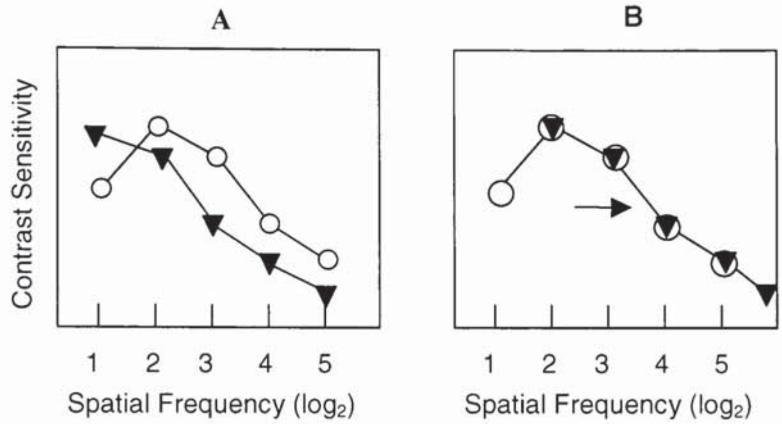


Figure 3.6. A method of measuring spatial scale. A. A contrast sensitivity function with size-scaled stimuli centred at the fovea (open circles) and compared with a peripheral location (filled triangles). B. The peripheral curve is moved horizontally to be superimposed on the foveal curve. The horizontal shift required is an estimate of local scale at the peripheral location. Adapted from Watson (1987).

To compare relative changes in performance across the visual field, the E_2 value is used, which defines the eccentricity at which foveal stimulus size must double in order to maintain performance equivalent to that at the fovea (Levi et al., 1985). Small E_2 values indicate that rapid increases in target size with eccentricity are required, whilst large E_2 values indicate that less increase in magnification is required. This eccentricity related rate of change in magnification appears to be dependent on the visual task in question. Tasks such as certain hyperacuities require much more eccentricity-related magnification (smaller E_2 values) than visual acuity, which in turn requires more magnification than movement or light detection tasks (Westheimer, 1982; Levi et al., 1985; Drasdo, 1991; Whitaker et al., 1992; Latham & Whitaker, 1996a). The rate at which all these tasks need to be magnified however, is always approximately linear as a function of eccentricity. Therefore, visual performance for most tasks can be equated across the visual field, provided the task is magnified appropriately.

The variation in scaling factor for different visual tasks has been found to be well over 100-fold (Whitaker et al., 1992) and speculations can be made about the factors underlying these differences. The anatomical and physiological factors limiting visual thresholds occur at various levels of the visual pathway. Levi et al. (1985) suggested that tasks limited at retinal level, such as resolution, would follow different E_2 values to cortically limited tasks such as hyperacuities. It has been proposed that psychophysical tasks are processed by the combined activity of two or more major channels in the visual system. Some are more foveally specialised, whilst others are more equally distributed across eccentricities. The rate of threshold increase (or E_2 values) in any given task would then depend upon the extent to which visual processing was mediated by the different types of channel (Whitaker et al. 1992; Latham & Whitaker, 1996a). Therefore, anatomical and physiological factors occurring at varying levels of the visual pathway could combine to result in the wide range of threshold gradients across the visual field for various tasks. The weighting of each threshold would therefore determine the final threshold gradient (or E_2 value).

3.5 PSYCHOPHYSICAL INVESTIGATION OF PERIPHERAL VISUAL FUNCTION

Spatial scaling has been used to describe and quantify foveal and peripheral visual performance for a number of different visual functions. These psychophysical observations of visual performance at different retinal eccentricities can be related to physiological and anatomical characteristics, at least at the retinal level. In the following sections, the relationships between foveal and peripheral visual performance and retinal anatomy are described for visual acuity, contrast sensitivity and reading speed. These visual measurements were shown in Chapter 2 to be important with respect to reading.

3.5.1 Visual Acuity

Since the studies of Wertheim in 1894 (Wertheim, 1980), visual resolution has been known to reduce with increasing eccentricity and has been the subject of many studies (Genter et al., 1981). More recently, interest has been developing in the processes that underlie the variation of visual resolution with eccentricity. At the fovea, photoreceptors and optics are reasonably well matched in the frequencies they can observe (Campbell & Gubisch, 1966; Williams, 1985). However, in peripheral vision, even though the anatomical and optical factors vary with eccentricity, these properties do not vary in unison (Anderson et al., 1991). To investigate which factor(s) actually limit spatial resolution, Anderson et al. (1991) measured spatial contrast sensitivity functions at various eccentricities, and from this data they derived spatial acuities for each eccentricity. They compared these results with data on human optical and anatomical retinal properties. In particular, they compared these functions with the maximum spatial frequency afforded by the optical properties of the eye, the maximum resolution predicted from the spatial filtering by the human cone aperture, and the Nyquist limits calculated from cone and ganglion cell densities. The Nyquist limit is the highest spatial frequency that can be reconstructed unambiguously from an array of spatially discrete cells, in this case, ganglion cells and cone cells. The variations of these factors with eccentricity are shown in Figure 3.7. This figure agrees with previous findings that foveal acuity (and acuity out to about 5 degrees) is dictated by the sampling density of the cone mosaic. However, further than about 5 degrees eccentricity, achromatic acuity declines with increasing eccentricity at a faster rate than the limits imposed by both the optical and receptoral properties of the human eye. It also declines faster than the Nyquist limit for the population of ganglion cells as a whole. Even so, qualitatively, if not quantitatively, the decline in visual acuity does follow ganglion cell densities as it reflects the naso-temporal asymmetry in ganglion cell density. From these results the authors suggested that achromatic acuity was limited by post-receptoral mechanisms in human peripheral vision.

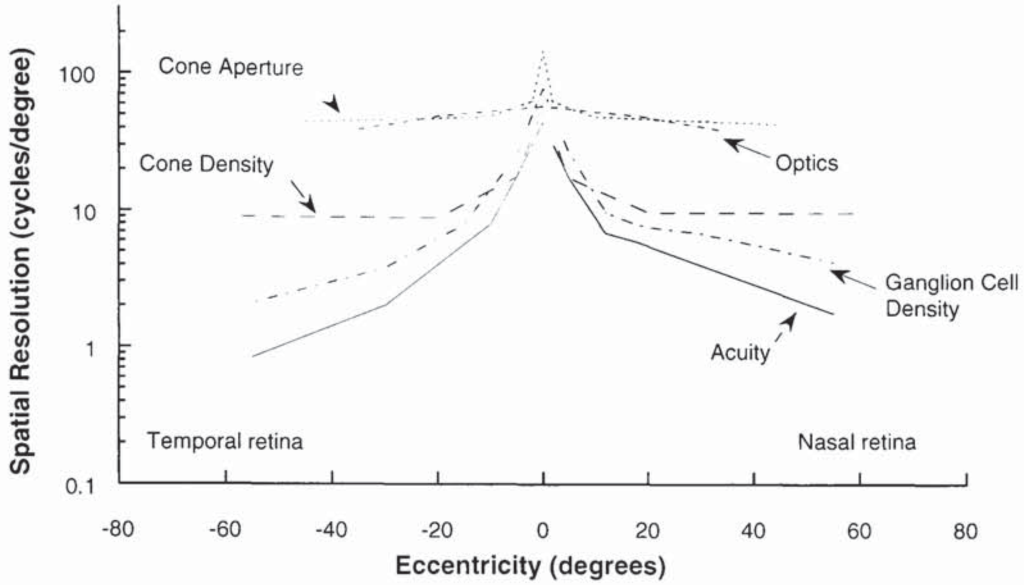


Figure 3.7. Retinal limitations to spatial resolution across the visual field. Acuity declines with increasing distance from the fovea but at a faster rate than that dictated by known optical and/or receptoral properties of the human eye. The limitations depicted include cone density, ganglion cell density, psychophysical resolution acuity (acuity), optics of the eye, and cone aperture size. Redrawn from Anderson et al. (1991).

Anderson et al. (1992) also found a relationship between retinal anatomy and visual resolution throughout the periphery. They measured grating resolution at 25 degrees eccentricity from the fovea at each of 8 principal meridians and also at 20 degrees either side of 0 degrees (nasal/horizontal). They found that resolution acuity was greatest near and along the horizontal meridian, and greater on the nasal retina than the temporal retina. Previous anatomical studies have also shown a greater density of ganglion cells along and either side of this horizontal nasal retina than any other retinal area, and a greater ganglion cell density in the nasal than temporal retina. This has been termed the 'visual streak' (Curcio & Allen, 1990). The data therefore suggest that resolution acuity in the periphery is limited by ganglion cell density and variations in acuity with peripheral retinal location reflect changes in ganglion cell density.

As explained above (Chapter 3.4), M scaling is a technique with the explicit purpose of equalising the number of retinal ganglion cells (and post-retinal cells) stimulated at different eccentricities. If visual resolution is limited by ganglion cell density then it follows that if a target is appropriately magnified (M-scaled), then visual resolution should be able to be equated at different eccentricities. To an extent, this is indeed what occurs. Virsu et al. (1987) tested cortical magnification theory on 5 different visual acuity tasks. The predictions of the theory were successful in 4 of these tasks, such that eccentricity dependence of the results was removed. The results however did show that M scaling was not always successful. Although the anatomical/psychophysical correlations are significant for most visual acuity tasks, as described in Chapter 3.4, the idea of using one scaling factor for all visual functions appears to be an oversimplification of the situation.

3.5.2 Contrast Sensitivity

Contrast sensitivity thresholds have also been investigated at different locations throughout the visual field (Koenderink et al., 1978a; Koenderink et al., 1978b; Koenderink et al., 1978c). In the first 2 of 4 papers, Koenderink and co-workers determined that the eccentricity dependence of contrast sensitivity thresholds to spatial sine wave patterns depended on the size of the target field (Koenderink et al., 1978a; Koenderink et al., 1978b). To investigate this further, a third study determined contrast detection thresholds at eccentricities between 0 and 50 degrees for target fields subtending between 30x30 minutes of arc up to 16x16 degrees. They found that the minimum contrast sensitivity threshold at any location in the peripheral visual field could be made equivalent to that found at the fovea if the field diameter was large enough. The results showed that the minimum threshold only shifted (horizontally) to lower spatial frequencies. In addition, it was the smallest linear dimension, not the total area that determined the contrast sensitivity.

To explain these findings, the authors then compared them with data of neuroanatomical retinal variation with eccentricity. They first calculated values of acuity for each eccentricity from the reciprocal of half a spatial wavelength of the sine wave pattern with a 50% contrast detection. For eccentricities between 0 and 50 degrees, the reciprocal of these acuities were then plotted against the reciprocal of the cortical magnification factor (M^{-1}, degrees/mm cortex) and the mean inter-ganglion cell distance (d, expressed in minutes of arc) as derived by Drasdo (1977). The results are re-plotted in Figure 3.8. The correlation fits remarkably well for 6, 21 and 50 degrees, although the foveal data is too low by about a factor of 2. Therefore, variation of contrast sensitivity with eccentricity correlates with both retinal and cortical neuroanatomical properties.

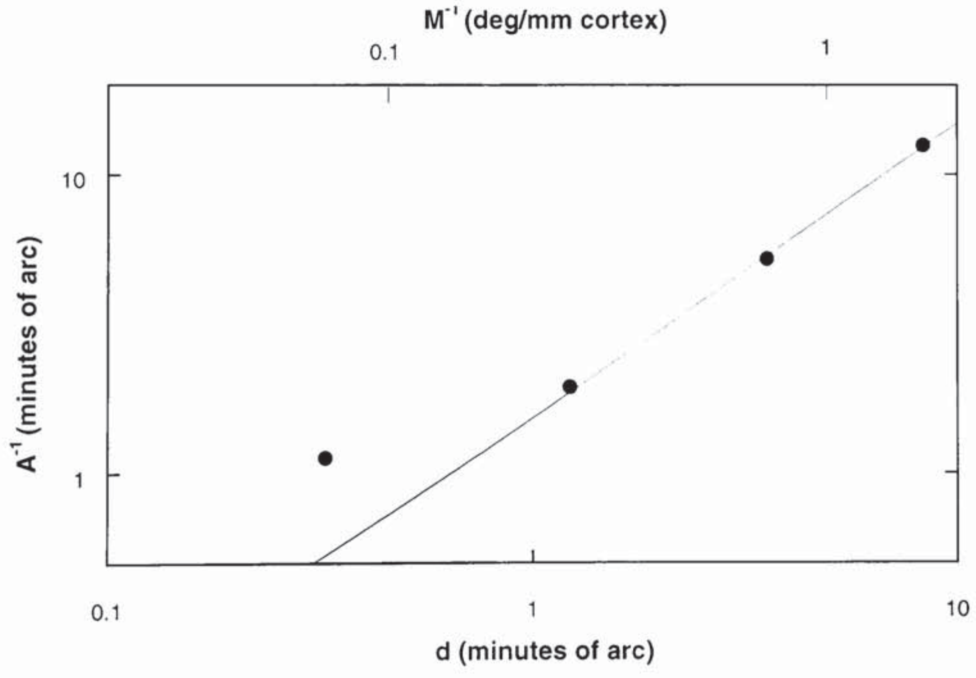


Figure 3.8. The reciprocal of acuity A^{-1} (minutes of arc) plotted as a function of the reciprocal of cortical magnification factor M^{-1} (degrees/mm cortex; upper scale) and the mean inter-ganglion cell distance d (minutes of arc; lower scale). The points are the data for eccentricities of 0, 6, 21, and 50 degrees (from left to right). Redrawn from Koenderink et al. (1978c).

3.5.3 Reading Speed

As seen above, both visual acuity and contrast sensitivity can be spatially scaled such that performance in the periphery can match that at the fovea. This is most likely due to ganglion cell densities limiting the performance of each of these functions. In contrast, one particular visual task that can not be equated across the visual field with a suitable scale is that of reading text.

Latham & Whitaker (1996b) measured word recognition thresholds and rapid serial visual presentation (RSVP) reading rates for both lists of unrelated words and meaningful sentences at the fovea and 5 and 10 degrees eccentricity. They found that both word recognition thresholds and reading rates for unrelated words could be equated across the different eccentricities with an increase in size scale with increasing eccentricity. In contrast, RSVP reading rates for meaningful sentences could not be equated across the visual field. The foveal reading speeds were always faster than those at 5 and 10 degrees eccentricity, irrespective of scale. Chung et al. (1998) also measured RSVP reading speeds for meaningful sentences of different print sizes at eccentricities up to 20 degrees. In agreement with the findings of Latham & Whitaker (1996b), they found that reading speed reduced with increasing eccentricity, regardless of the size of the text. They concluded from this data that print size was not the only factor limiting maximum reading speed in normal peripheral vision.

It appears therefore that the fovea is unique in the task of reading meaningful sentences. This finding agrees with the clinical observation that patients with central field loss (CFL), fixating with an eccentric retinal locus, read slower than normally sighted subjects reading with their fovea, despite magnification. A number of studies and hypotheses have considered the possible reasons for the superiority of the fovea to reading performance and these are described in the following section.

3.5.4 Peripheral Retina and Reduced Reading Performance

Chaparro & Young (1993) investigated the role of the cone visual system in the superiority of the fovea seen for reading by using text that could only be seen with rod vision. Reading speeds for random words were measured when text was located at different parts of the visual field. They found that despite the isolation of the rod visual system, reading speeds were still maximum at the fovea. This suggested that the faster reading speeds recorded with foveal fixation compared with peripheral fixation were independent of the intrinsic differences between rods and cones. More specifically, they were not dependent on an exclusive property of the cone visual system.

The problem of poor peripheral reading speeds has also been attributed to inadequate eye movement control (Whittaker et al., 1988; Rubin & Turano, 1994). Fixation variability, eye drift and an increased number of saccades per word were considered to be the cause of reduced performance in the periphery. However, measurements of reading using rapid serial visual presentation (RSVP), which minimised the need for saccadic eye movements, still found reduced reading speeds in peripheral retina compared with the fovea (Rubin & Turano, 1994; Latham & Whitaker, 1996b; Chung et al., 1998). These findings therefore indicated that oculomotor factors could not explain the entire deficit in reading speed caused by central field loss.

Another hypothesis attributes the deficit to an inability of peripheral vision to perform complex pattern recognition and resolution. For example, declines in letter acuity, grating acuity and contrast sensitivity with increased eccentricity are well documented. However, these declines are not enough to explain peripheral reading deficits. In fact, many peripheral visual thresholds, including visual acuity, can be normalised to foveal levels by increasing size (Koenderink et al., 1978a; Koenderink et al., 1978b; Rovamo & Virsu, 1979; Whitaker et al., 1992; Latham & Whitaker, 1996b). There is however, as studies of cortical magnification (Chapter 3.4.1) have shown, no single scale factor that will normalise all peripheral thresholds to central field values (Westheimer, 1979; Whitaker et al., 1992). It has therefore been suggested that different types of tasks may be limited by different factors (Levi et al., 1987). For example, conventional acuities could be limited by retinal factors and positional resolution limited by cortical factors.

Another possibility is the effect of crowding. This is the phenomenon where visual acuity is better when letters are presented singularly rather than in groups or lines. It is known that the peripheral visual acuity is more sensitive to the effect of crowding than the fovea (Hess et al., 1978; Jacobs, 1979; Latham & Whitaker, 1996a). This suggests that optimal spacing differs for central and peripheral vision. However, although there is evidence to show that letter spacing affects peripheral word recognition (Whittaker et al., 1989) and reading rate (Legge et al., 1985; Latham & Whitaker, 1996b), there is disagreement about the importance of this factor. Using 6 degree characters, Legge et al. (1985) found that reading speeds actually reduced slightly with increased letter spacing for both normal and low vision observers even though all observers preferred the intermediate spacing condition. In contrast, Whittaker et al. (1989) reported that word recognition in peripheral retina approximately equalled that for foveal fixation if character spacing was increased for the peripherally presented text compared with that presented at the fovea. Also, Latham & Whitaker (1996b) measured reading speeds for random word lists of five words, presented foveally and at 5 degrees inferior retina. They reported a slight advantage in terms of reading speed when using letters spaced at 2X letter separation compared with those spaced 0.25X letter separation.

Another possible explanation for the decline in maximum reading speed in peripheral vision is the reduction in the number of characters that can be recognised in a single fixation or the 'visual span'. Legge et al. (1997a) have presented data consistent with the idea that slow reading in normal central vision at low contrast, as well as reading speed deficits in some forms of low vision, are due to a shrinkage in the visual span. Indeed, more recently, Legge et al. (1997c) obtained evidence that the visual span for RSVP reading reduces in size in the periphery. They found that the reduction in size of the visual span as a function of retinal eccentricity, approximately paralleled that of reading speed with eccentricity. Chapter 10 of this thesis investigates the effect of eccentricity on the size of the visual span in more detail.

Although a number of suggestions have been made, studies to date have not been able to determine the precise cause of reduced peripheral reading performance. Considering the complex nature of the reading process however, rather than being a single cause, there are more likely to be a number of contributing factors.

3.6 SUMMARY

Limitations are placed on foveal and peripheral vision at every level of the visual pathway, from photoreceptors and retinal ganglion cells to the visual cortex and beyond. Although anatomical factors, at least at retinal level, can be shown to greatly influence the characteristics of foveal and peripheral vision, there is still much about the anatomy of the visual pathway that is uncertain, or indeed unknown. For example, the relative distributions of retinal ganglion cell types such as M and P cells are not known with certainty. Also, the results of many studies that have carried out mappings of the primate visual cortex vary considerably and consist of very little human data. Therefore, any studies that describe the relative abilities of foveal and peripheral vision based on anatomical data should be viewed with caution. Alternatively, psychophysical observations of foveal and peripheral visual performance can be made without any *a priori* assumptions about anatomical factors. Such procedures may be able to reveal much about the visual system, in particular the relative deficit of peripheral visual performance.

Chapter 4

MEASURING VISUAL FUNCTION

4.1 INTRODUCTION

Traditionally, objective visual function tests have been used in clinical situations as a quantifiable measure of a patient's visual performance. In fact, clinicians routinely quantify a number of visual functions. A standard measure can therefore be obtained against which future measures of vision may be assessed and compared, both within and between individuals. Clinically, the measurement of visual function is important in order to detect change and any deviation from 'normality'. In this way, the effect of treatment such as surgical or rehabilitative outcomes can be assessed. Also, the early detection of problems, when values change from baseline, relies on a repeatable and reliable test of visual function.

For low vision patients, the measurement of visual function is necessary for definition and registration of visual impairment. It is also measured as an attempt to quantify the patient's own subjective impression of visual performance in their daily environment. However, there is growing opinion that the ability of visual function tests to indicate the level of visual disability experienced by the patient is limited. There is also an increasing awareness of the importance of patients' subjective assessment of their own visual performance. For this reason, quality of life questionnaires are being developed as a subjective measure of visual performance, as well as a measure of emotional well-being and social function. Subjective measures reflect perceived need for the patients and add meaning to, as well as justifying the use or appropriateness of objective clinical tests.

4.2 OBJECTIVE TESTS OF VISUAL FUNCTION

4.2.1 Visual Acuity

Visual acuity is defined as the smallest target size of which the details can be resolved by the observer at high contrast (Westheimer, 1992). The most common clinical method of visual acuity (VA) measurement is the recognition task, whereby Snellen letters must be identified correctly (Riggs, 1965). The Snellen distance acuity chart determines the ability to discriminate the smallest possible letters of nominally 100% contrast. However, it has been shown that Snellen visual acuity has a number of limitations as a method of measuring high contrast visual acuity (Bailey & Lovie, 1976; Wild & Hussey, 1985; Lovie-Kitchin, 1988; McGraw & Winn, 1993). The progression of letter sizes on the chart is irregular, and thus does not allow interpolation of scores between lines, which reduces the sensitivity of the test. The variation in the number of letters on each line and the unequal legibility of the test letters means that the steps on the chart are not equally discriminable (Bailey & Lovie, 1976). Also, at higher acuities the scale is truncated, thus preventing the use of parametric statistics (Wild & Hussey, 1985).

Problems with the design and format of Snellen charts have led to the development of alternative charts (Bailey & Lovie, 1976; Ferris et al., 1982; McGraw & Winn, 1993). The most notable feature of all these charts is the logarithmic progression in letter size (Bailey & Lovie, 1976; Ferris et al., 1982; McGraw & Winn, 1993). There is also an equivalent task difficulty at each level, ensuring that the angular size of the letter is the only variable parameter. These charts have been shown to be reliable and accurate for the measurement of visual acuity (Bailey & Lovie, 1976; Lovie-Kitchin, 1988).

The Bailey-Lovie chart (Bailey & Lovie, 1976) is the most widely accepted of these alternative charts. Similar to the Snellen chart, it consists of lines of nominally 96% contrast letters. However, the progression of letter sizes between lines on the chart is logarithmic, with 0.1 log units between lines. The logMAR (logarithm of the minimum angle of resolution) scale makes adjusting the visual acuity scores for different viewing distances simple, which is particularly suited for low vision assessments. The logarithmic scoring also makes the measurements suitable for statistical analysis, making it a useful research tool. Using this system, each correct letter scores –0.02 logMAR, with a correct line of 5 letters scoring –0.1 logMAR. A normative value of Snellen 6/6 is equivalent to 0.0 logMAR. Also, the between-letter spacing is equal to one letter width, making the crowding effect constant for all lines. Repeatability of a test can be measured by calculating the coefficient of repeatability (Bland & Altman, 1986). This gives the 95% confidence limits for the amount of difference between two sets of results. It is calculated as 1.96 multiplied by the standard deviation of the mean differences between test and re-test data. The coefficients of repeatability (COR) for high contrast acuity for subjects of all ages vary with different studies. It has been determined as 0.2 logMAR (Reeves et al., 1991) and 0.16 logMAR (Lovie-Kitchin, 1988).

Near visual acuity is measured in clinical tests as word or sentence acuity. As such, it is described in Chapter 4.2.3 under reading tests.

4.2.2 Contrast Sensitivity

The measurement of high contrast VA is limited in its usefulness due to its lack of ability to determine a patient's ability to see large objects and low contrasts. For a more accurate estimate of visual function, it has been argued that some form of contrast sensitivity measurement is necessary (Maroon & Bailey, 1982; Rubin, 1986; Lennerstrand & Carl-Otto, 1989; Elliott et al., 1990; Rubin et al., 1994). The contrast sensitivity function (CSF) is a measure of contrast thresholds for a range of object sizes (Figure 4.1). Conventionally it is measured by determining the threshold contrast to sine wave gratings of varying spatial frequencies or sizes (Woods & Wood, 1995). However, there are a number of different types of contrast sensitivity tests available. These include grating tests (Arden & Jacobson, 1978; Ginsburg, 1984; Della Sala et al., 1985), edge contrast tests (Verbaken & Johnston, 1986) and letter charts (Regan & Neima, 1983; Pelli et al., 1988; Bailey, 1993). The tests used in the studies described in this thesis were chosen because they are considered reliable, are most suitable for low vision populations and the results obtained are appropriate for statistical analysis.

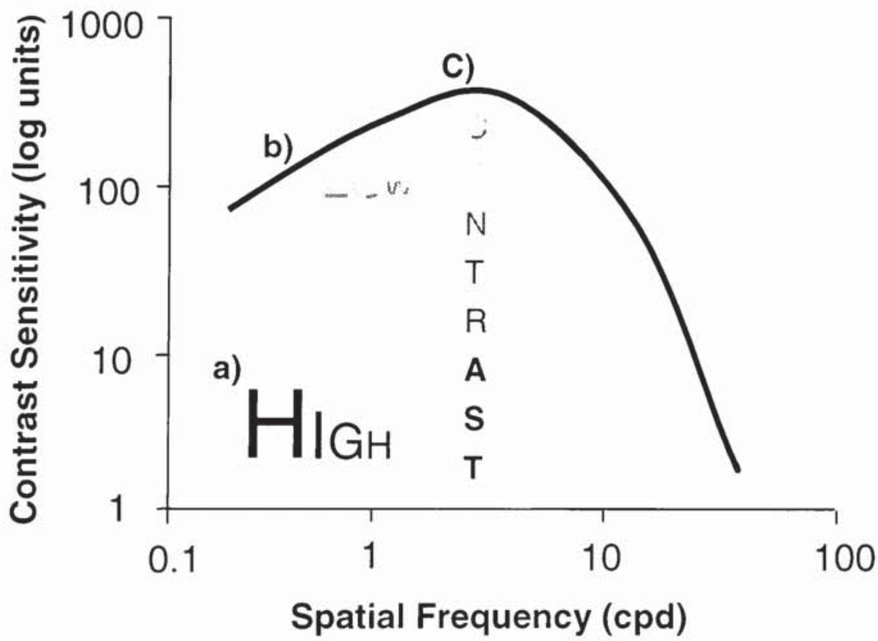


Figure 4.1. A typical contrast sensitivity function of a normally sighted observer. Higher contrast is required to detect smaller objects (higher spatial frequency). Objects finer than 30-60 cycles per degree (cpd) cannot be distinguished even when the contrast is 100%. This resolution limit is related to visual acuity. Peak contrast sensitivity occurs for medium spatial frequencies of 3-5 cpd. This figure is also a diagrammatic represention of the way in which contrast sensitivity is assessed: By a test comprising letters of either high (a) or low (b) contrast of variable size such as the Bailey-Lovie chart. c) A test comprising of letters of fixed size and variable contrast such as the Pelli-Robson chart. Adapted from Woods & Wood (1995).

Pelli-Robson Contrast Threshold Chart

The Pelli-Robson chart (Pelli et al., 1988) is a variable contrast letter chart consisting of 16 letter 'triplets' of constant size spread over eight lines (Figure 4.2). The recommended working distance is 1 metre, and although higher spatial frequencies (due to the use of letter targets) will be detected, the fundamental spatial frequency of the letters at this distance is about 0.5 to 2 cycles per degree. The contrast of each 'triplet' reduces in 0.15 log CS steps as the patient reads down the chart, from 0.0 log CS units (or 100% contrast) at the top left of the chart to 2.25 log CS units (or 0.56% contrast) at the bottom right. In the original instructions for the test, the last triplet where at least two letters were read correctly was scored. To improve the reliability, Elliott and co-workers (Elliott et al., 1990) suggested scoring each correct letter at 0.05 log CS units and scoring correct a call of 'C' for an 'O' and vice-versa. This latter method of scoring was used for the experiments in this thesis. The average score for a young 20-30 year old is 1.90-1.85 and the majority of older patients (>50 years) will obtain a score of at least 1.65 (Elliott et al., 1990; Elliott & Bullimore, 1993). The coefficient of repeatability of the Pelli-Robson chart is ±0.18 logCS (Elliott & Bullimore, 1993). When considering the contrast sensitivity function (CSF) (Figure 4.1), when the patient reads from the top to the bottom of the Pelli-Robson chart, in CSF space they are moving upwards from the abscissa slightly below (0.5 – 2 cpd) the peak frequency of the CSF.

Bailey-Lovie Low Contrast Acuity Chart

The Bailey-Lovie logMAR chart described above is also available with low contrast letters (10% contrast) (Bailey, 1993). To be precise, this chart is actually a measure of low contrast VA rather than a contrast sensitivity test *per se*. However, along with true contrast sensitivity tests, it is able to determine a patient's ability to detect low contrasts, something that is not achieved by the standard visual acuity tests described above. The position in which the test is located in CSF space is shown in Figure 4.1. These charts are scored in log units, in the same manner as the high contrast charts. Typically, normal patients perform just over 2 lines worse on the low contrast Bailey-Lovie chart compared with the high contrast chart (Brown & Lovie-Kitchin, 1989). This difference increases only slightly with age from about 0.22 logMAR at age 30 years to 0.25 logMAR by age 60 years (Brown & Lovie-Kitchin, 1989).

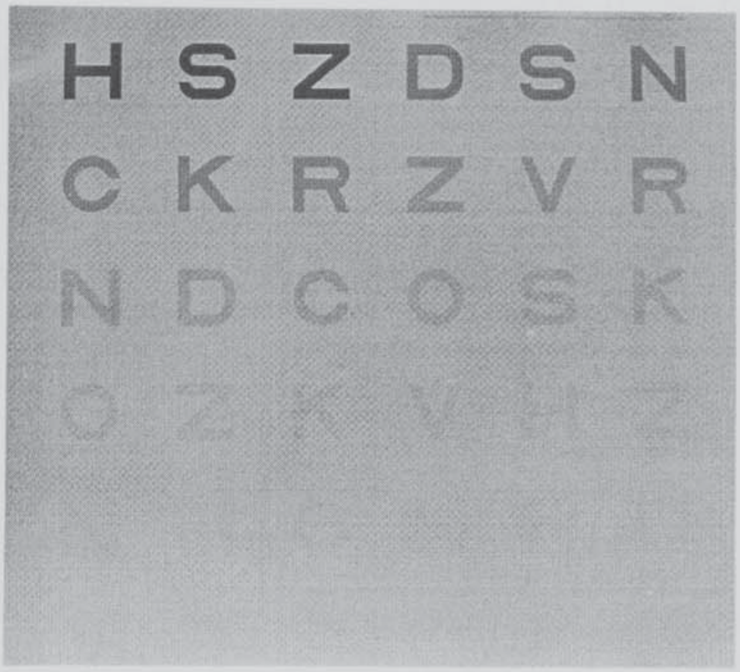


Figure 4.2. Pelli-Robson Contrast Sensitivity Chart.

4.2.3 Reading Tests

Reading is often the primary rehabilitation goal of the low vision patient (Farrall, 1991; Elliott et al., 1997). Clinical tests of reading can measure reading ability in terms of reading acuity and/or reading speed. Reading acuity is the smallest size text that an observer is able to read, regardless of the speed. Reading acuity does not correlate well with distance acuity (Sloan & Brown, 1963; Dickinson, 1998), and as such, a specific reading test is an important part of visual function assessment. There are a number of different charts available that have different formats as well as units of measurement. Some use meaningful sentences or even paragraphs (Sloan & Brown, 1963, Legge et al., 1989a; Mansfield et al.. 1993; Ahn et al., 1995) whereas others use unrelated words (Bailey & Lovie, 1980; Baldasare et al., 1986). Some of these charts measure reading speed as well as reading acuity (Bailey & Lovie, 1980; Baldasare et al., 1986; Mansfield et al., 1993); whilst both the computer-based and card versions of the MNREAD test (Legge et al., 1989a; Ahn et al., 1995) measure reading speed for text sizes below acuity threshold (i.e. the scales are not truncated).

The charts used in the experiments described in this thesis are the Bailey-Lovie Word-Reading Chart (Bailey & Lovie, 1980) and the Minnesota Low-Vision Reading Test (MNREAD) Acuity Chart (Mansfield et al., 1993). These charts were chosen because they were both designed for low vision observers and are based on a logarithmic progression of sizes (Bailey & Lovie, 1976). The advantages of this logMAR based system have been discussed in Chapter 4.2.1. Both these tests are described below:

MNREAD Acuity Chart

The MNREAD Acuity Chart was developed from the computer-based MNREAD test by Mansfield et al. (1993) (Figure 4.3). The sentences that make up the MNREAD Acuity Chart provide reading material that demands similar visual processing and eye-movement control to that required for normal text reading. Each sentence is 60 characters in length, and consists of words that appear in high frequency reading material for 7-8 year old readers. Each sentence is laid out in three equal-length lines, and the same number of characters per line are used at each print size. The sentences are printed in 19 different sizes, which are measured as the height of a lower-case 'x'. When viewed at the recommended 40 cm, the print sizes range from 1.3 to –0.5 logMAR (Snellen equivalent 6/120 to 6/1.8). As with the Bailey-Lovie acuity charts, each sentence on the MNREAD Acuity Chart is 0.1 logMAR units smaller than the previous sentence. Reading acuity can therefore be easily calculated when the card is used at non-standard viewing distances. The cards are printed with a serif font with proportional spacing in order to simulate text in newspapers and books. They are available in normal (black letters on white background) and reverse (white letters on black background) contrast.

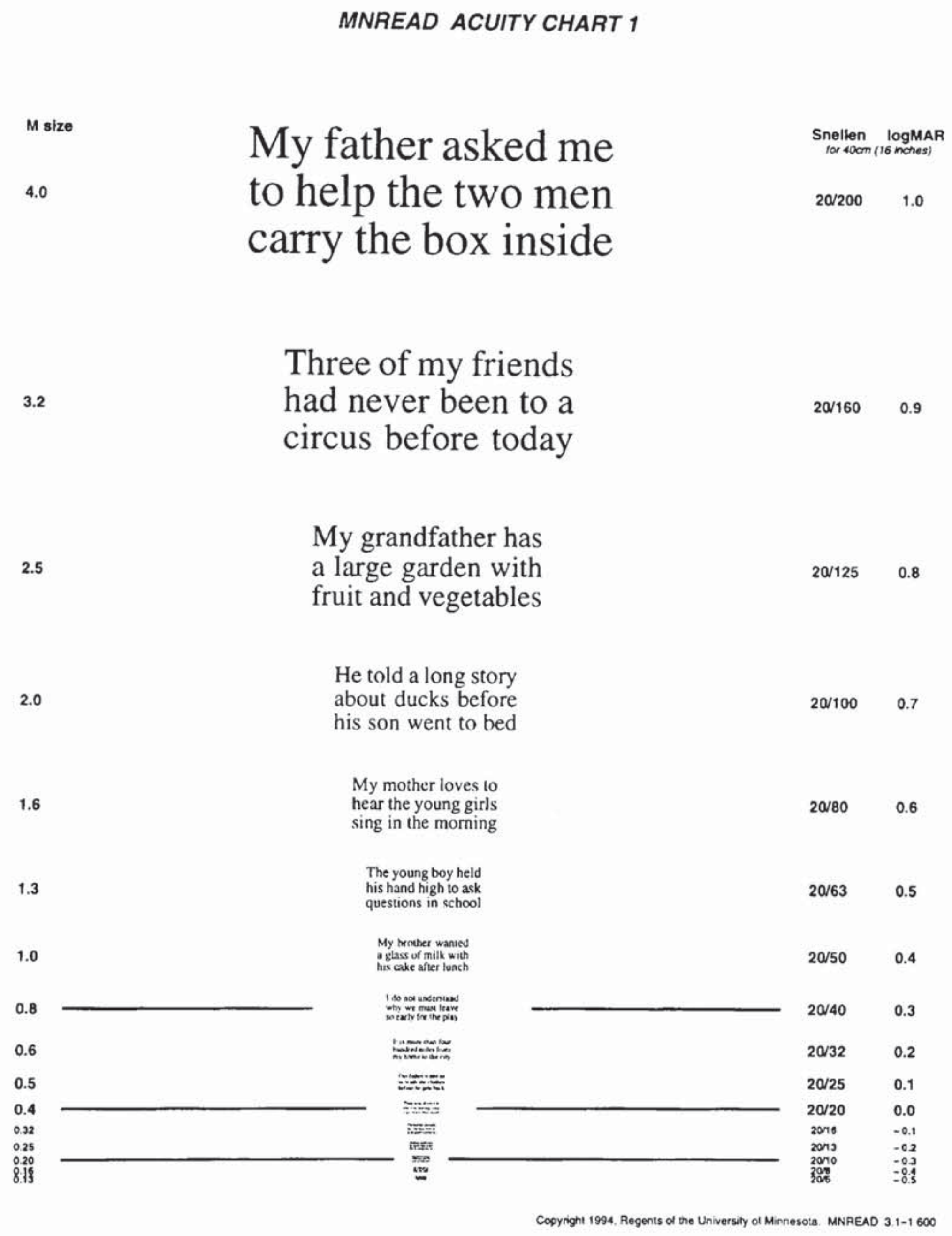


Figure 4.3. The MNREAD Acuity Chart. Actual size is 11 x 14 inches.

The patient is instructed to read the sentences aloud from large to small print sizes until they cannot read any words in a sentence. The reading time in seconds is recorded for each sentence on the score sheet provided (Figure 4.4). For an accurate measure of reading acuity, each sentence is divided into 10 'standard words' (Chapter 2.3.1) of 6 characters each (including a space), with each word counting as 0.01 logMAR. If the number of sentences in which the subject could read any of the words (number of sentences read), and the number of incorrect actual words (number of errors) is counted, the reading acuity (in logMAR) can be calculated using the following formula:

$$\text{Reading Acuity (logMAR)} = 1.4 - (\text{no. of sentences read} \times 0.1) + (\text{no. of errors} \times 0.01)$$

Equation 4.1

The MNREAD Acuity Charts can also be used to measure reading speed at different print sizes, and therefore the print sizes that enable maximum reading speed (MRS) can be determined. The patient is instructed to read each sentence aloud as quickly and accurately as possible. The time taken to read each sentence is measured to the nearest 0.1 sec and the words that are missed or read incorrectly are taken into consideration. Reading speed (wpm) can be calculated by:

$$\text{Reading speed (wpm)} = 60 \times (10 - \text{no. of errors})/(\text{time in seconds}) \quad \text{Equation 4.2}$$

Measurements obtained from the MNREAD Acuity Chart enable a plot of reading speed (wpm) against print size (logMAR) to be drawn for each reader (Figure 4.5). Inspection of the reading-speed plot will enable both the maximum reading speed (MRS), and the smallest print size that could be read close to the maximum reading speed (critical print size or CPS) to be estimated. Data obtained in the studies described in Chapters 7, 9 and 10 of this thesis are used to obtain reading–speed plots similar to those described in the instructions of the MNREAD Acuity Chart. In order to obtain more accurate MRS and CPS values, the data were analysed using an algorithm developed by Mansfield et al. (1996). This algorithm is described in Chapter 2.5.1.

Bailey-Lovie Word-Reading Chart

The Bailey-Lovie Word-Reading Chart (Bailey & Lovie, 1980) consists of lines of unrelated words. At the recommended viewing distance of 25 cm, the words range in size from 1.6 logMAR to 0.0 logMAR (6/240 to 6/6) in steps of approximately 0.1 log units. Depending on the letter size, there are between 2 and 6 words per line, and word lengths between 4 and 10 letters in length are used. At smaller letter sizes there are always 2 x 4, 2 x 6 and 2 x 10 letter words. The text is lower case Times Roman typeface in normal (black letters on white background) contrast. As with the Bailey-Lovie Distance Acuity Charts, the logarithmic progression enables its use at non-standard working distances. The progression also enables prediction of changes in reading performance that will result from changes of viewing distance, or the dioptric power or magnification of visual aids (Bailey & Lovie, 1980; Johnston, 1991).

To determine reading speed, Bailey & Lovie (1980) suggested measuring the time taken (in seconds) to read six words. One disadvantage of the chart is that there are only 2 or 3 words per line for print sizes larger than 1.0 logMAR. The suggested method of estimating reading speed would therefore not be possible at these larger sizes. Reading speed can be plotted as a function of print size.

MNREAD ACUITY CHART **CHART 1**

Name J. Smith	**Date** 20/1/2000
Eye tested OU☐ OS☐ OD☒	**Test distance** 40cm☒ other

1.3 logMAR 8.0 M 20/400 My father takes me to school every day in his big green car	**0.7 logMAR 2.0 M 20/100** He told a long story about ducks before 3.3 his son went to bed	**0.1 logMAR 0.50 M 20/25** Our father wants us to wash the clothes 3.9 before he gets back
1.2 6.3 20/320 Everyone wanted to go outside when the rain finally stopped	**0.6 1.6 20/80** My mother loves to hear the young girls 3.9 sing in the morning	**0.0 0.40 20/20** They would love to see you during your 4.2 visit here this week
1.1 5.0 20/250 They were not able to finish playing the game before dinner	**0.5 1.3 20/63** The young boy held his hand high to ask 3.7 questions in school	**–0.1 0.32 20/16** The teacher showed the children how to 4.8 draw pretty pictures
1.0 4.0 20/200 My father asked me to help the two men 4.0 carry the box inside	**0.4 1.0 20/50** My brother wanted a glass of milk with 3.4 his cake after lunch	**–0.2 0.25 20/13** Nothing could ever be better than a hot 8.0 fire to warm you up
0.9 3.2 20/160 Three of my friends had never been to a 3.4 circus before today	**0.3 0.8 20/40** I do not understand why we must leave 3.4 so early for the play	**–0.3 0.20 20/10** The old ~~man caught~~ a fish ~~here~~ when he 15.0 went out in his boat
0.8 2.5 20/125 My grandfather has a large garden with 4.4 fruit and vegetables	**0.2 0.6 20/32** It is more than four hundred miles from 3.7 my home to the city	**–0.4 0.16 20/8** Our mother tells us that we ~~should wear~~ 24.6 ~~heavy~~ coats ~~outside~~
		–0.5 0.13 20/6 One of my brothers went with his friend to climb a mountain

Reading time (sec)

Errors

Figure 4.4. An example of a score sheet for the MNREAD Acuity Chart. The reading speeds recorded in this figure are plotted on the graph of reading speed as a function of text size in Figure 4.5.

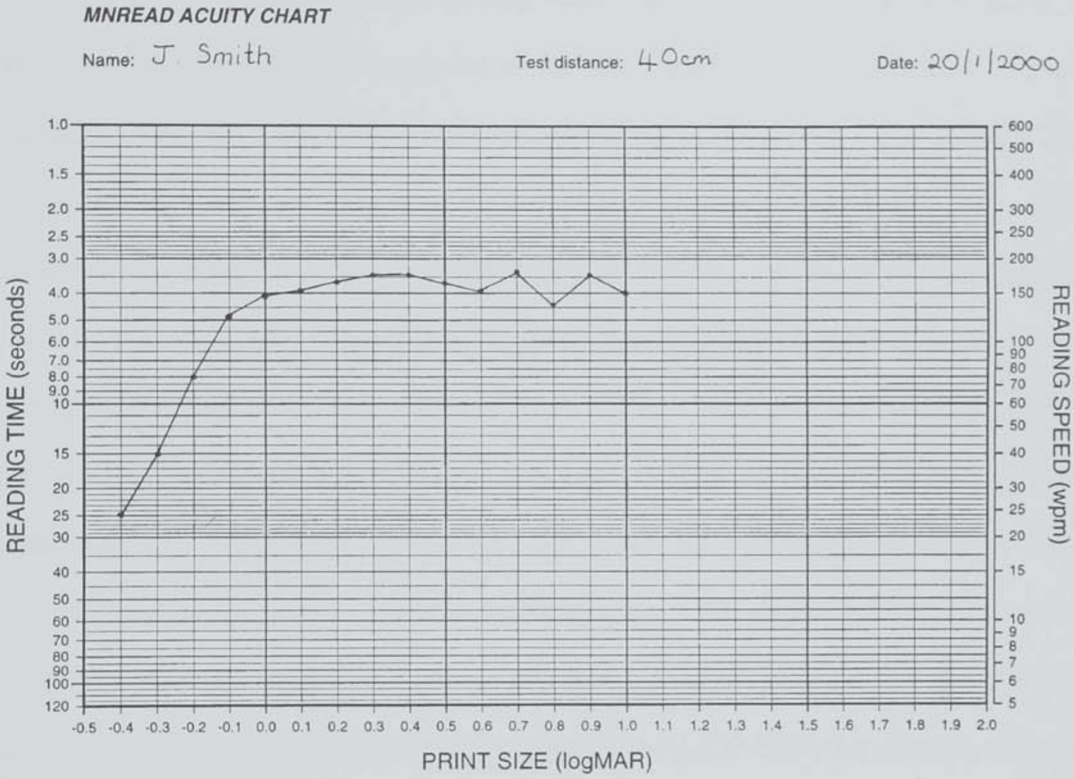


Figure 4.5. The reading speed results of the MNREAD Acuity Chart (as recorded in Figure 4.4) plotted as a function of print size (logMAR). Note that errors have not been accounted for in this graph. The MRS can be estimated by inspection of the speed at which the reading speed values form a 'plateau'. The CPS is the print size at which the reading speeds fall below the MRS.

4.3 A SUBJECTIVE MEASURE OF VISUAL FUNCTION – THE QUALITY OF LIFE QUESTIONNAIRE (QOLQ)

4.3.1 Introduction

The previous section outlined objective methods for measuring visual function. Under the World Health Organisation's (WHO) (World Health Organisation, 1980) classifications of low vision, these tests provide a measure of the vision impairment of the person. Vision impairment describes the reduced visual function of the visual system. For example, the impairment of a cataract patient would be uniformly blurred vision and the vision impairment of a glaucoma patient would be peripheral field loss. However, this does not tell us how a person functions. How disabled or handicapped a person is would depend on their visual needs. Visual disability is the lack, loss or reduction of a person's ability to perform certain tasks. It is the person's needs that determine whether a vision impairment causes a visual disability. Visual handicap considers the abilities of a person in the context of the social and physical environments within which they live. The degree to which a person is handicapped depends on the attitudes of the society towards its impaired and disabled people. In recent years, attention has become more focussed on the consequences of health care for the patient in their own environment. As such, subjective methods of assessing visual function have been developed that assess the individual's disability or handicap. Measures of visual disability and visual handicap both take into consideration the abilities of the person in the context of the social and physical environments within which they live. The following section describes the quality of life questionnaire as a subjective assessment of the patient's perceived visual performance.

4.3.2 Health-Related Quality of Life (HRQOL) Questionnaires

Over recent decades, health status measures have gradually developed to include a wide number of concepts including 'quality of life'. Encouraged by both government and public demand for accountability of health care services, clinicians and health care researchers are increasingly focusing their attention on the measurement of health care outcomes or consequences of care (Johnson, 1998). As such, there is a growing awareness of the importance of patients' subjective assessment of their own visual performance. Subjective measures have been developed in the form of questionnaires. These measures reflect perceived need for the patients and add meaning to, as well as justifying the use or appropriateness of, objective clinical tests.

The World Health Organisation Quality of Life Group (WHOQOL) define quality of life as 'individuals' perceptions of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns' (WHOQOL, 1998). Quality of life questionnaires therefore assess the perceived impact of ill-health on physical, psychosocial and other (sleep, hobbies, home management) aspects of life. Questionnaires are classified as being 'generic' or 'disease-specific'.

Generic instruments are designed for the general population and can be applied across demographic and cultural sub-groups. They are intended to be applicable across types and severity of disease, and across different medical strategies, and are designed to assess general health and functional status. An example of such a questionnaire is The Sickness Impact Profile (SIP) (Bergner et al., 1981), which assesses sickness-related dysfunction in 12 different categories, producing a score for each category. Categories can then be combined to produce a physical dimension score, a psychosocial dimension score, and an overall score. Another type of generic questionnaire is the Quality of Well-Being Scale (QWB), which characterises the health of a population for cost-effectiveness analyses. The scores of the different areas combine to produce a single index value, the quality-adjusted life years (QALY). This score can be used to compare the cost per QALY gained from different health interventions (Patrick & Deyo, 1989).

Disease-specific instruments are designed to detect changes in a patient's quality of life following an intervention within a particular type of disease or clinical condition. Their development arises from the need for clinical trials and practitioners to be able to measure clinically significant changes over time (Patrick & Deyo, 1989). Questionnaires that are specific allow accurate and comprehensive assessment of a particular clinical condition, but do not necessarily fully describe the range of disability and impairment experienced by sufferers of other conditions. In contrast, generic instruments allow comparisons to be made between different eye diseases, but may fail to address important issues within a specific situation or fail to respond to clinically important changes (Frost et al., 1998; Mangione et al., 1998).

4.3.3 Vision-Related Quality of Life (VRQOL) Questionnaires

In addition to the health-related quality of life (HRQOL) instruments described above, vision-related quality of life (VRQOL) questionnaires have also been developed that aim to address issues raised by the vision impaired. Similar to the HRQOL instruments, the vision-related instruments may be 'generic' and apply to a wide range of ophthalmic diseases and conditions (Frost et al., 1998; Mangione et al., 1998; Harper et al., 1999), or be 'disease-specific' to a particular type of vision loss or ophthalmic disease. Disease-specific questionnaires have been developed for a number of conditions including glaucoma (Lee et al., 1998), cataract and the effect of cataract extraction (Bernth-Peterson, 1981; Elliott et al., 1990; Mangione et al., 1992; Lundström et al., 1994; Steinberg et al., 1994; Pesudovs & Coster, 1998), and retinitis pigmentosa (Lowe & Drasdo, 1992; Geruschat et al., 1998).

National Eye Institute – Visual Function Questionnaire (NEI-VFQ)

One of the most commonly used vision-related quality of life questionnaires is the 51-item National Eye Institute – Visual Function Questionnaire (NEI-VFQ) (Mangione et al., 1998). This questionnaire is a generic type. It was designed to measure vision-related functioning and the influence of vision problems on HRQOL for common eye conditions. The content was developed from questioning of condition-specific focus groups. The focus groups contained people suffering from glaucoma, diabetic retinopathy, age-related macular degeneration, cytomegalovirus retinitis, age-related cataract or low vision of any cause resulting in visual acuity of 6/60 or poorer. The questionnaire provides a measure of overall health on a 5-level scale that ranges from excellent to poor and a measure of overall vision on a 6-level scale that ranges from excellent to blind. Each of these scores is achieved by combining results of a number of different general health and vision related sub-scales that are scored on a 0 to 100 scale, in which 100 represents the best possible score. These scales are designed so that they can be specific to a variety of diseases. In fact, the authors claim that the scores of these scales are able to predict the potential problems faced by patients with particular conditions. For example, age-related macular degeneration patients scored badly in scales affected by deficits in central acuity. However, the group of low vision patients, probably due to their heterogeneity, scored poorly in almost all sub-scales.

The findings of the focus-group questioning was reported to show that the influence of vision problems on HRQOL was similar across conditions. For this reason, the authors suggest that a more generic vision-targeted HRQOL questionnaire could have content validity for persons with various eye conditions. The questionnaire includes questions associated with psychological and emotional issues of vision impairment, as well as practical ability of various tasks. It therefore provides a complete assessment of vision related quality of life that can be applied to different causes of vision impairment.

The Vision-Related Quality of Life (VQOL) Instrument

The questionnaire used in the studies described in Chapters 5 and 6 of this thesis was the VQOL instrument (Frost et al., 1998). It was developed for the measurement of vision-related quality of life. The questionnaire is specifically designed for the assessment of ophthalmic interventions and has a modular design.

The questionnaire (Frost et al., 1998) was developed from an initial pool of 232 questions, which were gained from questioning of focus groups. These questions underwent a pre-testing phase, which tested the questions on individuals with a wide variety of ocular pathologies, levels of visual impairment and social backgrounds. This phase of testing enabled further refining of issues already generated and enabled modification of the questionnaire in order to maximise its relevance. The result of this pre-testing phase is a 139 item 'parent' questionnaire (the VQOL) from which individual items or groups of items can be selected. Each item in the 'parent' questionnaire is a 6-point ordinal scale which ranges from 0 (no problem) to 5 (extreme problem). From the 'parent' questionnaire, a 'core' questionnaire (the VCM1) was developed. It contains ten items referring to physical, social and psychological issues and acts as a global measure of concern about vision. The reliability of the test, or the likelihood of an individual obtaining a similar score on re-test was high (alpha = 0.93). Validity assesses how well the measure accurately represents the area of interest, and this was also found to be high. The VCM1 score ranges from 0.0 (no problem) to 5.0 (extreme problem) and is strongly associated with responses to questions about a wide range of quality of life issues including mobility, reading and leisure. In addition to the VCM1, other items can be selected from the 'parent' questionnaire to meet particular needs in specific studies. It can therefore be made relevant to specific groups of subjects. In this thesis we were interested in reading with central field loss (CFL), so a reading module was used. The items that were associated with reading were chosen and combined into a single scale ranging from 0.0 (no problem) to 5.0 (extreme problem). This section of the questionnaire was described as the 'reading scale'. The values for each question within each section (VCM1 and reading scale) were summed for each subject to provide a total score for the VCM1 (Range: 0-50) and reading scale (Range: 0-75). Each total score was then divided by the number of questions in each section (i.e. 10 for the VCM1 and 15 for the reading scale) providing values with a range from 0-5.

This questionnaire was chosen for use in this thesis over a more commonly used instrument such as the NEI-VFQ due to the modular design. The VCM1 contains questions that provide a more global measure of concern about vision. In addition, groups of questions can be taken from the pool of questions making up the 'parent' questionnaire that are applicable to the individual or subject group of interest. For example, the group of reading related questions chosen for the reading scale used in the studies described in Chapters 5 and 6 are particularly pertinent to central field loss patients, who are known to have difficulties with reading. The responses to this group of relevant questions can then be allocated a specific score. The ability to adapt the questionnaire to the subject group minimises irrelevant questions that may occur in a more generic design such as the NEI-VFQ. It also isolates the responses to the topic(s) of interest, which minimises the chance of bias from the responses to questions of more peripheral interest.

4.4 SUMMARY

In a clinical setting, measures of visual function are used to determine the success or otherwise of patient management, surgery or rehabilitation, as well as detecting deviation from 'normality'. This assumes that the results on objective tests of visual function equate with how a patient feels about their vision or copes in daily life. Although a necessary universal measure that can be compared between individuals and populations, objective results ignore the individual needs and situation of a patient. In every day living, these individual circumstances could place an entirely different meaning on the same numerical result obtained from two patients. Quality of life questionnaires are a subjective measure of perceived visual performance that can be used in addition to objective clinical tests. By considering the environment or visual needs of the individual, they are able to place a true life meaning on the results obtained from the objective visual function tests. In an era where the demand for accountability of health care services is increasing, quality of life questionnaires are being used more and more for clarifying health care outcomes.

Chapter 5

VISUAL FUNCTION AND SUBJECTIVE QUALITY OF LIFE IN ACQUIRED MACULAR DISEASE

5.1 INTRODUCTION

Macular degeneration is a disease process that leads to loss of central vision. The presence of a central scotoma causes daily difficulties for those affected, in particular with regards to reading (Chapter 2). The precise measurement of visual function in patients with acquired macular disease is necessary for both the estimation of need for therapeutic and supportive interventions and for the measurement of the outcomes of such care.

High contrast distance visual acuity (VA) (Chapter 4.1.1) is the most commonly used measurement of vision in clinical practice. It is from this measurement that many clinical and surgical decisions are made in the process of patient management and treatment. Therefore, it is assumed that the measurement of a patient's ability to see high contrast letters is a good indication of their everyday visual function. However, a high contrast visual acuity measurement can actually be a poor predictor of a number of aspects of visual function (Hess & Woo, 1978; Paulsson & Sjostrand, 1980; Maroon & Bailey, 1982; Owsley & Sloane, 1987; Lennerstrand & Carl-Otto, 1989; Elliott & Hurst, 1990; Elliott et al., 1990; Mangione et al., 1994). Other measures of visual function can be better predictors of visual performance. For example, contrast sensitivity has been measured in different patient groups and found to correlate well with various aspects of visual ability including orientation and mobility (Maroon & Bailey, 1982; Lennerstrand & Carl-Otto, 1989; Elliott et al., 1990;

Rubin et al., 1994), reading speed (Rubin, 1986; Leat & Woodhouse, 1993) and driving (Rubin et al., 1994). Low contrast VA has been shown to be better than high contrast VA at predicting problems with orientation and discrimination in patients with macular degeneration (Lennerstrand & Carl-Otto, 1989).

Reading is often the primary rehabilitation goal of the low vision patient with central field loss (Farrall, 1991; Elliott et al., 1997). A number of studies have investigated the relationship in low vision observers between reading speed, as a measure of reading performance, and clinical measures of visual function. High contrast VA has been shown to be unrelated (Goodrich et al., 1977; Brown, 1981; Legge et al., 1989b) or weakly related (Sloan & Habel, 1973; Krischer & Meissen, 1983; Legge, 1991; Legge et al., 1992; Ahn & Legge, 1995) to reading speed (Chapter 2.5.2). However, previous authors have found a correlation between low vision reading speed and contrast sensitivity when contrast sensitivity was measured using gratings (Brown, 1981; Rubin & Legge, 1989; Leat & Woodhouse, 1993). The measurement of contrast sensitivity is therefore likely to be of value in the assessment of patients with acquired macular disease.

Chapter 4 of this thesis describes the two methods that can be used to determine which tests of visual function are relevant to visual performance. Vision test results can be compared with performance-based measures, for example reading speed or the time taken to complete an obstacle course. Alternatively, vision test results can be compared with self-reported visual performance measured as the score of a visual performance questionnaire. In this study a questionnaire-based approach was used to determine subjects' perceived quality of visual performance. Visual performance associated with reading was examined specifically, as well as general visual performance. This is because the subject group all have central field loss (CFL), shown in Chapter 2 as being particularly detrimental to tasks such as reading. Individual questions about reading performance have been asked in other questionnaires (Elliott et al., 1990; Mangione et al., 1992; Sloane et al., 1992; Lundström et al., 1994; Steinberg et al., 1994; Mangione et al., 1998), but in the present study a wider range of reading questions were employed, the results of which were combined as a separate score. These questions were derived from patients' own comments on vision-related quality of life. There is a growing awareness of the importance of patients' subjective assessment of their own visual performance. Subjective measures reflect perceived need for the patients and add meaning to, as well as justifying the use or appropriateness of, objective clinical tests.

5.2 AIMS

In this study, the reading performance of macular disease patients was of particular interest due to the detrimental effect CFL has on this visual task. Many studies have used reading speed as a measure of reading performance. However, it cannot be assumed that reading speed is necessarily the measure upon which readers base their perceived performance. Therefore the aim of this study was to determine, without prior assumptions, which tests of visual function correlated best with perceived reading performance, as well as those that correlated with general perceived visual performance. We studied patients with acquired macular disease as representative of CFL patients. The ability to understand and quantify the subjective visual performance of the vision impaired is important if we are able to accurately determine the success or otherwise of the management of these patients.

5.3 MATERIALS AND METHODS

5.3.1 Subjects

The subjects for this study were all patients of Birmingham Heartlands & Solihull National Health Service Trust. They were due to undergo surgery to remove choroidal neovascular membranes (CNV) that were idiopathic or associated with presumed ocular histoplasmosis syndrome (POHS) or age-related macular degeneration (ARMD) (Benson et al., 1998b). There were 12 patients (11 females and 1 male; age range 23 – 46 years) with idiopathic membranes or membranes associated with POHS and 16 ARMD patients (9 females and 7 males; age range 51 – 80 years). With sub-foveal membranes, these subjects are a selective sub-set of all patients with maculopathies. However, they can be considered representative of late stage maculopathy patients (IAMESG, 1995) because they all have loss of central visual field. It is central field loss that is the most debilitating characteristic of macular disease (Faye, 1984) and therefore it is important to be able to assess its effect on quality of life.

Aston University and Birmingham Heartlands and Solihull Hospital Ethics Committee approvals were obtained and all patients gave informed consent.

5.3.2 Quality of Life Questionnaire

The questionnaire used in this study was the VQOL instrument (Frost et al., 1998) which was developed for the measurement of vision-related quality of life. The questionnaire is specifically designed for the assessment of ophthalmic interventions and has a modular design. Details of its development and the assessment of its reliability and validity are discussed in Chapter 4.2.3.

In the present study the core group of questions, the VCM1, was used in addition to a group of questions associated with reading, called the Reading Scale. The values for each question within each section (VCM1 and Reading Scale) were summed for each subject to provide a total score for the VCM1 (Range: 0-50) and Reading Scale (Range: 0-75). Each total score was then divided by the number of questions in each section (i.e. 10 for the VCM1 and 15 for the Reading Scale), and these values (range 0-5) were used for regression analysis. If the patient was unable to read the questionnaire it was administered by the examiner in a standardised manner. All subjects were given the same instructions and were asked to answer the questionnaire considering their eyesight over the past month, using both eyes and whilst using any habitual spectacles, contact lenses or low vision aids.

5.3.3 Visual Function Tests

All tests were carried out in the same room with photopic lighting conditions provided by two fluorescent strip ceiling lamps and a 60 Watt angle-poise lamp for near tasks. All tests were carried out in the same order for each subject by the same examiner.

The following tests were completed after subjective refraction was carried out for each subject. Details of these tests are given in Chapter 4.

1. *High contrast distance visual acuity* with best refraction was measured using a 3 metre externally illuminated Bailey-Lovie logMAR Chart (Bailey & Lovie, 1976). Acuity was measured monocularly in each eye with the fellow eye covered with a black patch. Subjects reported no problems with rivalry under these conditions. Visual acuities were recorded on a letter by letter basis, where each letter read was given the value 0.02 log units. The chart luminance was 95 cd/m^2, as measured with a Minolta CS-100 spot photometre.
2. *Low contrast distance visual acuity* measured with a 3 metre externally illuminated Bailey-Lovie logMAR Chart. Visual acuity was measured monocularly in each eye and acuities were recorded in the same way as for the high contrast chart. The chart luminance was 95 cd/m^2 and the Michelson contrast was 10%.

3. *Near word acuity* measured with a Bailey-Lovie Near Word Chart (Bailey & Lovie. 1980) at 25 cm with a +4.00 DS reading add if necessary. Acuities were measured monocularly and were recorded as the smallest letter size where at least 3 of the 5 words on the line were read correctly. The chart luminance was 120 cd/m^2.
4. *Contrast sensitivity* using a Pelli-Robson Chart at 1 metre. Contrast sensitivity was measured monocularly and scored per letter with each correctly read letter given a value of 0.05 log units (Elliott et al., 1991). A 'C' mistaken for an 'O' and vice-versa was taken as correct (Elliott et al., 1990). The chart luminance was 85 cd/m^2 and a +1.00D add was used where necessary.
5. *Oral reading speed* was measured binocularly using a paragraph of justified text of 66 words in length, which was of early secondary school level. All subjects had an educational standard that exceeded this level ensuring that reading speed measures were not compromised by difficulty in comprehension of the text. The time taken to read the passage was recorded in words per minute (wpm). The text size was at least 0.2 log units larger than the near word acuity (a conservative guideline for prescribing magnification (Lovie-Kitchin & Bowman. 1985; Whittaker & Lovie-Kitchin, 1993) as measured with the Bailey-Lovie Near Word Chart. Errors were not recorded since few were made at this level above acuity threshold. The chart luminance was 120 cd/m^2.

The above tests were carried out after subjective refraction in order to subsequently facilitate eventual comparisons after surgery. Although subjects would have responded to the questionnaire with regards to their habitual visual performance, there was no statistically significant difference between the best corrected and habitual visual acuity for either the better ($t(27)$ 0.45, $p=0.65$) or worse eye ($t(27)$ 0.33, $p=0.75$). The best corrected visual acuities were therefore used in the analysis.

5.3.4 Analysis

Monocular vision test results were obtained from right and left eyes for the 28 subjects but were separated according to whether they were from the better or worse eye, according to high contrast distance visual acuity (values ranged between –0.14 and 1.68 logMAR). The data were analysed using both SPSS® and SAS® software. The psychometric properties of the group of reading questions were evaluated by calculation of inter-item correlations (Spearman), item-total correlations and Cronbach alpha coefficient. Principal components analysis was also performed. The relationships between Reading Scale, VCM1 and vision test results were also investigated by calculating Spearman correlation coefficients. The associations between vision test results and questionnaire scores were further explored by performing step-wise forward multiple regression analysis with the vision test results as potential explanatory variables.

The variables for each subject were as follows:

1. VCM1 score.
2. Reading Scale score.
3. High contrast logMAR acuity in each eye.
4. Low contrast logMAR acuity in each eye.
5. Pelli-Robson contrast sensitivity (CS) in each eye.
6. Bailey-Lovie near word acuity in each eye.
7. Binocular text reading speed.

The VCM1 and Reading Scales were categories, and as such are were ordinal values. However, the scores for each scale were accumulative, and therefore these values were very likely to be normally distributed and therefore appropriate to use within regression analysis. Tests for skewness and kurtosis also indicated that the sample population did not deviate significantly from a normal distribution, thus ensuring appropriate use of the analyses described.

5.4 RESULTS

The descriptive statistics for the questionnaire and each of the tests of visual function are shown in Tables 5.1 and 5.2. There was a large variation in performance between subjects. The group of reading questions showed high internal consistency. Spearman inter-item correlation coefficients are a measure of how each question within the questionnaire correlated with every other question. These values ranged between 0.7 and 0.9, where 0 represents no correlation and 1.0 represents a perfect correlation. Corrected item-total correlations, a measure of how well each individual item correlates with the total of the remaining items, (Table 5.1) were all above 0.8. The reliability of the test or the likelihood of an individual obtaining a similar score on re-test was high, as shown by the high Cronbach alpha coefficient of 0.98. Principal components analysis found a dominant first principal accounting for 77% of the variation in the data, one principle component accounting for 8%, one accounting for 5%, and all other components accounting for 2% or less, suggesting the presence of a single underlying factor. All reading items were evenly weighted in the first principal component. These results suggest that the Reading Scale is a valid and reliable questionnaire for assessing perceived reading performance.

Table 5.3 shows the correlations between each section of the questionnaire and each of the visual function tests. When analysed in this univariate manner, all of the tests of visual function correlated significantly with perceived visual performance. For both questionnaire scales (Reading Scale and VCM1) there were higher correlations for the better eye results compared with the worse eye results. Also, each of the better eye and binocular visual function test results showed a slightly higher correlation with the Reading Scale than the VCM1. The worse eye measurements correlated more highly with the VCM1 than the Reading Scale. There are limitations to this analysis however, as it does not tell us which tests of visual function explain most of the variation in perceived visual performance. For this reason multiple regression analysis by the forward method was used to highlight the most significant visual function tests and the results of this analysis are shown in Table 5.4. Step-wise multiple regression analysis determines the relationships between a variable of interest (dependent variable) and a number of independent variables. From the group of independent variables, it chooses which variable(s) are most able to explain or predict the dependent variable. The forward method chooses these variables in order (greatest to least) of their ability to predict the dependent variable.

The visual function test that accounted for most of the variation in the VCM1 was the binocular text reading speed (R^2=0.65, $p<0.001$). The high correlation between binocular text reading speed and VCM1 score is shown in Figure 5.1.

The tests that accounted for most of the variance in the Reading Scale were the better eye low contrast VA which explained 78% of the variance ($p<0.001$), and the contrast sensitivity in the better eye which explained an additional 5% of the variation ($p<0.001$) (Table 5.4). Figure 5.2 shows the relationships between the better eye low contrast VA and contrast sensitivity in the better eye with the Reading Scale.

Despite the wide age range of the subject group, when age was included as a factor in the analysis it did not correlate with any of the variables. For this reason it was not included in the analysis described here.

				SCORE			
ITEM	**0**	**1**	**2**	**3**	**4**	**5**	**Item Total Correlation**
1. Dials	10	3	5	1	5	4	0.883
2. Labels	8	3	6	3	3	5	0.885
3. Coins	15	3	2	1	5	2	0.884
4. Cheques	15	1	3	4	2	3	0.881
5. Handwriting	16	2	1	3	3	3	0.856
6. Forms	11	2	5	3	1	6	0.940
7. General Reading	3	3	7	5	6	4	0.896
8. Ordinary Print	4	4	6	2	4	8	0.889
9. Large Print	12	4	5	2	3	2	0.905
10. Small Print	3	4	5	5	2	9	0.889
11. Reading Mail	11	0	6	4	2	5	0.940
12. Medicine Label	8	3	4	5	2	6	0.923
13. Wrist-watch	11	1	5	2	6	3	0.853
14. Telephone	12	2	6	3	2	3	0.852
15. Phone Directory	8	1	5	3	2	9	0.900

Table 5.1. Number of responses in each category for the 15 reading questions of the questionnaire. Item total correlation is also shown for each question.

The reading questions are: How much has your eyesight interfered with the ability to...? 1. read numbers on dials; 2. read labels or prices on tins, packets etc; 3. identify coins, bank-notes; 4. write cheques/pay bills; 5. see own handwriting; 6. fill forms; How much has eyesight interfered with...? 7. reading in general; 8. reading ordinary sized print; 9. reading large print; 10. reading small print; 11. reading mail; 12. reading labels/instructions on medicines; 13. seeing numbers/hands on a wrist-watch; 14. seeing numbers on a telephone dial; 15. seeing a number in the phone directory.

The response numbers indicate: 0=Not at all; 1=Hardly at all; 2=A little; 3=A fair amount; 4=A lot; 5=Can't do because of eyesight; 6=Can't do for reasons other than eyesight (N.B. This response option was not chosen for any of the questions.).

	Mean	Std. Dev.	Median	Minimum	Maximum
Questionnaire Score					
VCM1	1.88	0.97	1.70	0.5	3.8
Reading Scale	2.03	1.68	1.55	0.0	4.9
Vision Tests					
HCVA worse eye (logMAR)	0.93	0.36	0.95	0.20	1.68
HCVA better eye (logMAR)	0.30	0.41	0.16	-0.12	1.46
LCVA worse eye (logMAR)	1.24	0.35	1.20	0.54	1.84
LCVA better eye (logMAR)	0.57	0.42	0.43	0.10	1.50
CS worse eye (log units)	0.96	0.36	0.95	0.00	1.65
CS better eye (log units)	1.40	0.36	1.50	0.45	1.80
Near VA worse eye (logMAR)	1.05	0.35	1.00	0.40	1.60
Near VA better eye (logMAR)	0.44	0.43	0.30	0.00	1.50
Binoc Reading Speed (wpm)	141.6	65.6	154.8	0.00	216.5

Table 5.2. Descriptive statistics for the questionnaire and the vision tests for all subjects.

Variables		VCM1	Reading Scale
VCM1	R	1.00	0.78
	p	0.001	0.001
Reading Scale	R	0.78	1.00
	p	0.001	0.001
HCVA worse eye	R	0.40	0.47
	p	0.033	0.01
HCVA better eye	R	0.76	0.86
	p	0.001	0.001
LCVA worse eye	R	0.34	0.30
	p	0.07	0.13
LCVA better eye	R	0.79	0.88
	p	0.001	0.001
CS worse eye	R	-0.36	-0.44
	p	0.061	0.020
CS better eye	R	-0.66	-0.66
	p	0.001	0.001
Near VA worse eye	R	0.34	0.24
	p	0.075	0.091
Near VA better eye	R	0.77	0.85
	p	0.001	0.001
Binocular Reading	R	-0.81	-0.77
Speed	p	0.001	0.001

Table 5.3. Correlations (R and p values) between each section of the questionnaire and each of the visual function tests.

Y-VARIABLE	X-VARIABLE	R	R^2	F	p<
VCM1	Binocular Reading Speed	0.81	0.65	48.50	0.001
Reading Scale	Better Eye Low Contrast VA	0.88	0.78	93.04	0.001
	CS Better Eye	0.91	0.83	60.53	0.001

Table 5.4. Results of the stepwise multiple regression analysis by the forward method for the 28 subjects with VCM1 and Reading Scale as the dependent (Y) variables and the range of visual function tests as the independent (X) variables. Only significant relationships are shown.

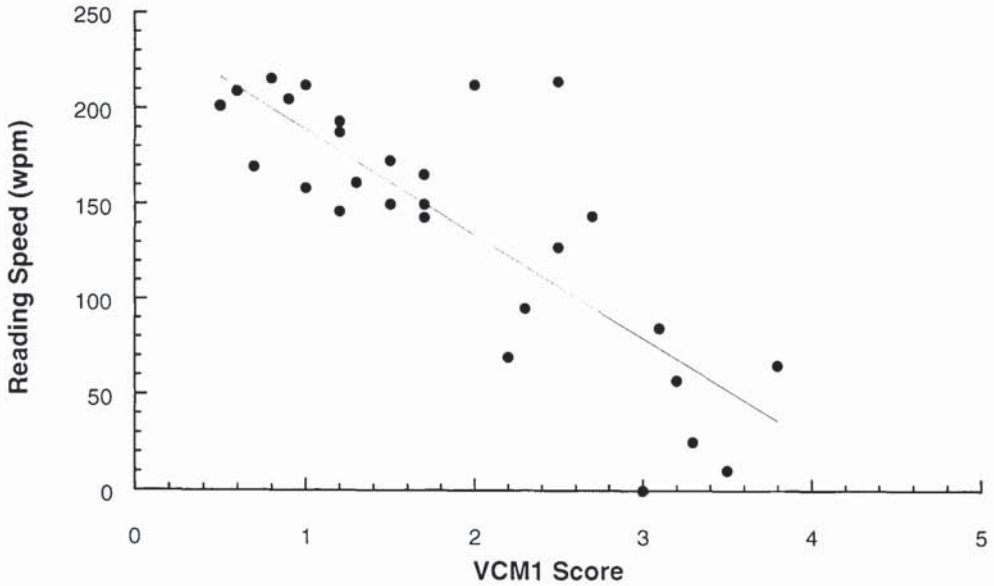


Figure 5.1. Binocular text reading speed (wpm) as a function of VCM1 score ($R^2 = 0.65$, $p<0.001$).

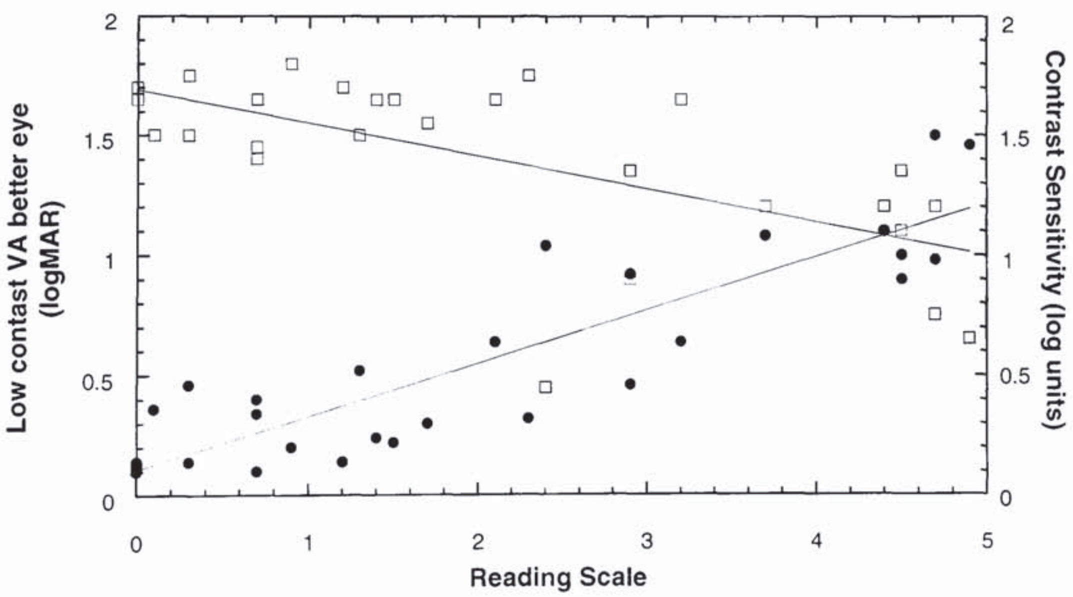


Figure 5.2. Low contrast VA in the better eye (closed circles) and CS in the better eye (open squares) as a function of Reading Scale.

5.5 DISCUSSION

All tests of vision correlated highly with reported vision-related quality of life, but low contrast tests explained most of the variance in self-reported problems with reading, and also correlated highly with overall concern about vision.

The results showed a close relationship between the VCM1 and clinical tests of visual function. The test that most strongly correlated with the VCM1 was the binocular text reading speed, accounting for 65% of the variance in the data. The impact that reading ability has on these macular disease patients' overall opinion of their vision is understandable when considering the importance of an intact central field on high acuity tasks such as reading, and the importance of such tasks in daily life.

Low contrast visual acuity and contrast sensitivity in the better eye accounted for significant amounts of the variance in the Reading Scale. Reading is generally considered to be a high contrast task, but the present study confirms earlier suggestions (Maroon & Bailey, 1982; Rubin, 1986; Lennerstrand & Carl-Otto, 1989; Elliott et al., 1990; Leat & Woodhouse, 1993; Rubin et al., 1994) that contrast sensitivity, within the limits of spatial resolution, may be more important than previously recognised. Apart from the controlled tasks undertaken in the clinic or laboratory, reading tasks are often of less than optimal contrast. The everyday reading tasks that were asked about in the questionnaire had been raised as issues by patients and support workers. They included reading labels and dials, as well as books, papers and magazines. All these reading materials can have less than optimum contrast and are often viewed under less than ideal conditions. Therefore, when a patient is asked about reading performance, they may be considering a relatively low contrast rather than a high contrast task. The relationship between contrast and reading in terms of 'contrast reserve' has been investigated (Whittaker & Lovie-Kitchin, 1993). It was found that for 'spot' or survival reading, a print contrast of 3 times the subject's threshold contrast (or contrast reserve of 3) was required whilst print size needed to be at acuity threshold (acuity reserve 1:1). Fluent reading requires much greater contrast and acuity reserves. Low-vision subjects with central field loss (CFL) have been shown to have a decreased tolerance to contrast reduction. The dependence of reading on contrast, however, has the same form as normals if scaled appropriately (Rubin & Legge, 1989). Hence, CFL patients are behaving like normal observers reading lower contrast text. These findings of an increased dependence on contrast for CFL subjects and the high correlation of perceived reading function and low contrast visual function found in this study suggest that print contrast is extremely important for reading. It is possible however, that poor contrast sensitivity may be the result of a larger central scotoma and poor reading performance may actually be related more closely to the use of more peripheral retina than contrast sensitivity *per se*. Regardless of the cause, contrast sensitivity appears to be important to CFL patients and therefore these findings have implications not only for the choice of vision tests but also for the design of reading materials. For example, consideration should be given by manufacturers when labelling products so that maximum word visibility can be obtained that will enable the easiest identification of the product and the information provided. The results also reinforce the need for eye-care professionals to give advice with regards to minimising glare and using focal lighting to optimise the person's contrast threshold (Rubin et al., 1994).

The better eye low contrast VA explained more of the variance in the Reading Scale than the Pelli-Robson contrast sensitivity of the better eye. Although low contrast VA and contrast sensitivity are similar, they are two distinct measurements. Low contrast VA measures acuity at low contrast, whereas CS measures sensitivity to contrast at a fixed size target. Low contrast VA may be more relevant in relation to reading as everyday tasks require patients to read text much closer to their acuity threshold than the letters on the Pelli-Robson chart.

Reading speed is often the dependent variable of reading research studies. In this study we found a significant correlation between reading speed and perceived reading (Table 5.3), but it was not the strongest relationship of any of the tests of visual function (Table 5.4). Discrepancies between self-reported visual performance and measured reading speed have been found previously. Friedman et al. (1999) found 10% of their subjects showed a substantial discrepancy between self-reported difficulty reading a newspaper and measured reading speed. They suggested these subjects may represent a transitional state in progressing from being fast to slower readers as function declines. Discrepancies may also occur because the measured function, although related, is not exactly the same function as is being reported on. In this study, ten of the fifteen reading related questions ask about 'spot' reading tasks such as reading labels, dials and prices rather than fluent reading tasks. The contents of these questions were derived from patients and support workers, which therefore suggests that 'spot' reading tasks are considered important to low vision patients. The perceived reading ability measured by the questionnaire is therefore largely a subjective measure of 'spot' reading ability rather than fluent reading ability. It would be anticipated that reading speed is better related to fluent and continuous reading than to 'spot' reading tasks. Although reading speed is often used as a measure of reading performance in research studies, our results suggested that reading speed could not be assumed to be the attribute upon which readers base their perceived reading performance.

The correlation between perceived visual quality of life and visual function will, to an extent, be specific to the cause of low vision and the types of visual function affected by the disease. Results similar to those found in this study would not necessarily be found for subjects with other visual problems. The subjects in this study all had late stage maculopathy and CFL. These findings may not be as applicable to those with earlier macular degeneration, but can be considered to be applicable to those with actual loss of central field. Further, different tasks may depend more heavily on different aspects of visual function. For example reading tasks require different visual qualities to those required for good orientation and mobility.

For these reasons, disease-specific questionnaires have been suggested to be more appropriate than generic questionnaires when considering a single disease group of subjects (Patrick & Deyo, 1989; Mangione et al., 1992; Wu et al., 1996). The choice of questionnaire for the subject group (and subject group for the questionnaire) is therefore important to consider when analysing the results. The main advantage of using the VQOL in this study is that it is modular. It contains one general section consisting of questions applicable to any group of people with visual problems and one section consisting of questions about a problem with which this group of patients have specific difficulties.

The subjects in this study were predominantly female. It is possible that a predominantly male group may have given different answers, but this is unlikely. In a comparison of self-reported and performance-based measures in the Beaver Dam Eye Study, gender differences were found to be small (Klein et al., 1999). Also, Monestam & Wachtmeister (1998) found that female cataract patients reported more problems with distance estimation and orientation, compared to men with similar pre-operative acuity. However, the observed gender differences were not consistent across a broader range of symptoms, and did not extend to self-reported reading ability.

The results of the correlation and regression analyses agreed with previous findings (Steinberg et al., 1994) that subjective appreciation of visual performance is more closely associated with visual performance in the better eye or binocularly. This suggests that these results are more important than worse eye measurements when considering performance in daily life.

When considering the results of the study, it is important to remember that perceived visual performance is not solely dependent on visual variables alone. A psychological or emotive element will also contribute to how well a patient believes they can see. Deterioration in the self-reported quality of life of patients can be a result of anxiety and it has been suggested that anxiety can occur prior to the stage where real difficulties are experienced (Ross et al., 1984). Studies have also noted that low vision patients (Elliott et al., 1990) and also the elderly (Ball & Owsley, 1993), can sometimes be poor at providing an accurate global description of their visual ability. Similarly, a short-term problem can be considered to be more distressing (and therefore more debilitating) to the patient than the same problem that has been evident for some time. In relation to this study, it would be expected that due to the emotional nature of the VCM1 questions, the VCM1 results would have been more affected by psychological factors than the Reading Scale. This would be seen in the results as weaker correlations between the visual function tests and the VCM1 score due to increased noise. However, the correlations between subjective and objective measures of visual function are high in both the Reading Scale and the VCM1, explaining up to 75% of the variance in the questionnaire scores. Such high correlations suggest that in this group of subjects, the visual aspects account for the vast majority of the variance, leaving little to be explained by psychological factors.

5.6 CONCLUSIONS

In conclusion, our aim was to determine, without prior assumptions, which clinical tests most closely reflect general visual quality of life and perceived reading performance in patients with acquired macular disease. All tests of vision correlated highly, but low contrast measures (low contrast VA and CS) explained most of the variance in self-reported problems with reading. These results highlight the importance of high contrast, both in the design of products and in the design of environmental lighting. Reading speed was most important for general visual quality of life. The results suggest valuable tests to supplement high contrast distance VA measurement in patients with acquired macular disease.

Chapter 6

VISUAL FUNCTION AND SUBJECTIVE QUALITY OF LIFE IN SURGICAL MANAGEMENT OF MACULAR DISEASE

6.1 INTRODUCTION

Choroidal new vessels (CNV) develop as vascular buds from the choroid that break through Bruch's membrane into the sub-retinal pigment epithelium (RPE) space. The stimulus for the growth of new vessels from the choroid is poorly understood. However, changes to Bruch's membrane as a result of age (as in age-related macular degeneration (ARMD)) and inflammation (as in presumed ocular histoplasmosis (POHS)) among other unknown factors enable this to occur. In general, progressive weakening of Bruch's membrane allows splitting to occur, through which the vessels can pass (Green et al., 1985; Lovie-Kitchin & Bowman, 1985). CNV may complicate a number of ocular conditions, but they occur most commonly in age-related macular degeneration (ARMD). Sub-foveal CNV in ARMD has a profoundly detrimental affect on the prognosis for the patient, generally leading to a marked loss of central vision. Although CNV occur in only 10% of those patients with ARMD, they occur in 90% of ARMD sufferers who become registered blind with the condition (Leibowitz et al., 1980; Hyman et al., 1983). Over the past 20 years, laser photocoagulation has been the only accepted means of treating CNV. This therapy has proven beneficial for extrafoveal and juxtafoveal membranes of various aetiologies (The Macular Photocoagulation Study Group, 1983a, 1983b, 1990a, 1990b, 1993). However, 80% of presenting CNV are untreatable with laser because they already lie beneath the fovea (Grey et al., 1979; Bressler et al., 1987). Laser treatment of sub-foveal CNV, although having been advocated to reduce the final extent of the central vision loss, produces an immediate drop in visual acuity of an average of 3 Snellen lines (The Macular Photocoagulation Study Group 1991, 1993). It is therefore a treatment rarely carried out in the U.K. (Benson et al., 1998a). Research into improvement of the management of CNV has lead to a number of techniques for the surgical excision of these membranes over the past decade (DeJaun & Machemer, 1988; Lambert et al., 1991; Thomas & Kaplan, 1991; Thomas et al., 1992; Ormerod et al., 1994; Thomas et al., 1994; Eckstein et al., 1998). The reported visual outcome from the excision of sub-foveal and extra-foveal CNV associated with conditions other than ARMD, such as presumed ocular histoplasmosis syndrome (POHS) and high myopia, has since been encouraging. However, when associated with ARMD, the vision improvement post-surgery is far more equivocal (Berger & Kaplan, 1992; Lambert et al., 1992; Thomas et al., 1992; Ormerod et al., 1994; Thomas et al., 1994). The difference in outcome between these two groups has been attributed to the loss of retinal pigment epithelium (RPE), which occurs when CNV associated with ARMD are excised. This loss of RPE occurs due to the diffuse RPE disease and multiple in-growth sites that occur in ARMD compared with the better preserved RPE and usually single in-growth site of idiopathic and inflammatory CNV (Thomas et al., 1994). As a way of improving the post-operative results in ARMD patients, the method of transplanting RPE cells in association with membrane removal has been developed (Algvere et al., 1994; Algvere et al., 1997). The technique however, is still in its infancy.

Despite the numerous reports of large series of patients undergoing surgical excision of CNV, visual data published in reports to date has relied chiefly on Snellen visual acuity measurements. Chapter 4 described the limitations of the Snellen visual acuity chart when comparing visual performance at different levels of the chart and when measuring acuity at poorer end of the visual spectrum. Also, in the previous chapter (Chapter 5), visual function tests in addition to high contrast visual acuity were suggested to be able to provide a more accurate picture of a patient's perceived visual performance. These results suggest there is scope to more accurately quantify the visual changes (both objectively and subjectively) that occur as a result of this surgery. The study described in Chapter 5 compared measures of visual function using clinical visual tests with perceived visual function as measured with a quality of life questionnaire. The study described here continues this investigation by comparing the effect of the surgical procedure (both with and without RPE transplantation) as measured with visual function tests to that measured from vision-related quality of life questionnaire responses.

6.2 AIMS

The aims of this study were to assess the effectiveness of the surgical excision of idiopathic and inflammatory sub-foveal CNV, as well as the effectiveness of the surgical excision of ARMD associated sub-foveal CNV followed by RPE transplantation. The results of a series of visual function tests, carried out pre- and post-surgery, will be compared to subjective measures of vision-related quality of life, in order to accurately quantify the visual changes that occur as a result of surgery. In this way, visual function test(s) that most accurately reflect the perceived changes in visual performance will also be determined.

6.3 MATERIALS AND METHODS

The patients in this study were seen on four occasions. These appointments were within 2 weeks prior to the operation (pre-operative), and 1 month, 3 months and 6 months after the operation. The number of patients undergoing RPE transplants in this study was less than initially intended. Before recruitment of all patients could be completed, authority and government concern over the spread of Bovine Spongiform Encephalopathy (BSE) via human neural tissue meant that for precautionary reasons, the use of foetal and cultured RPE cells for transplantation had to cease. In addition, for various reasons there was a greater than anticipated loss of patients during post-surgery follow-up. Data for each appointment was only included in the analysis if a patient was able to attend for this appointment within two weeks of the scheduled date calculated from the date of the operation. Data for six patients (3 ARMD and 3 idiopathic/inflammatory) was lost due to re-growth of the membrane or complications associated with the surgery; four patients missed appointments due to illness; two patients were lost to follow-up; and one patient died before the completion of the study.

6.3.1 Subjects

The 25 patients for this study were all patients of Birmingham Heartlands & Solihull National Health Service Trust. 19 of these patients participated in the study described in Chapter 5. The pre-operative data reported in the study described here for these 19 patients is the data reported in Chapter 5. An additional 6 patients were added to this original group of 19 patients. In this study there were 11 patients (9 females and 2 male; age range 23 – 47 years) with idiopathic membranes or membranes associated with presumed ocular histoplasmosis syndrome (POHS) and 16 age-related macular degeneration (ARMD) patients (10 females and 6 males; age range 52 – 80 years). During the analysis of the data (see below), it was decided to divide these patients into binocularly affected and monocularly affected groups, in terms of high contrast visual acuity. When split in this manner, there were 10 binocularly affected and 15 monocularly affected patients respectively. The monocularly affected group consisted of 6 patients with CNV associated with ARMD and 9 patients with idiopathic/inflammatory CNV. The binocularly affected group consisted of 8 patients with CNV associated with ARMD and 2 patients with idiopathic/inflammatory CNV. A table showing the demographics and pre-operative visual functions of the 25 subjects is shown in Appendix B.

Aston University and Birmingham Heartlands and Solihull Hospital Ethics Committee approvals were obtained and all patients gave informed consent.

6.3.2 Quality of Life Questionnaire

The questionnaire used in this study was the VQOL instrument (Frost et al., 1998), which was used in the study described in Chapter 5. The format of the questionnaire and the method of scoring were also the same as that described in Chapter 5. Details of its development and the assessment of its reliability and validity are discussed in Chapter 4.2.3.

The questionnaire was given to patients at each appointment. All patients were given the same instructions and were asked to answer the questionnaire considering their eyesight over the previous month, using both eyes and whilst using any habitual spectacles, contact lenses or low vision aids. If the subject was unable to read the questionnaire, it was administered by the examiner in a standardised manner.

6.3.3 Visual Function Tests

At each appointment subjective refraction was carried out for each patient. Following this, a series of visual function tests (listed below) were carried out. The procedure for each test is described in Chapter 5, and details of the tests can be found in Chapter 4.

1. High contrast distance visual acuity (logMAR) (HCVA), each eye.
2. Low contrast distance visual acuity (logMAR) (LCVA), each eye.
3. Near word acuity (logMAR) (Near VA), each eye.
4. Contrast sensitivity (log units) (CS), monocularly in each eye and binocularly.
5. Oral reading speed (wpm), monocularly in the operated eye and binocularly.

The above tests were carried out after subjective refraction in order to facilitate comparisons between appointments. Although patients would have responded to the questionnaire with regards to their habitual visual performance, there was no statistically significant difference between the best corrected and habitual visual acuity for either the operated ($t(24)$ 0.46, n.s.) or non-operated ($t(24)$ 0.31, n.s.) eye in the pre-operative data or the post-operative data at 1month (operated eye: ($t(22)$ 0.36, n.s.); non-operated eye: ($t(22)$ 0.47, n.s.)), 3 months (operated eye: (t(19) 0.39, n.s.); non-operated eye: (t(19) 0.56, n.s.)) or 6 months (operated eye (t(16) 0.27, n.s.); non-operated eye: (t(16) 0.34, n.s.)).

6.4 ANALYSIS AND RESULTS

Initial analysis was aimed at investigating the change in visual function over time, in order to determine the effect, if any, of the surgical procedures. A split-plot RCB Anova using Super Anova® software was carried out across all four appointments for each visual function. This was done for all of the patients combined and also when the patients were separated into those with idiopathic/POHS CNV (young) who had membranes removed and those with CNV associated with ARMD (old) who had membranes removed and RPE transplanted. The results of this analysis revealed that only low contrast visual acuity (LCVA) significantly changed over time when all patients were included together ($F(24, 113)$ 2.95, $p=0.05$), and when the young patients were analysed separately ($F(10, 50)$ 3.01, $p=0.05$). There was no significant change when the old patients were considered separately ($F(13, 57)$ 1.20, n.s.). The interaction between time and eye (operated or non-operated) was not significant for either condition. Table 6.1 shows the Anova table for the young subjects only and LCVA as the dependent variable. Average LCVA values (±1SEM) for the operated eye over the four appointments (pre-operative, 1 month, 3 months, and 6 months respectively) and with all patients included were 1.25±0.07, 1.06±0.09, 0.99±0.09 and 1.05±0.09 logMAR. These values demonstrate an improvement following surgery of approximately 2 lines. The average LCVA values (±1SEM) for the non-operated eye were 0.6±0.10, 0.57±0.11, 0.53±0.11 and 0.54±0.12 logMAR respectively, demonstrating an improvement after surgery of approximately half a line. For the young patients, the average LCVA values (±1SEM) of the operated eye were 1.1±0.06, 0.89±0.09, 0.79±0.09 and 0.84±0.09 logMAR for the pre-operative, 1 month, 3 months, and 6 months respectively, thus demonstrating an improvement of approximately 3 lines. The same measures for the non-operated eye were

0.44±0.1, 0.36±0.1, 0.36±0.1 and 0.42±0.1 logMAR respectively, showing only an initial improvement in vision of less than one line.

	df	*Sum of Squares*	*Mean Square*	*F-Value*	*P-Value*
Subject	10	4.61	0.46	8.85	0.0001
Eye	1	6.21	6.21	20.09	0.001
Subject*eye	10	3.09	0.31	5.94	0.0001
Time	3	0.47	0.16	3.01	0.05
Time*eye	3	0.30	0.10	1.94	0.14
Residual	50	2.60	0.05		

Table 6.1. The Anova table for the Split-plot RCB Anova with the young subjects alone and LCVA as the dependent variable.

The older subjects in this study had CNV associated with ARMD, and these subjects underwent CNV removal and RPE transplantation. The younger group of subjects had idiopathic or inflammatory CNV and these subjects underwent CNV removal without subsequent RPE transplantation. It would seem logical to analyse the results with the subjects split into those two groups. However, initial analysis showed little significance when the results were analysed in this way. It is possible that the lack of significance in the data was due to the heterogeneity of the patient group that remained even when the subjects were divided. In order to investigate whether this was the case, principal components analysis (PCA) was carried out with the patients included as variables and the visual function tests and questionnaire scores included as factors. Principal components analysis found a dominant first principal accounting for 51% of the variation, one principal component accounting for 33%, one accounting for 8%, and all other components accounting for 2% or less, suggesting the presence of two major underlying factors. A cluster diagram was then plotted of Factor 1 as a function of Factor 2. This diagram (Figure 6.1) revealed that the patients could be separated into two distinct groups. Investigation of the visual function characteristics of the patients within these two groups was carried out with un-paired t-tests.

This analysis revealed that one group had significantly better non-operated eye visual abilities than the other group and hence could be considered to be monocularly affected. The two groups were not significantly different with respect to age ($t(23)$ –1.87, n.s.). The two groups from the PCA therefore separated the subjects into those who were monocularly affected and those who were binocularly affected, where to be binocularly affected both eyes had to have HCVA measures of 0.4 logMAR or worse. In view of this, it was decided to re-analyse the data separating the patients into monocularly affected and binocularly affected groups, so that the heterogeneity within the patient groups might be reduced. A split-plot RCB Anova for the monocularly affected patients revealed that LCVA significantly changed over time ($F(14, 68)$ 2.754, $p=0.05$). The average LCVA values (±1SEM) for the monocularly affected patients were 1.3±0.1, 0.9±0.1, 0.8±0.1 and 1.0±0.1 for the pre-operative, 1 month, 3 month and 6 month appointments respectively. The interaction between time and eye (operated or non-operated) was non-significant suggesting that the change in the operated eye over the time course of the study was similar to the change in the non-operated eye. There was no significant change in visual function or questionnaire values over time for the binocularly affected patients.

The above results suggest that there was very little change in the visual function measurements as a result of the operation. That is, there was no improvement or deterioration in the operated eye relative to the non-operated eye post-surgery. However, it was also of interest to determine whether there was any change in the patients' perceived visual performance. To investigate this a Repeated Measures Anova using Statview® software was carried out. In the Split-Plot RCB Anova carried out above, the measures for both eyes were included. In this Repeated Measures Anova however, there was only a single VCM1 or Reading Scale score for each subject, which consequently reduced the power of the analysis. Therefore, in order to maintain enough statistical power, only the pre-operative, 1 month and 3 month data were used. The results showed that for the monocularly affected patients, there was no significant change in the VCM1 score ($F(10, 20)$ 1.45, n.s.) or Reading

Scale score (F(10, 20) 0.04, n.s.) over time. The was also no significant change in VCM1 score (F(6, 12) 2.77, n.s.) or Reading Scale score (F(6, 12) 0.06, n.s.) over time for the binocularly affected patients.

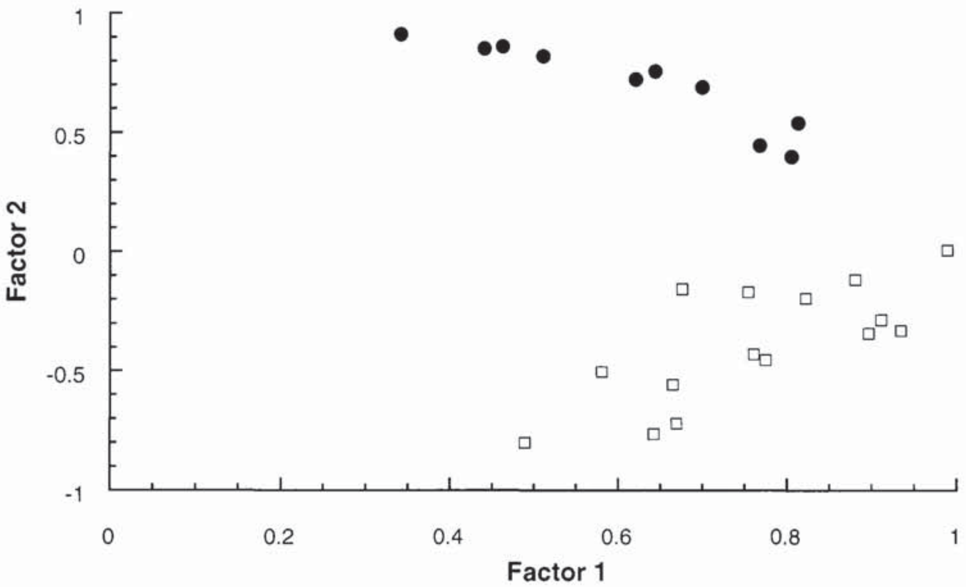


Figure 6.1. A factor plot from the results of the principal components analysis. Factor 1 and Factor 2 are the two main factors determined from the analysis and each point on the plot represents one of the 25 subjects. Open squares represent subjects who are monocularly affected (i.e. one eye HCVA better than 0.4 logMAR) and closed circles represent subjects who are binocularly affected (i.e. both eyes HCVA 0.4 logMAR or worse). The analyses in this study were carried out with the subjects divided into two separate groups as determined from this plot.

The associations between the change in vision test results and change in questionnaire scores over the four visits were explored by performing step-wise forward multiple regression analysis with the vision test results as potential explanatory variables. Due to the reduced number of patients and higher than anticipated drop-out rate, if the data were analysed with the patients split into monocularly and binocularly affected groups, the analyses would not be powerful enough to draw any definite conclusions from the data. However, there was too much heterogeneity within the patient group to analyse the data with the patients combined. Therefore these analyses are described below for the monocularly and binocularly affected patients as ways of further analysing the data if sufficient patient numbers were available. It is not suggested that the results be used to draw concrete conclusions as any of the following significant results could have occurred by chance.

In addition to determining whether there was change in visual function or performance over time, it was also of interest to determine how any changes in the visual function measurements compared with changes in perceived visual performance. To address this, the difference between the pre-operative results and the 6 month post-operative results were calculated and step-wise multiple regression analysis by the forward method was carried out on this data. Step-wise multiple regression analysis chooses the independent variables that are most useful in explaining the dependent variable. The forward method starts with no variables in the model and adds independent variables in order (from greatest to least) of their ability to predict the dependent variable. For this analysis, the change in the VCM1 score and the change in the Reading Scale were each used in turn as the dependent variables and the change in the visual function measures were used as the independent variables.

For the monocularly affected group, a change in VCM1 score was most closely related to change in binocular page reading speed (R^2=0.50, p<0.05). A change in binocular near VA, explained an additional 23% of the variance (p<0.01) (Figure 6.2). Figure 6.2 shows that an improvement in VCM1 score (negative change) is associated with improvements in both binocular reading speed and binocular near VA. The change in the Reading Scale score was most closely related to the change in binocular contrast sensitivity (CS) (R^2=0.64, p<0.01) (Figure 6.3). Figure 6.3 shows that greater improvements in Reading Scale score (greater negative change) are associated with greater improvements in binocular contrast sensitivity. For the binocularly affected patients, the change in VCM1 score was most closely related to the change in the low contrast visual acuity (LCVA) in the non-operated eye (R^2=0.91, p<0.01) (Figure 6.4). The change in Reading Scale score was most closely related to the monocular (operated eye) page reading speed (R^2=0.85, p<0.01) (Figure 6.5). Figure 6.5 shows that subjects who showed greater improvements in Reading Scale score, also showed greater improvements in monocular page reading speed post-operatively.

In order to understand fully the effectiveness of the surgery, it was of interest to determine how pre-operative patient characteristics related to change in visual function or perceived performance. To determine which pre-operative visual function measures were most closely related to changes in perceived visual function, step-wise multiple regression analysis by the forward method was again used with the pre-operative visual function measures as independent variables. The difference in VCM1 and Reading Scale scores for the pre-operative and 6 month appointments were each used in turn as the dependent variable or variable of interest. For the monocularly affected patients, the change in VCM1 score was most closely related to the pre-operative HCVA in the operated eye (R^2=0.50, p<0.01). In addition, Figure 6.6 shows that an improvement in VCM1 score (negative change) is associated with better pre-operative HCVA's. The change in Reading Scale score was most closely related to the pre-operative non-operated eye unaided vision (R^2=0.44, p<0.03) (Figure 6.7). Figure 6.7 shows that greater improvement in Reading Scale score (negative change) is associated with relatively worse pre-operative non-operated eye vision. This is understandable considering that if the visual function in the non-operated eye is poor, any change in the operated eye visual function will have a greater effect on the responses to the questionnaire (answered with regards to binocular vision) than if the vision in the non-operated eye was originally good. For the binocularly affected patients, no visual function variable was selected to be associated with the change in VCM1 score. The change in Reading Scale was most closely related to the pre-operative monocular page reading speed (R^2=0.58, p<0.08), although this did not reach significance, most likely due to the small number of subjects. The pre-operative LCVA in the operated eye accounted for an additional 27% of the variation (p<0.01). Figure 6.8 shows that subjects who showed the greatest improvements (negative change) in Reading Scale score had the poorer pre-operative monocular page reading speeds and the better pre-operative LCVA values in the operated eye.

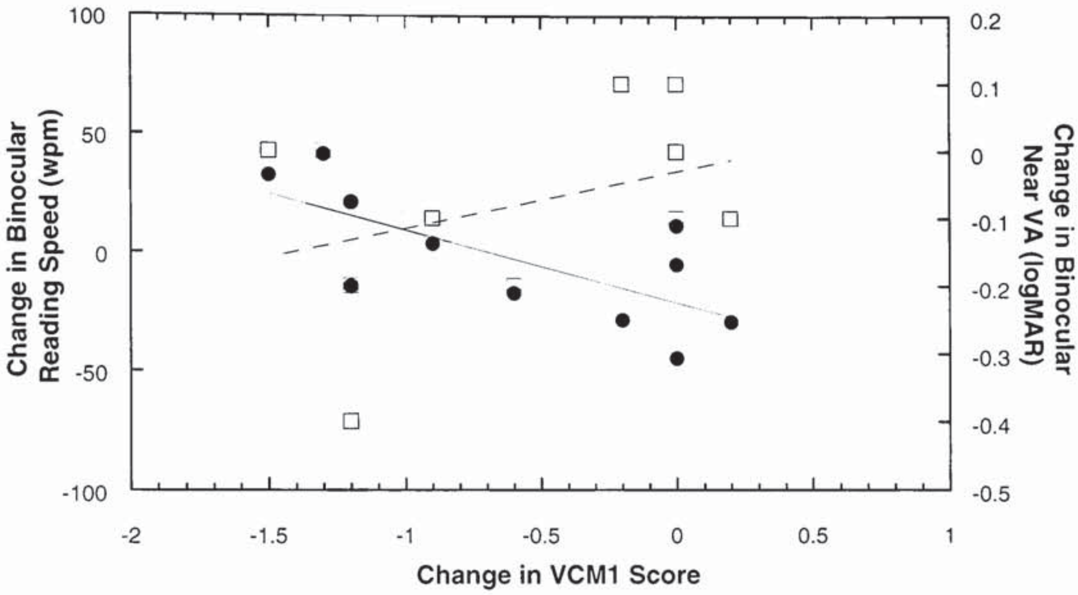


Figure 6.2. Change in binocular page reading speed (wpm) (closed circles; solid line) and change in binocular near VA (logMAR) (open squares; dashed line) as a function of change in VCM1 score. Data is for the monocularly affected subjects only.

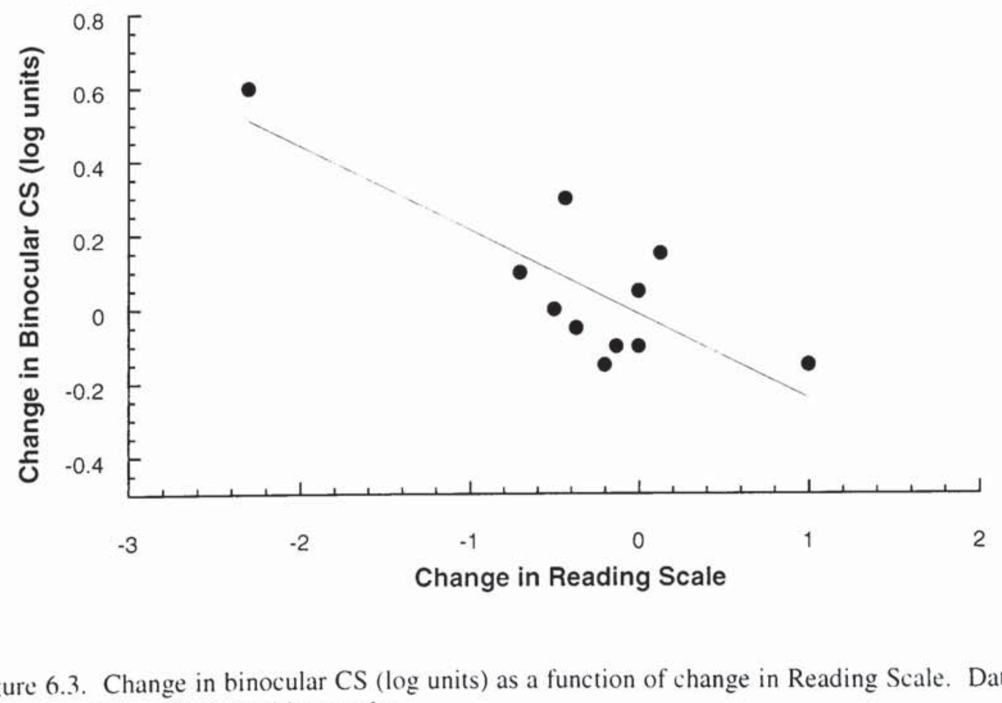


Figure 6.3. Change in binocular CS (log units) as a function of change in Reading Scale. Data is for the monocularly affected subjects only.

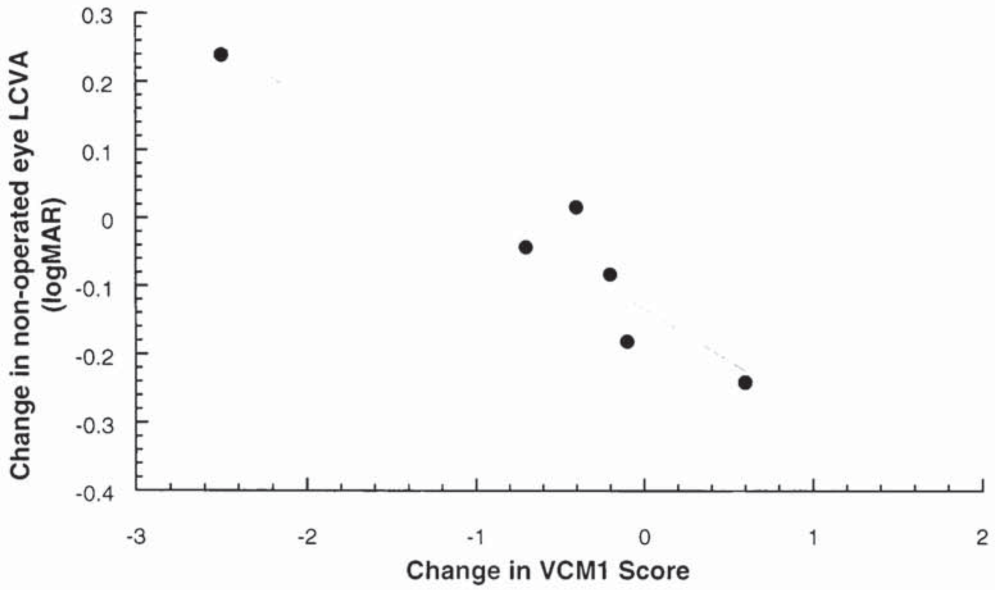


Figure 6.4. Change in non-operated eye LCVA (logMAR) as a function of change in VCM1 score. Data is for the binocularly affected subjects only.

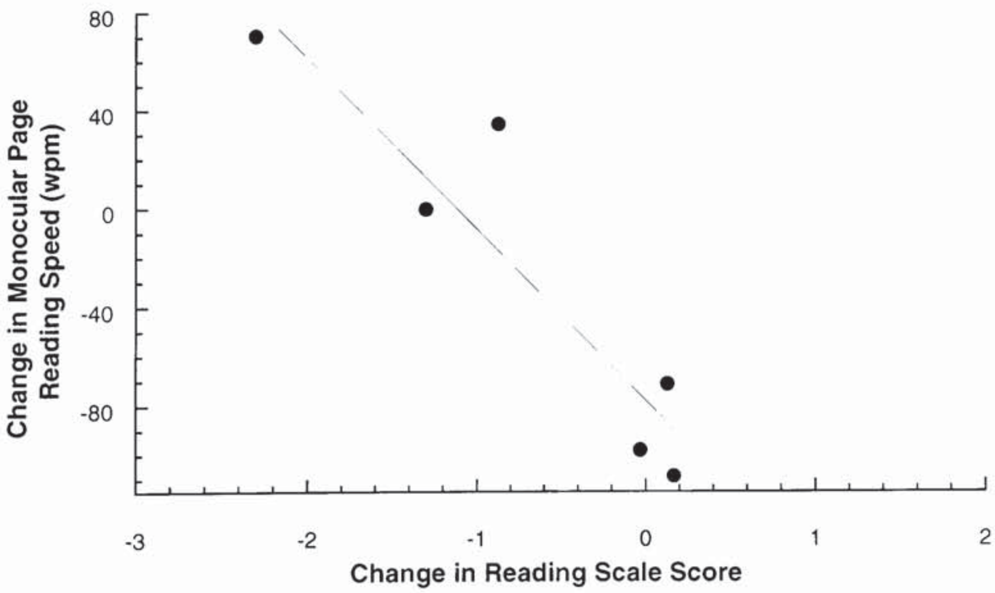


Figure 6.5. Change in monocular (operated eye) page reading speed as a function of change in Reading Scale score. Data is for the binocularly affected subjects only.

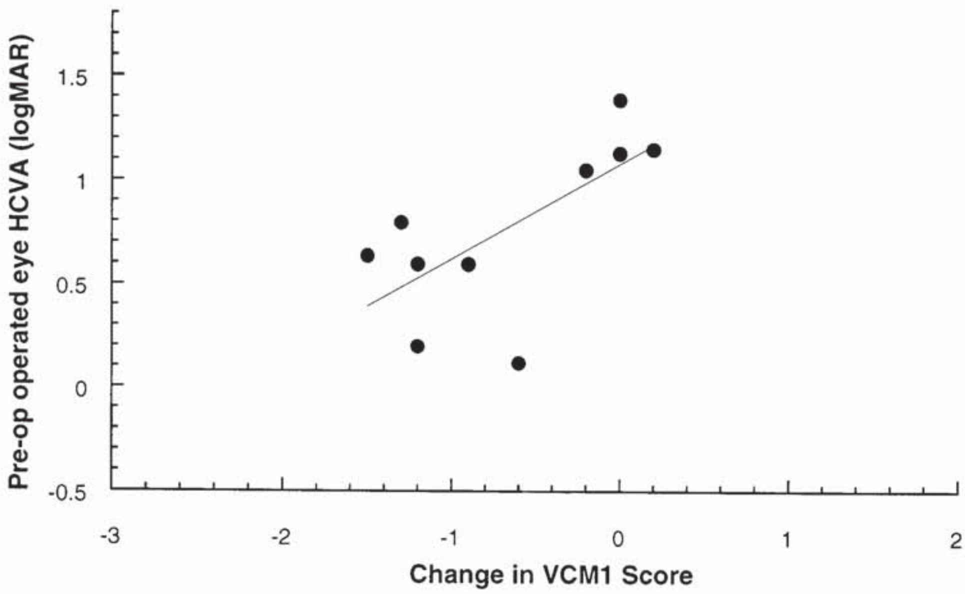


Figure 6.6. Pre-operative operated eye HCVA as a function of change in VCM1 score. Data is for the monocularly affected subjects only.

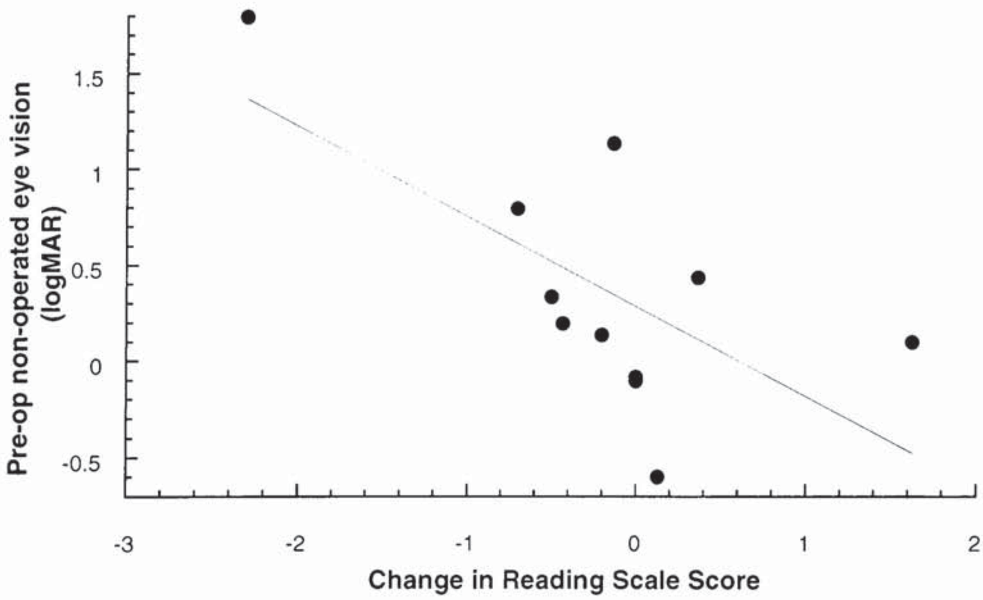


Figure 6.7. Pre-operative non-operated eye vision (logMAR) as a function of change in Reading Scale score. Data is for the monocularly affected subjects only.

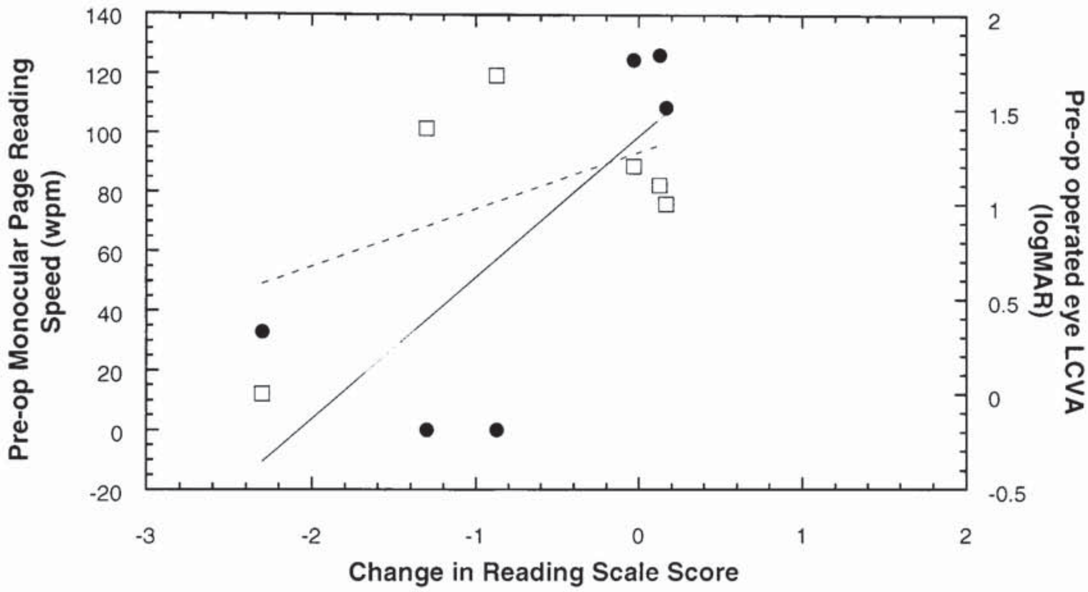


Figure 6.8. Pre-operative monocular page reading speed (wpm) (closed circles; solid line) and pre-operative operated eye LCVA (logMAR) (open squares; dashed line) as a function of change in Reading Scale score. Data is for the binocularly affected subjects only.

6.5 DISCUSSION

The results showed that the operation had little effect on either the visual function or perceived visual performance of the patient group as a whole or even when split into 'old' and 'young' groups. Principal components analysis was consequently carried out to investigate the potential heterogeneity in the subject group. On the basis of the results of the principal components analysis, the patient group was split into those who were either monocularly affected or binocularly affected. However, despite this little change in visual function or perceived visual performance was reported as a result of the surgery. Low contrast visual acuity was the only visual function measure to change significantly over the 6 months of the study. Although not statistically significant, there was a trend for a greater improvement in LCVA over time for the operated eye compared with the non-operated eye. These results however suggest that the surgery was not successful at significantly improving the visual ability of the patients or the perceived visual performance. It is commonly known however that eyes with CNV have poor visual prognosis (Leibowitz et al., 1980; Hyman et al., 1983). Bressler et al. (1982) reported that for non-treated sub-foveal CNV, visual acuity falls below 6/60 (1.0 logMAR) or worse in 70% of those affected over a 2 year period. Therefore, although there was no significant change in visual function, it is possible that membrane removal (and RPE transplantation for the ARMD associated CNV) may have allowed stabilisation of vision, at least until 6 months post-surgery, which could have otherwise deteriorated. This may have been particularly significant for the patients with CNV associated with ARMD, since for these patients, removal of the sub-foveal CNV (without RPE transplantation) has poorer visual prognosis than removal of idiopathic or inflammatory sub-foveal CNV (Berger & Kaplan, 1992; Lambert et al., 1992; Thomas et al., 1992; Ormerod et al., 1994; Thomas et al., 1994). However, when the results were analysed with the subjects split into 'young' and 'old' groups, the 'young' group of subjects only showed a significant improvement in LCVA measures over time, compared with no significant improvement for any of the visual function measures for the 'old' group. Thus there was only a slight tendency for the 'young' group to have better post-operative results than the 'old' group.

Algvere et al. (1994) reported on the results of membrane removal and foveal RPE transplantation of 3 subjects. The transplants survived for at least 3 months post-surgery, however, light detection and foveal fixation was only observed for 1 month post-surgery. After this time, macular oedema compromised visual function. Visual acuity for the three subjects changed from a pre-surgery average of 1.0 logMAR to 1.38 logMAR at two weeks post-surgery and 1.4 logMAR 3 months post-surgery. In a more recent study, Algvere et al. (1997) reported that 4 of the 5 patients with RPE transplants after removal of sub-foveal membranes had a gradual loss of acuity over 12 months after surgery and one patient maintained her pre-surgery visual acuity. No significant change in visual acuity occurred during 8-12 months post-surgery. Therefore, as with the study reported in this chapter, previous studies have also shown equivocal (and even poorer) results from RPE transplantation. Complications such as developing macular oedema and epiretinal membranes have minimised the likelihood of even stabilisation of long term vision. Indeed, it is important to note that the results reported in the study described here do not include the data of those with complications and hence will appear more promising than if all data was included. Algvere et al. (1997) have suggested that improvements in surgical techniques that minimise ocular trauma are necessary before acceptable results are achieved. It remains to say that the little published data on combined CNV removal and RPE transplantation in ARMD patients shows no significant improvement over CNV removal alone in these patients (Algvere et al., 1994; Algvere et al., 1997). In order to be more confident of the results found for the study described here, larger subject numbers and a longer follow-up time would be required.

As well as determining the success or otherwise of the surgical procedure, the purpose of this study was also to investigate the relationship between visual function as measured with clinical tests, and perceived visual performance as measured with a quality of life questionnaire. As explained above, unfortunately the patient numbers did not provide enough statistical power for the results of the analyses not to be significantly affected by chance. Therefore, the analyses have been carried out as a means to demonstrate methods of further investigating the data if sufficient patient numbers were available. The results will be discussed below as potential trends in the data and to provide points of interest for further investigation.

The data were analysed to investigate how perceived visual performance changed compared with the change in measured visual function as a result of the surgery. This was done using step-wise multiple regression analysis by the forward method. The data from the monocularly affected patients were analysed separately to the binocularly affected patients to minimise heterogeneity in the results. For the monocularly affected patients, the change in VCM1 score was most closely related to the change in binocular page reading speed and the change in binocular near VA. In addition, greater improvements in VCM1 score were associated with greater improvement in binocular page reading speed and binocular near VA. The VCM1 score is a measure of the patients' overall concern about their vision and the effect that it has on their daily life. Both of these measures are reading related measures. Therefore this finding is understandable considering the detrimental effect that macular disease has on central vision and hence near reading tasks. This finding also correlates with the results of Chapter 5 where the VCM1 score was also most closely related to the binocular page reading speed. For the patients in the study described here, the Reading Scale was most closely related to binocular contrast sensitivity. Patients with greater improvements in Reading Scale score also showed greater improvements in binocular contrast sensitivity. The Reading Scale score is derived from the responses to questions specifically about reading type tasks, which would generally be presumed to be high contrast tasks. However, these results also agree with those of the study described in Chapter 5, where Reading Scale score was found to be associated with LCVA and contrast sensitivity measures. As explained in

Chapter 5, apart from the controlled tasks undertaken in the clinic or laboratory, reading tasks in daily life are often of less than optimal contrast. If this is the case for the tasks considered by the patients answering the questionnaire, contrast sensitivity and low contrast acuity abilities therefore become more important in determining their perceived reading performance. For the binocularly affected patients the change in VCM1 score was most closely related to the change in the LCVA in the non-operated eye. In 5 out of 6 of the binocularly affected patients the non-operated eye had the better visual function of the two eyes. Considering the poor average acuity amongst the binocularly affected group, it could be perceived that the eye with the better visual ability would have an effect on perceived performance. The change in Reading Scale was most closely related to the monocular page reading speed. However, as only 6 binocularly affected patients could be included in these latter two analyses, little weight should be placed on these findings.

One of the chief complaints of patients with sub-foveal CNV is that of distortion. Although in this study perceived visual performance does not change significantly as a result of the surgery, a proportion of the subjects commented on improvement of their vision post-surgery as a result of the reduction in distortion caused by macular oedema. Indeed, patients often reported favourably of the reduction or elimination of this distortion post-operatively, even though their HCVA remained unchanged and there was little change in their quality of life scores. Throughout the course of the study it became apparent that the presence or absence of central distortion had a significant effect on the patients' perceived visual performance. Unfortunately no question in the questionnaire directly addressed this question and at present there is also no quantitative method for measuring distortion. However, the development of such a clinical test may be of use in more accurately determining the success or otherwise of medical intervention for patients with macular disease.

One of the main difficulties for surgeons with regards to patients with CNV is that of patient selection. It is commonly agreed that CNV associated with ARMD have a poor prognosis.

Similarly, any cases where photoreceptor and/or RPE damage has occurred will also have a poor prognosis (Thomas et al., 1992). This may be due to pre-operative factors such as post-inflammatory scars, haemorrhage, lipid, fluid or scar growth resulting from neovascularisation, or due to previous photocoagulation (Thomas et al., 1992). However, surgically induced mechanical damage or damage from prolonged endoillumination could also be causes of RPE damage and poor visual outcome (Zilis & Machemer, 1991). With regards to pre-operative visual acuity, findings of this and previous studies are more inconclusive. In the study described in this chapter, there was no association between the pre-operative HCVA and the final (6 month post-operative) HCVA. Thomas et al. (1994) reported that from a study of sub-foveal CNV in POHS, eyes with pre-operative visual acuity of 20/100 or better had significantly better final visual acuity than eyes with initial visual acuity of 20/200 or less ($p=0.02$). However, it is unclear from the report whether the patients with the better visual acuity showed better results when the two groups were normalised for initial visual acuity. Also for non-ARMD associated CNV, Benson et al. (1998a) reported relatively worse visual results for patients with better pre-operative visual acuity (>6/24) and Eckstein et al. (1998) reported no significant association between the final visual outcome and the pre-operative visual acuity. It would be of benefit to be able to determine more precisely which patients were more likely to benefit from surgery than others. Therefore step-wise multiple regression analysis was again used to determine which pre-operative visual function measures were most closely related to changes in perceived visual function. In the monocularly affected patients, a change in VCM1 score was most closely related to a change in pre-operative HCVA in the operated eye. Figure 6.6 shows that greater improvement in VCM1 score post surgery is associated with better pre-operative HCVA values. Indeed, as cited above, other studies have shown pre-operative visual acuity to be associated with post-surgery prognosis (Thomas et al., 1994; Benson et al., 1998a). The change in Reading Scale was most closely related to the pre-operative unaided vision in the non-operated eye, possibly a spurious finding resulting from the low number of subjects. For the binocularly affected patients, no pre-operative visual function values were significantly associated with the change in either VCM1 or Reading Scale scores. This was possibly due to the small patient numbers and the variability in the patient group characteristics. However, considering that there was no significant change in questionnaire scores, it is reasonable to accept that this analysis would reveal little significant associations.

6.6 CONCLUSIONS

In conclusion, the results of the study suggest that with the exception of low contrast visual acuity, the surgery for both ARMD associated and idiopathic/inflammatory CNV did not significantly improve or cause deterioration in the measured visual functions. There was also no significant change in perceived visual performance. These equivocal results are similar to previously published data for surgical removal of CNV and for RPE transplantation, which have measured the effect of surgery on HCVA alone. At the present stage, the results of surgical procedures carried out in this study are greatly influenced by physiological processes in the retina that are not fully understood and require long-term evaluation. The results suggest however, that this research avenue should continue to be explored.

Chapter 7

THE EFFECT OF VISUAL FIELD LOCATION ON READING PERFORMANCE

7.1 INTRODUCTION

Chapter 2 of this thesis describes how people with central field loss use a single area of their retina with which to fixate (Cummings et al., 1985; Sunness et al., 1996; Fletcher & Schuchard, 1997). This is known as the preferred retinal locus (PRL) (Timberlake et al., 1986) or pseudo-fovea (Guez et al., 1993). More specifically, studies have shown that patients with juvenile macular degeneration (JMD) usually have a PRL below their scotoma in visual field space (Sunness et al., 1996), whereas patients with age-related macular degeneration (ARMD) use a PRL either below or to the left of the scotoma in visual field space (Guez et al., 1993; Sunness et al., 1996; Fletcher & Schuchard, 1997).

It might be predicted that reading would be better in the left visual field, since there is a streak of greater retinal cell density running horizontally across the retina (Curcio & Allen, 1990; Curcio et al., 1990; Chapter 3). Psychophysically, differential light sensitivity (Latham et al., 1993; Latham et al., 1994), contrast sensitivity (Rovamo & Virsu, 1979; Virsu & Rovamo, 1979), resolution (Latham & Whitaker, 1996a), and acuity (Wertheim, 1980; Anderson et al., 1992) all require greater object sizes in the inferior field than in the left field in order to achieve the same level of performance.

Studies have shown however, that patients with JMD read faster than those with ARMD (Legge et al., 1992; Sunness et al., 1996). One potential reason for this difference is the PRL location used by these groups. Since people with JMD tend to use an inferior field PRL, there may be an advantage to using the inferior visual field for reading. However, these findings could be confounded by factors such as age and differences in the integrity of the remaining retina in these different forms of macular degeneration. In this study, to avoid the potentially confounding effects of age and pathology, reading with eccentric fixation was examined in inferior and left visual field using normal observers.

Previous studies of reading using simulated scotomas and involving eye movements suggest that there may be an advantage to using a PRL in the inferior visual field. Fine & Rubin (1999) found that page reading in normals was faster with a hemifield mask forcing attention to inferior rather than left or right visual field. One reason for the apparent advantage of the inferior field for reading page text may be that although information to the left of fixation affects reading, it is the text that has not yet been fixated that is most important in guiding eye movements (Rayner et al., 1980). As such, the ideal position of the PRL for reading page text would be below the scotoma as none of the current line of text is blocked from view. Another advantage to the inferior field might be that control of eye movements is better when the text is orthogonal to the fixation point (as in the inferior field) rather than radial to the fixation point (as in the left visual field) (Peli, 1986).

To determine whether the advantage of inferior field for eccentric fixation is due to differences in eye movements, the rapid serial visual presentation (RSVP) method (Chapter 2.4.3) was used with retinally stabilised images. Using this method, words are presented in succession at the same point on a monitor, thus minimising fixational eye movements. In addition, the use of stabilised images means an artificial scotoma is not used. Therefore, any differences observed are not due to differences in masking of the text in left and inferior field. Under these conditions, if the advantage of the inferior field observed with standard page reading disappears when the RSVP technique is used, then differences in eye movements or masking of the text by a scotoma may explain the advantage of inferior field over left field in normal reading. Conversely, if differences are observed between the parameters for optimum reading in inferior and left visual fields using the RSVP method, then a functional advantage is suggested which is not due to differences in eye movements for the two locations.

7.2 AIMS

The aim of the study described in this chapter was to compare reading performance in inferior and left visual field space to determine which is the better for reading in the absence of central fixation.

7.3 MATERIALS AND METHODS

In summary, normally sighted subjects read sentences presented using RSVP at 5 degrees in inferior and left visual field of the right eye. Seven letter sizes were examined and the text was stabilised on the subject's retina.

7.3.1 Subjects

Six subjects with a spherical refractive error of less than –3.00DS and astigmatism of less than 0.75DC participated in the study. The mean age of the subjects was 25 years with a range of 21-29 years. All subjects had visual acuity better than 0.0 logMAR. Ethical committee approval from Johns Hopkins University Hospital was received and subjects were compensated for their time. All subjects read and signed an informed consent prior to testing. Other than subjects CH and KL, the subjects had no previous experience of RSVP experiments and were unaware of the question under study.

7.3.2 Apparatus

Subjects viewed the stimuli through a Generation-V dual-Purkinje-image eye tracker (SRI International), in combination with an image stabiliser (CX-660 General Scanning Inc.)

(Crane & Clark, 1978; Crane & Steele, 1985). The image stabiliser had a nominal spatial accuracy of 1 minute of arc and a temporal delay of 1-2 ms. This was sufficient to produce image fading in stabilisation studies.

Stimuli were presented on an Apple ColorSync 17-inch CRT display (16.1-inch viewable display size), positioned 80 cm from the optical plane of the image stabiliser. The monitor measured 32.6 cm horizontally by 24.0 cm vertically and displayed 640 x 480 pixels in 8-bit resolution. The screen refresh rate was 67 Hz. In this and another experiment (described in Chapter 8) using the same equipment and similar methods, there was an intermittent 15ms inter-stimulus interval due to occasional mis-synching of the display software and the refresh of the monitor. It was therefore not consistent within or across stimuli. There was no difference in the pattern of the data across conditions when the data were analysed with and without the additional 15ms per word. The data presented for these two studies include the additional 15ms per stimulus. A Macintosh Performa 6115 running version 7.6 system software controlled the display. The stimuli were presented and controlled by 'RSVP' software, version 4.03 (Williams & Tarr, 1998).

7.3.3 Stimuli

The stimuli were sentences presented using the RSVP method (Potter, 1984) (Chapter 2.4.3). The stimuli were MNRead formatted sentences (Legge et al., 1989a) from an extended corpus of 324 sentences and were presented centred in the middle of the monitor in Helvetica (a variable-pitch sans-serif font). Each sentence was 9-14 words long with a mean length of 11.5 words per sentence and a standard deviation of 1.1 words. The mean word length was 3.86 characters, with a range between 1 and 13 characters per word. Each sentence was preceded and followed by a string of five capital Xs presented in the same place on the monitor as the text. These Xs served as a forward mask on the first word of the sentence and a backward mask on the last. This was done to equalise the masking conditions across all the words in the sentence. The Xs were always presented for 1000 ms, except for the set preceding the first stimulus trial when they were presented for 6000 ms to allow the subject to adapt to the abrupt change in luminance of the display that occurred when the trial sequence began. The last word of each sentence had a full stop at its end to indicate that the end of the sentence had been reached. None of the subjects had previously seen the sentences and no sentence was shown to any observer more than once. Letter size was measured as the height of a lower case letter with no ascenders or descenders. Seven letter sizes were used, from 0.50 degrees to 2 degrees in 0.1 log steps. Stimuli were presented in reverse polarity with a Weber contrast of about 99% (letters of luminance 63 cdm^{-2} presented on a background of luminance 0.03 cdm^{-2}, as measured with a Minolta CS-100 spot photometer).

7.3.4 Set-up

The subject sat restrained by a dental impression bite-bar and forehead rest, with the right eye looking through the optics of the eye tracker. The left eye was covered with a black eye patch. The subject was asked to align a fixation dot in the centre of the eye tracker's optics with a target positioned at the centre of the monitor. The eye tracker was then zeroed to set its null point to the centre of the monitor.

To provide stabilised text presented in the periphery, the eye tracker was then aligned in the following way. The subject manually aligned the fixation dot at the null point of the eye tracker's optics with a target presented at a point at 5 degrees eccentricity to the right or above the central position of the monitor (as appropriate). When text was then presented in the centre of the monitor, it appeared at 5 degrees in the subject's left or inferior visual field. Once aligned and engaged, the image stabiliser would present an image to the same area of the retina regardless of eye movements.

7.3.5 Procedure

Following a practice session, sentences were presented in RSVP format at 5 degrees eccentricity in the left and inferior visual fields. Eccentricity was defined as the angular distance between the foveal fixation point and the centre of the word at the bottom of the letter. Inferior and left visual fields were examined in random order.

The subject's task was to repeat the sentence to the examiner. The subject stayed on the bite bar to give the response, but by dropping their lower jaw to speak, this was audible and understandable. The only errors allowed were gender changes (he for she and vice versa), plurals (eg. stars and star), tense (eg. is and was, drops and dropped) and dropped determiners (eg. that, the, this). Added, dropped or changed adjectives were counted as incorrect. Response options by the examiner were correct, incorrect, or retry (e.g. if the eye tracker lost track during a trial).

A one-up, one-down staircase with unequal step sizes (Kaernbach, 1991; García-Pérez, 1998) was employed for each letter size with word duration as the dependent variable. A 0.28 ratio of up/down step sizes was used to give an estimate of the word duration giving 78% correct responses. After a correct response, stimulus duration was reduced by one half, while after an incorrect response stimulus duration was multiplied by 1.8 to give the subsequent presentation duration. Stimulus durations were rounded to the nearest frame (15 ms). For each letter size, one set of 18 sentences was shown to the observer. The 1.58 degree letter size was examined first, with an initial duration of 300ms/word. The smaller stimulus sizes were then examined at the same sitting in descending order of size, with the starting duration of each staircase taken as the last stimulus duration in the previous run. If the word duration exceeded 3600 ms/word (i.e. a reading rate of less than 10 wpm), the staircase continued at the same presentation duration while incorrect responses were made. If a subsequent response was correct, the duration halved and the staircase continued. For analysis of the data the reversal points in words per minute were averaged, excluding the fastest and slowest values at reversal. The mean and standard error of the mean are reported.

At a second sitting, the 2 degree and 1.58 degree stimuli were presented. The 2 degree size was added to ensure that the maximum reading speed had been achieved. The 1.58 degree data point is shown in the results as the mean value from the first and second sittings. The two values for reading speed with the 1.58 degree size did not differ significantly in either the inferior ($t(5)$ –1.803, $p=0.13$; mean difference – 43 wpm, mean values (±sd) for first session 435±110 wpm, for second session 478±75 wpm) or left ($t(5)$ 0.74, $p=0.49$; mean difference 42 wpm, mean values (±sd) for first session 317±88 wpm, for second session 274±84 wpm) fields.

7.4 RESULTS

The results from the 6 observers are shown in Figure 7.1, with closed circles representing the inferior field and open squares the left field. For all observers, as character size increases, reading rate increases until it reaches a plateau at its maximum rate. The data were analysed using the algorithm (Mansfield et al., 1996) described in Chapter 2.5.1. This algorithm identifies the maximum reading speed (MRS), the critical print size (CPS) and the 95% confidence intervals for both these parameters. The MRS is shown for each subject by the solid lines in Figure 7.1. The CPS is the smallest print size included in the maximum reading speed range. The dotted (inferior field) and dashed (left field) lines in Figure 7.1 shows the 95% confidence intervals for the MRS.

Figure 7.2 shows the MRS and 95% confidence intervals for each observer in both meridia examined. The MRS in the inferior visual field is greater than that in the left visual field for all observers. In addition, for 4 of the 6 observers the 95% confidence intervals do not overlap. That is, the minimum value for inferior reading speed is greater than the maximum value for reading speed in the left field. Maximum reading speed in the inferior field is significantly faster than maximum reading speed in the left visual field ($t(5)$ 6.0, $p<0.01$: mean difference – 186 wpm, mean inferior field maximum reading speed (±sd) 436±98 wpm, mean left maximum reading speed 250±34 wpm).

The data are less clear with respect to critical print size. For three of the observers (KL, CH, JM), a larger print size was required to reach maximum reading speed in the left field than in inferior field. For the other three observers (AG, JB, and MC) a larger print size was required in the inferior field than in the left field. Overall, no significant difference in print size required to reach maximum reading speed in inferior or left visual fields was observed ($t(5)$ 0.26, ns). This data is shown in Figure 7.3. The open squares represent the data for the nasal visual field and the closed circles represent the data for the inferior visual field.

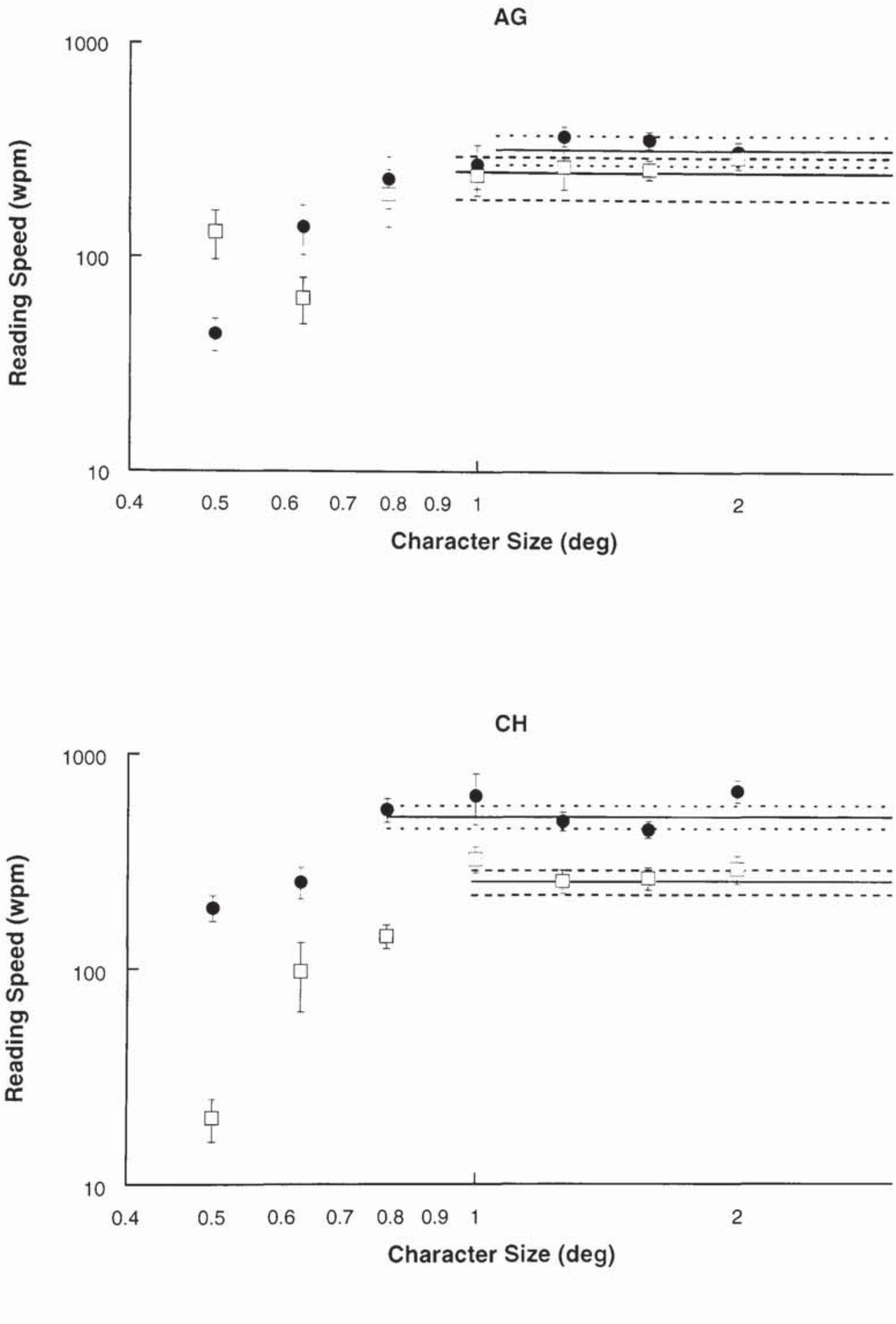
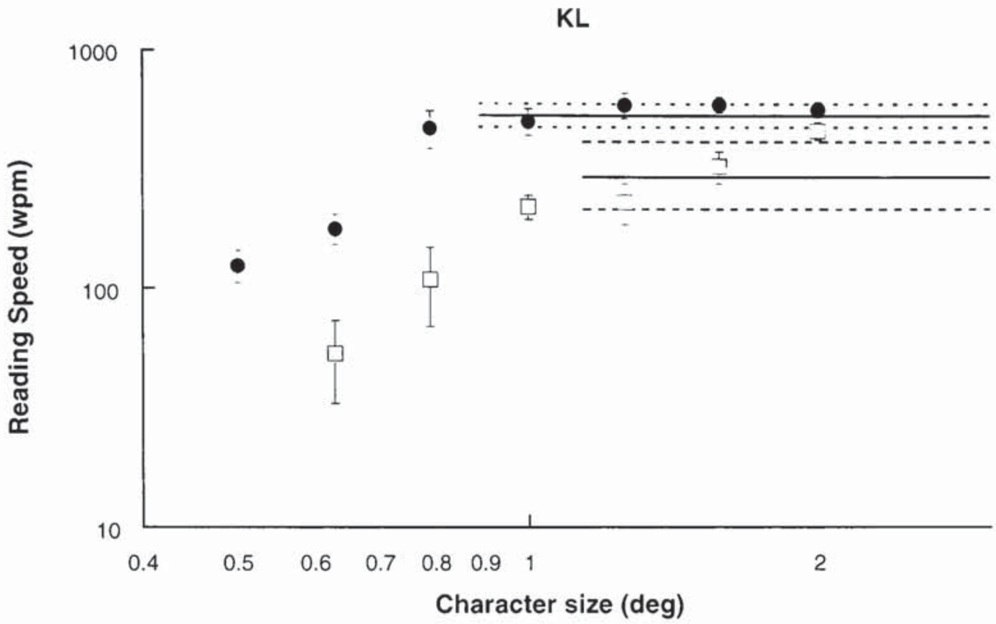


Figure 7.1. Reading speed (words per minute) as a function of character size (degrees) for all six observers. Mean reading speeds and standard error of the mean are plotted for inferior visual field (closed circles) and left visual field (open squares). The solid lines indicate maximum reading speeds and the dotted and dashed lines indicate the 95% confidence limits to the estimates of maximum reading speeds in inferior and left visual field respectively. The x-axis point corresponding with the left-hand end of the solid line represents the critical print size, or the print size below which reading speed falls from its maximum.



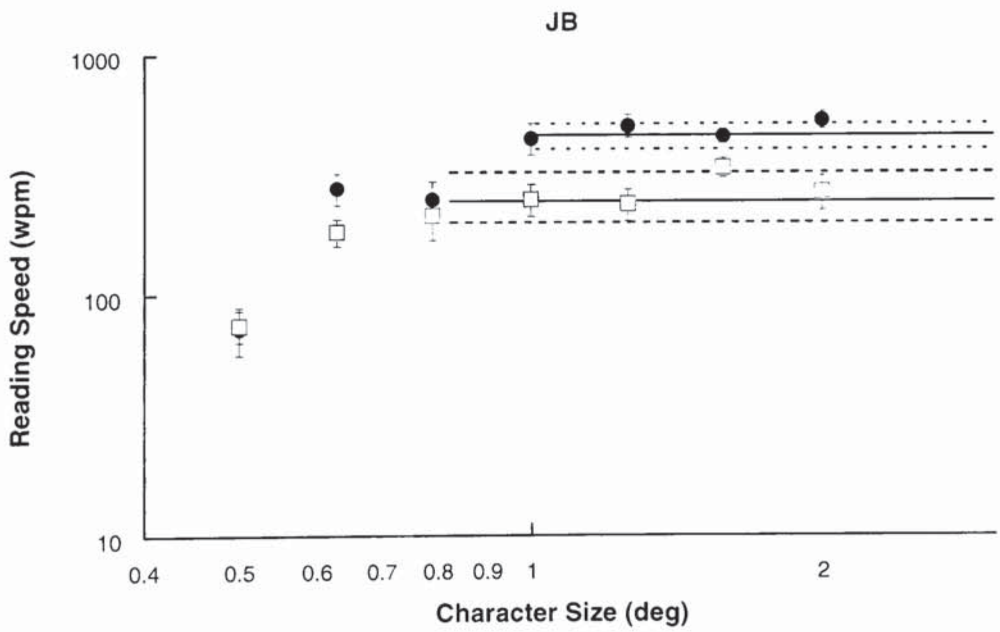
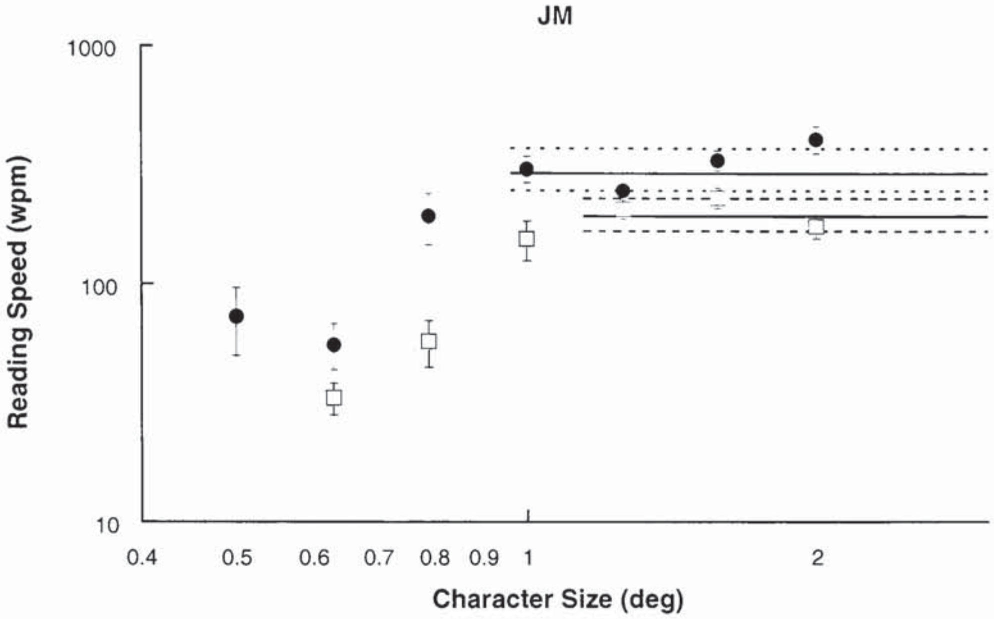


Figure 7.1 continued.



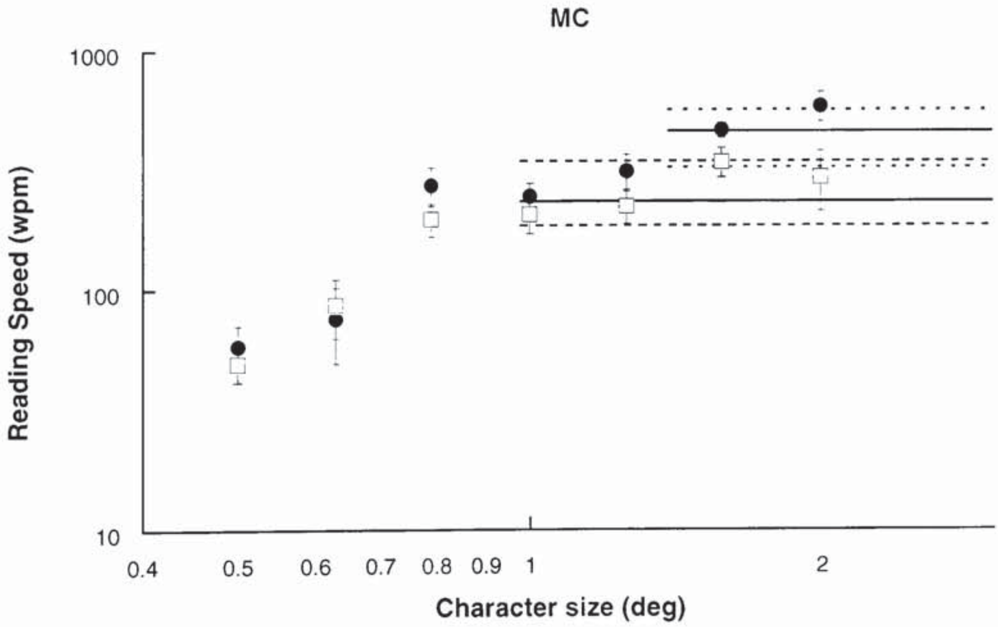


Figure 7.1 continued.

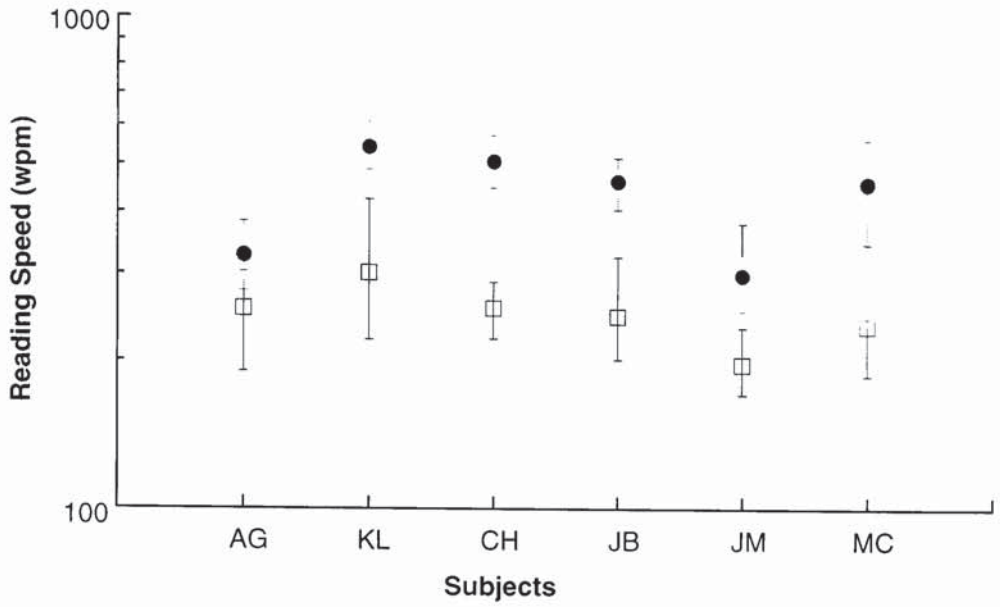


Figure 7.2. Maximum reading speeds and 95% confidence intervals for all observers for inferior (closed circles) and left (open squares) visual fields.

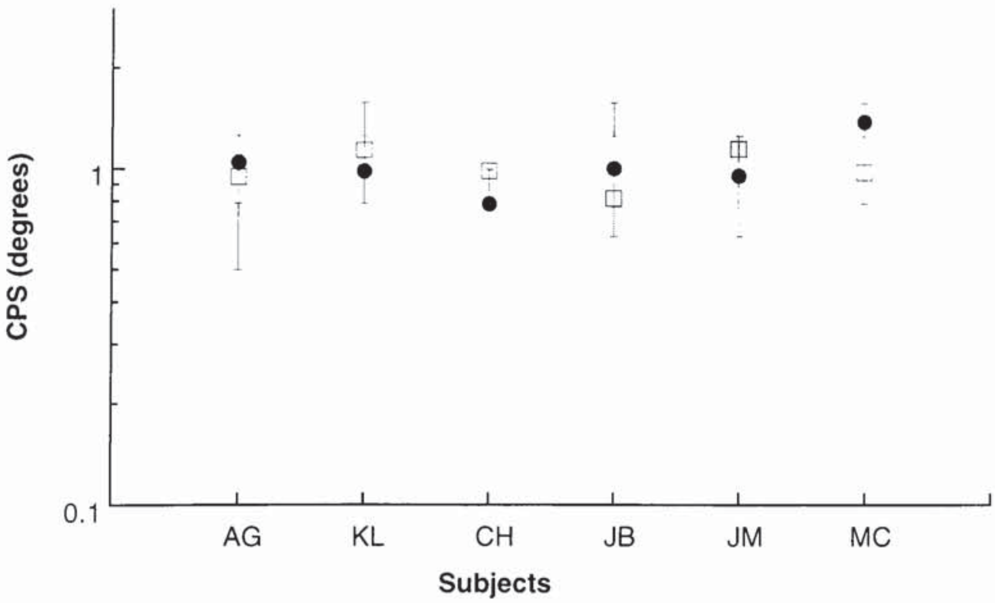


Figure 7.3. Critical print size and 95% confidence intervals for all observers for inferior (closed circles) and left (open squares) visual fields.

7.5 DISCUSSION

The results show that even if print size is appropriately magnified for peripheral viewing, RSVP reading speed in the inferior field of normal observers is faster than in the left field. For reading tasks not involving eye movements, there is a functional advantage in eccentrically fixating such that text falls in the inferior rather than the left visual field. These results agree with those of Fine & Rubin (1999) who found an advantage to using inferior visual field when subjects read a page of text with an artificial scotoma. The advantage of the inferior field was considered to be due to the fact that none of the current line of text was masked by the scotoma and that information needed to guide an accurate return sweep was also available. However, the results of the study described in this chapter suggest that this reasoning cannot entirely explain the advantage seen, since in this experiment masking was similar in both conditions due to the RSVP format.

The reading speed advantage of the inferior field would not be predicted on the basis of the distribution of retinal ganglion cells, since there are fewer ganglion cells at a given eccentricity in superior retina than there are in temporal retina (Curcio & Allen, 1990; Curcio et al., 1990). However, although peripheral visual acuity is dependent on ganglion cell densities (Anderson et al., 1992; Chapter 4), maximum reading speed does not correlate well with acuity (Rubin, 1986; Legge et al., 1992; Sunness et al., 1996; Chapter 2). Therefore, it is not so surprising that left visual field does not show an advantage over inferior field in terms of reading speed. It might be expected, however, that variations in ganglion cell density would be reflected in the critical print size found for the two meridia examined. The critical print size represents the letter size at which maximum reading speed is reached. Some previous studies (Legge et al., 1985; Whittaker & Lovie-Kitchin, 1993) have shown that acuity can predict the magnification required to reach maximum reading speed. The critical print size data in this study show no trend for text in inferior visual field to require more magnification than text in the left field (Figure 7.3).

One obvious difference between inferior and left field presentations is the variation in eccentricity of the words presented in left field as compared to those presented in inferior field. Consider a 5 letter word of the largest letter size tested (2 degrees) presented at 5 degrees eccentricity. Text of this size is large enough for the MRS to be obtained in both locations. In the inferior visual field, the bottom of the central letter of the word is at 5 degrees eccentricity while the beginning and end of the word are at an eccentricity of about 7 degrees from the fovea. In the left visual field the centre of the word is also at 5 degrees eccentricity, but the beginning of the word is at a greater eccentricity (10 degrees) than the end of the word (at the fovea, or 0 degrees). The slower reading speed observed in left visual field might be due to the greater eccentricity of part of the word as compared to the same word presented in inferior field. It is known that the MRS is slower at greater eccentricities in peripheral visual field (Chung et al., 1998; also see Chapter 9) and therefore, the lower MRS in the left visual field may be related to factors other than acuity which reduce eccentric reading speed.

Although in left field the beginning of the word is at a greater eccentricity than that specified, the latter part of the word is closer to the fovea. This might have been expected to assist the observer however, this is not seen to be the case. Even so, various studies have shown that it is the beginning of the word, which in left field is farthest from fixation, that is most important for word recognition (Rayner, 1979; O'Regan et al., 1984; Nazir et al., 1992; Farid & Grainger, 1996; Clark & O'Regan, 1999). If this is true, it suggests that reading in the right visual field would be faster than that in the left visual field. To address this question, additional reading speeds were obtained for the right visual field.

In order to examine reading in the right visual field, words had to be presented to the left eye. This was because presentations to the right visual field of the right eye fell partially within the blind spot. The eye tracker and image stabiliser could not be used with the left eye, so subjects maintained voluntary fixation on a central target. Reading in the left and inferior visual fields were also assessed in the same way for comparison, but with words presented to the right eye. Although the method of fixation control differs from that used in the main study, the results of the study described in Chapter 8 show that voluntary fixation gives similar results to those with stabilised images in this type of task. The methodology was the same as that used in the main study in all other respects. Four observers read sentences of print size 2 degrees, large enough to be representative of maximum reading speed. One subject (CH) had also participated in the main study, and achieved similar results for left and inferior visual fields (main study: inferior field 678±80 wpm, left field 293±44 wpm; control study: inferior field 567±74 wpm, left field 313±58 wpm). The other three observers were normally sighted subjects who had not participated in the main study. In the inferior visual field, the mean reading speed for the 4 observers was 437±54 wpm, and in left field the mean was 212±35 wpm. These values are similar to those found in the main study (inferior field 436±98 wpm; left field 250±34 wpm). In the right visual field mean reading rate was 311±52 wpm. Analysis of variance showed a significant effect of visual field location on reading rate ($F(2, 9)$ 5.5, $p=0.03$), and post-hoc analyses (Scheffe, 5% level) showed that, as before, reading speed in the inferior field was significantly faster than reading rate in left visual field (mean difference 225 wpm). On average, reading speed in the inferior field was faster than that in right field by 126 wpm, but this difference was not statistically significant. Left and right visual field reading speeds were also not significantly different, although on average, reading speeds in the right field were faster than that in the left field by 99 wpm. This additional data is shown in Figure 7.4.

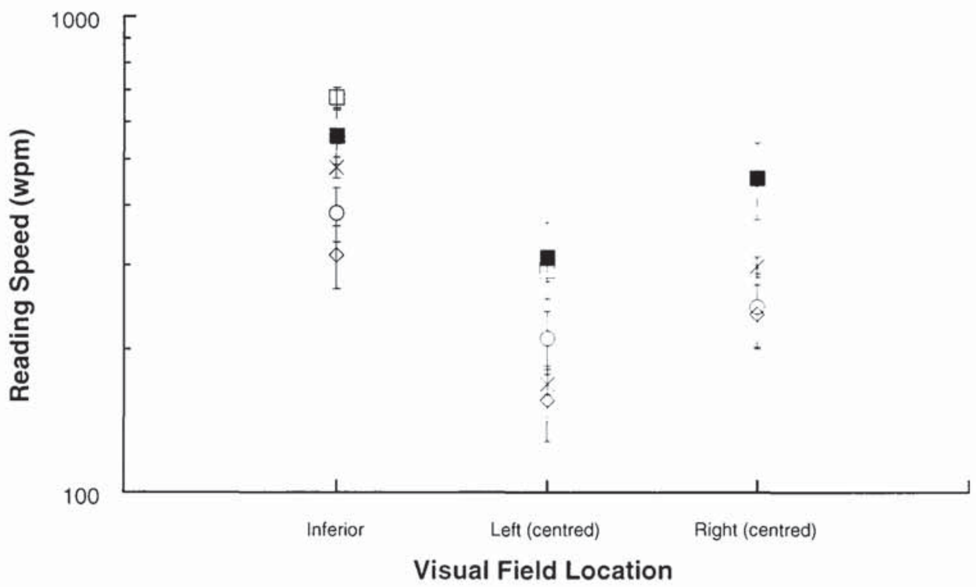


Figure 7.4. Additional data showing maximum reading speeds (±1SD) for subjects in inferior, left and right visual fields. Original data for inferior and left visual fields for subject CH (CH1) is also shown, as well as the repeated data (CH2) for inferior, left and right visual fields. Subject LK = open circles; SB = open diamonds; JL = crosses; CH1 = open squares; CH2 = closed squares.

This data provides some support for the hypothesis that the beginning of the word is more important than the end of the word for recognition, since reading in the right visual field was slightly faster than in left visual field. The results can potentially explain some of the difficulties encountered with reading with left visual field, since in this condition the beginning of the word is farthest from fixation. However, the eccentricity of the beginning of the word cannot explain all the differences observed between inferior and lateral visual fields since inferior field is still the location at which fastest reading speeds are achieved.

An advantage of inferior visual field over left visual field is also seen in page reading tasks where eye movements are involved. As mentioned above, Fine & Rubin (1999) found that reading with attention forced to lower visual field required fewer saccades and was faster than when attending to left visual field. This could partly be due to the artificial scotoma blocking some text from view in the left visual field condition. However, it should be noted that saccades were smaller and more numerous when attending to left visual field than to inferior visual field. A smaller saccade size in the left visual field could suggest that the visual span, defined as the area either side of fixation within which characters of a given size can be recognised (O'Regan, 1990; Legge et al., 1997a; also see Chapters 2 and 10), is smaller in left field than in inferior field. Legge et al. (1997c) and also the results of the study described in Chapter 10, suggest that the visual span is reduced in size in the periphery. The size of the visual span may also be influenced by the site of the PRL relative to the scotoma (Legge et al., 1997b). A smaller visual span could explain our observation of reduced reading rate in left visual field when eye movements are not involved. If a word is presented which is of greater length than the visual span, then in normal reading a subsequent fixation would be required to identify the word. In the absence of being able to make such a fixational eye movement, as in this study, the only way to correctly identify the word would be to compare the incomplete information obtained from the single fixation with an internal lexicon. Additional contextual information could be obtained from other words presented as part of the sentence which were smaller than the visual span. This could limit the relevant choices from the lexicon. On some occasions the 'guess' made by the subject would be correct, but on other occasions it would not, and reading speed would be slower than that observed when all words fell within the visual span. The consequence of a smaller visual span would be reduced reading speed, which is what is observed here for the left visual field.

7.6 CONCLUSIONS

In conclusion, the inferior and left visual fields are the locations most commonly used as sites for a preferred retinal locus by people with central field loss. The results show that for normally sighted subjects reading eccentrically with RSVP text, the inferior visual field is a better position for presentation of text. This is because the maximum reading speed achieved is faster in the inferior than in the left visual field. When reading with eye movements, reading in inferior field is also faster than in left visual field, with fewer saccades (Fine & Rubin, 1999). Since the advantage of the inferior field is not limited to reading tasks involving eye movements, other factors are at least partly responsible for the higher reading speed supported by inferior field.

The results of this study are likely to underestimate the advantage of inferior visual field for people with a central scotoma. In the presence of a scotoma, text must be justified to the edge of the scotoma, rather than centred as has been used here. This will make little difference for text in the inferior field, but when presented in the lateral field text will be seen at greater eccentricities than in this study and reading rates are likely to be further reduced (Chapter 8).

There are difficulties in extrapolating these findings for normal observers to those with low vision. Considering these difficulties however, for a person with central field loss needing to fixate eccentrically, the inferior visual field is recommended as the better PRL location.

Chapter 8

THE EFFECT OF VISUAL FIELD LOCATION ON CONTEXT ADVANTAGE

8.1 INTRODUCTION

Chapter 2 of this thesis discussed how reading with a central scotoma made reading more difficult. This can partly be explained by the decreased acuity and contrast sensitivity performance of the peripheral retina. In addition, it has been suggested that the ability to process meaningful information is reduced when the visual information is imaged outside the fovea. Chaparro & Young (1993) investigated the role of the cone visual system in the superiority of the fovea seen for reading by using text that could only be seen with rod vision. Reading speeds for random words were measured when text was located at different parts of the visual field. At each eccentricity, wavelength and luminance manipulations were used to isolate rods and cones. They found that despite the isolation of the rod visual system, reading speeds were still maximum at the fovea. This suggested that the faster reading speeds recorded with foveal fixation compared with peripheral fixation were independent of the intrinsic differences between rods and cones. More specifically, they were not dependent on an exclusive property of the cone visual system. Unfortunately, in this study the size of the letters relative to acuity threshold at each eccentricity (estimated from the scaling functions of Farrell & Desmarais (1990)) varied from 2.6X at 5 degrees to 0.82X at 20 degrees. Therefore, each letter of the words at 20 degrees eccentricity was below single letter acuity threshold. Considering that the acuity for words is better than for single letters, even in the periphery (Fine & Rubin, 1999), it is understandable that subjects took longer to identify the words that were moved farther into the periphery.

Inappropriate magnification is common to several other studies that have looked at changes in the ability to read using non-foveal retina and concluded that the fovea had an inherent advantage for understanding text (Rayner & Bertera, 1979; Rayner et al., 1981; Ferguson, 1992). More recently, Latham & Whitaker (1996b) came to a similar conclusion using appropriately magnified text. In their study, subjects were presented with either 5-word sentences or lists of random words matched in frequency to the words in the sentences. These sentences and lists of random words were presented using rapid serial visual presentation (RSVP) (Chapter 2.4.3). The texts were presented at the fovea and at 5 and 10 degrees eccentricity. If the ability to understand text is the same regardless of where on the retina the text is imaged, then the ratio of reading speeds for sentences to random words (context advantage) should be the same at all test locations. For one of the two subjects they tested, context advantage in the periphery was much less than the context advantage found at the fovea, and for the other subject, there was no context advantage in the periphery (the ratio of reading rates did not differ from 1.0). From this data, Latham & Whitaker concluded that the fovea had a functional advantage over peripheral retina for understanding text. Using a similar paradigm Chung et al. (1998) found that context advantage was also less in the periphery (5-20 degrees eccentricity) than at the fovea. The results of the study described in Chapter 9 of this thesis also show a decline in context advantage with increasing eccentricity of fixation for normally sighted readers. In addition, from Chapter 9 it can be seen that even subjects with long-term central field loss (CFL) have reduced context advantage when using their preferred retinal locus (PRL) compared to normally sighted subjects using their foveae.

In contrast, Fine & Peli (1996) compared reading speeds for patients with CFL for sentences and random words presented using RSVP. They found no difference in context advantage (there called sentence gain) between their patient group and a group of age matched, normally sighted subjects reading with their foveae. This similarity between the normally sighted subjects and the subjects with central field loss indicated that there was no foveal advantage for reading.

The discrepancies between Fine & Peli's study and the others could be due, at least in part, to the methodologies used. In the study by Latham & Whitaker (1996b), subjects fixated a central fixation marker while the stimuli were presented to their inferior visual field. Similarly, the normally sighted subjects in Chung et al. (1998) fixated a centrally located horizontal line, while reading text presented to the inferior field. In Fine and Peli's study (Fine & Peli, 1996), the patients were unable to fixate a central target due to their scotomata. Therefore they were required to fixate with their PRL. It is possible that the need to fixate the central target reduced the processing capacity available to the subject that would normally be used to understand the context of a sentence.

Another difference between these studies is the location in the visual field where the stimuli were presented. Latham & Whitaker (1996b) and Chung et al. (1998) presented the sentences and random words in the subject's inferior visual field. Most of the patients in Fine and Peli's study (Fine & Peli, 1996) had age-related macular degeneration (ARMD). Studies have shown that most patients with ARMD who adopt a stable fixation location outside their scotoma use an area to the left (and to a lesser extent the right) of their scotoma in visual field space (Sunness et al., 1996). Although fixation was not measured, it was assumed that most patients in Fine and Peli's study fixated either to the left or right of their scotoma. There is some evidence that the effects of attention on information processing differ depending on the location of the stimuli in the subjects visual field (Mackeben, 1996) and that the ability to segment figure from ground is also visual field dependent (Rubin et al., 1996). Given these findings, the advantages of sentences over random words may differ depending not only on whether the text is presented to the fovea or peripheral retina, but where in the periphery the stimuli are presented.

8.2 AIMS

The aims of this study were firstly to determine whether the location of the text in the subject's visual field affects context advantage. Secondly, in order to rationalise the apparently conflicting data in the literature, it was necessary to determine whether the need to maintain fixation affects context advantage. In this study, subjects read sentences and lists of random words presented to their fovea and at 5 degrees eccentricity. Sentences and random words were presented at both 5 degrees in the left visual field and 5 degrees in the inferior visual field. To determine whether the need to maintain fixation affects context advantage, subjects read texts presented at 5 degrees eccentricity when they maintained voluntary fixation on a central target and also when the text was stabilised on their retina.

8.3 MATERIALS AND METHODS

Subjects read sentences and lists of random words presented using RSVP at their fovea, at 5 degrees in the nasal (left) visual field and at 5 degrees in the inferior visual field of the right eye. The temporal (right) field was not chosen because in pilot testing some subjects were unable to see portions of words presented to the temporal field due to their physiological blindspot. In addition, it was not possible to use the eye tracker with the left eye. With the nasal and inferior presentations, the stimuli were either stabilised on the subjects' retina or they were asked to fixate a red LED while their eye movements were monitored to ensure appropriate fixation.

8.3.1 Subjects

Six subjects between 21 and 45 years of age (mean 28 years) with normal visual acuity (0.0 logMAR or better) participated in this experiment. All read and signed an informed consent before testing began and were compensated for their time. Ethical committee approval was received from The Johns Hopkins University Hospital.

8.3.2 Apparatus

The text was stabilised and eye movements were monitored with an SRI Generation V dual-Purkinje-image eye tracker (Crane & Steele, 1985). Text was stabilised on the retina using an optical image stabiliser (Crane & Kelly, 1983). The image stabiliser reduces the luminance of the display at the subject's eye, therefore the optics of the image stabiliser remained in place throughout the experiment and the stabiliser was turned off when it was not in use. The image stabiliser can only present text to the right eye. The subject's left eye was patched throughout the experiment.

A fixation mark that was not stabilised on the subject's retina was used to align the image stabiliser in the same method as described in Chapter 7. In this way, text was stabilised either 5 degrees inferior to the fovea or 5 degrees nasal to the fovea.

During the voluntary fixation trials, subjects were asked to fixate a red LED attached to the monitor. To monitor fixation, the eye tracker was calibrated by realigning the zero position from the centre of the monitor to either the superior or temporal locations indicated above. The subjects were then asked to fixate four small crosses at the corners of a 2 degree square surrounding the fixation point. Each of these points was fixated twice. Subjects were asked to move their eye to each of the crosses and indicate they were fixating the correct location by pressing a joystick button. The horizontal and vertical outputs from the eye tracker were recorded for 500 msec following the button press. The average fixation location when the subjects indicated they were fixating each of the four crosses was used to define a 2 degree square surrounding the LED. If the subject's eye strayed outside the square during a trial, the computer gave an audible warning, and the trial was discarded.

Stimuli were presented on an Apple ColorSync 17-inch CRT display as described in Chapter 7. The screen refresh rate was 67 Hz, and similar to the experiment described in Chapter 7, an additional 15 msec per stimulus interval was accounted for in the results presented here. The monitor was controlled by a Mac Performa 6115 and 'RSVP' software, version 4.03 (Williams & Tarr, 1998).

8.3.3 Stimuli

Text was presented in 96 point Helvetica. This size had previously been found to be sufficient to allow maximum reading rates for sentences (Chapter 7). The letters were white on a black background. The luminance of the text was 63 cd/m^2 and the background was 0.03 cd/m^2, providing a Weber contrast of about 99%. The x-height of the letters was 2.2 cm or 1.58 degrees at the 80 cm testing distance used.

The sentences had 5-7 words, and each word had one to seven letters. The average word length for the sentences was 4.4 letters. The random word lists had 5 words of three to seven letters each. None of the words were repeated within a list. The average word length for the random word lists was 5.2 letters. The words in the random lists were approximately matched in frequency to the words in the sentences. Each sentence (or list of random words) was preceded and followed by a string of 5 X's to serve as forward and backward masks for the first and last words in the sentence. The X's were always displayed for 1000 msec, except for the initial X's on the first sentence in each trial run, which were displayed for 6000 msec. This longer display period served to adapt the subject to the abrupt change in luminance of the display that occurred when the trial sequence began.

The sentences and random lists of words were presented using RSVP (Chapter 2.4.3). Each word within a sentence or word list was presented for the same duration and there was no inter-stimulus interval. The words were centred for the inferior conditions and right justified for the nasal conditions. At the fovea subjects read both centred and right justified displays. In the nasal condition the words were right justified, and therefore, all of each word was presented beyond 5 degrees eccentricity. This increased the difficulty of the task because most of the text was presented to more peripheral retina. However, this situation is more similar to how a patient with central field loss would be forced to fixate; that is justifying the letters to the edge of their scotoma.

8.3.4 Design and Procedure

Subjects always read at the fovea first. The order of right justified or centred text was randomly selected for each subject. The order for sentences and random words was also randomly determined for each text alignment condition, but both sentences and random words were read with each alignment before the alignment was changed. Stabilised and voluntary fixation trials were blocked and their order was counter-balanced across subjects. Within each fixation condition (stabilised or voluntary), the order of nasal and inferior was also counter-balanced across subjects. As with the foveal presentation, stimulus order was randomised, and both stimulus types were read at each location before the location was changed.

For each stimulus type under each presentation condition (location and fixation strategy), subjects read 18 stimuli. A one-up, one-down staircase with unequal step sizes (Kaernbach, 1991; García-Pérez, 1998) was employed with word duration as the dependent variable and was used as described in Chapter 7. A sentence was marked correct if all of the words were reported in the correct order (the same criteria were used for the random word lists). The unequal step size chosen gave an estimate of word duration that gave 78% correct responses (Kaernbach, 1991; García-Pérez, 1998). This is the same performance criterion selected by Chung et al. (1998) and Fine & Peli (1996) in two previous studies of context effects with RSVP. Stimulus duration in msec was converted to reading rates in words per minute (wpm) for analysis. The trials with the fastest and slowest reading rates were discarded and the remaining reversal points were averaged.

When text was presented at the fovea, the subjects were free to fixate at any point on the display and fixation was not monitored. When text was stabilised, trials were eliminated if the eye tracker lost track of the subject's eye during a trial, in which case the stimulus was no longer appropriately stabilised. During the voluntary fixation trials, trials were eliminated if the subject's eye strayed outside the 2 degree box defined during the calibration phase. This happened only rarely when the text was presented inferior to fixation. However, in the nasal condition, subjects found maintaining fixation difficult when they read the random words. In order to retain as much data as possible, those subjects who were having difficulty maintaining fixation were asked to indicate to the experimenter if they had directly fixated any of the words on a given trial. Only those trials during which the subject reported directly fixating the stimuli were eliminated. Although this method is sub-optimal, loss of fixation often occurred *after* the subject had reported the word. When display rates were very slow, the subjects were often able to finish vocalising the current word before it was replaced by the next word. In addition, even when the eye tracker indicated that the subject had lost fixation, more often than not the current word was misread.

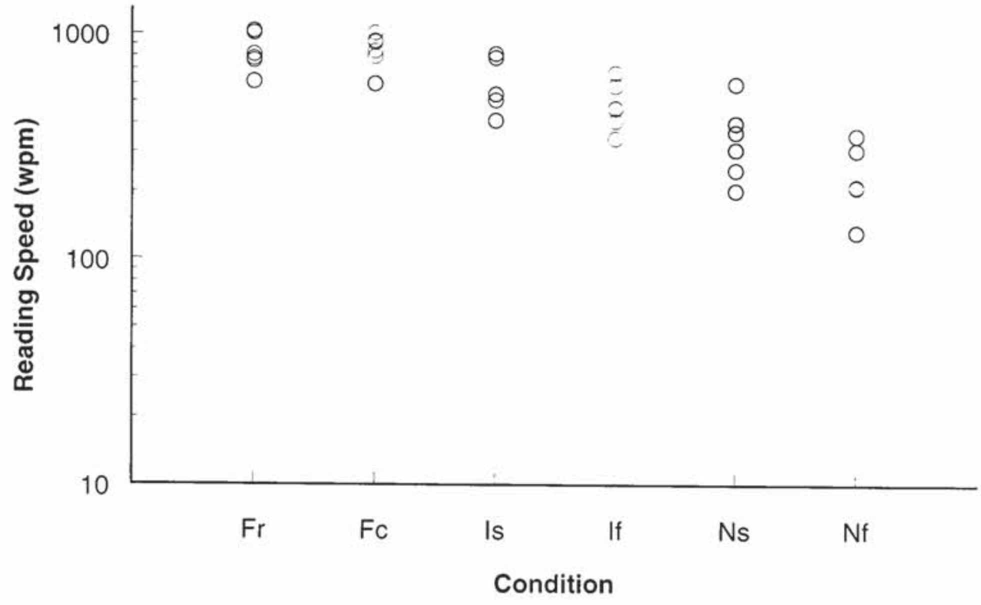
8.4 RESULTS

Figure 8.1 shows reading rates in wpm for a) sentences and b) random words for each of the six conditions tested. As can be seen from the graphs, reading rates were slower for the random words than they were for the sentences, and this was consistent across subjects. Text justification (centre or right) did not interact with stimulus type when subjects read using their fovea ($F(1, 20)$ 0.06, n.s.). There was no interaction between fixation strategy and stimulus type in either the inferior field ($F(1, 20)$ 0.52, n.s.) or the nasal visual field ($F(1, 20)$ 2.03, n.s.).

Context advantage was defined as the ratio of the reading rate (in wpm) for sentences to the reading rate for random words and these values are shown in Figure 8.2. There was no difference in context advantage values between the centred and right justified text at fovea ($F(1,20)$ 0.05, n.s.). There were also no differences in context advantage depending on fixation condition in either the inferior ($F(1,20)$ 2.89, n.s.) or nasal fields ($F(1,20)$ 3.5, n.s.). For all subsequent analyses of context advantage, data for each subject was combined across text justification (fovea) or fixation condition (inferior and nasal).

Analysis of variance showed a significant effect of visual field on context advantage ($F(2, 33)$ 15.9, $p=0.001$). Post hoc analyses (Scheffe, 5% level) indicated that context advantage was larger in the nasal visual field than at either the fovea (mean difference = 5.07) or the inferior visual field (mean difference = 5.16). The context advantage values at the fovea and inferior visual field were not significantly different (mean difference = 0.09).

a)



b)

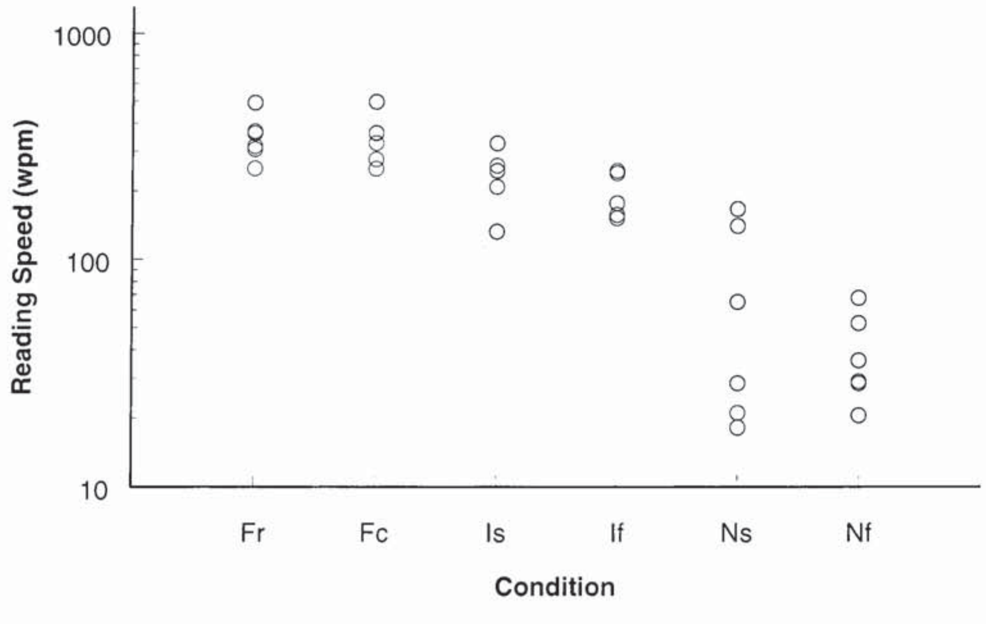


Figure 8.1. Reading speeds for a) sentences and b) random words in wpm for each subject. Fr = fovea right justified; Fc = fovea centre justified; Is = inferior stabilised; If = inferior voluntary fixation; Ns = nasal stabilised; Nf = nasal voluntary fixation. Mean values (±1SEM) (wpm).
Sentences: Fr = 847.4±66.5; Fc = 871.2±60.5; Is = 619.4±68.5; If = 509.3±51.1; Ns = 368.0±60.5; Nf = 246.2±34.2.
Words: Fr = 350.4±33.4; Fc = 348.3±35.6; Is = 238.6±26.2; If = 194.1±17.2; Ns = 74.2±27.0; Nf = 39.4±7.4.

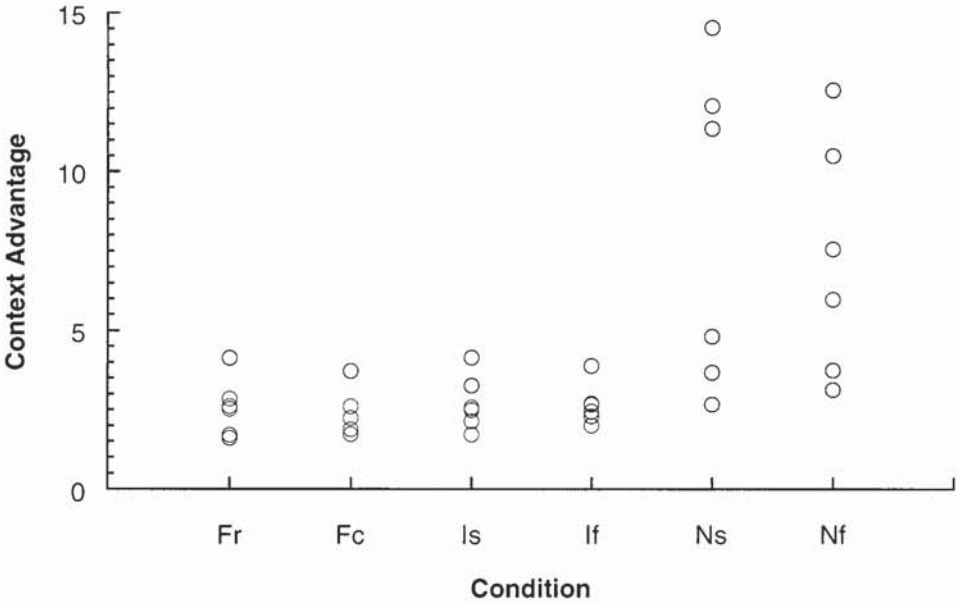


Figure 8.2. Context advantage for each subject. Fr = fovea right justified; Fc = fovea centre justified: Is = inferior stabilised; If = inferior voluntary fixation; Ns = nasal stabilised; Nf = nasal voluntary fixation.

8.5 DISCUSSION

Subjects showed similar context advantage values in the fovea and inferior visual fields, and much larger context advantage values in the nasal field. This was true for when the subjects fixated a target at the fovea as well as when the text was stabilised on their retinae. No difference in performance was found between the voluntary fixation and stabilised conditions of the study described here. This implies that the need to fixate a target at the fovea does not place additional demands on processing resources used to understand text compared with those used in the stabilised condition. As such, the need to maintain fixation does not affect context advantage.

It is interesting that the context advantage was so much greater in the nasal field than in the inferior field. This was mostly due to a decrease in random word reading speeds. Reports from the subjects as well as their measured reading rates (see Figure 8.1a) and b)) indicate that reading in the nasal field was the more difficult task. This difficulty was most likely due, at least in part, to the fact that all except the last letter of each word was beyond 5 degrees eccentricity. As indicated earlier, subjects had the most difficulty fixating the LED in the voluntary fixation condition when the random words were presented to the nasal field, again indicating that the task was more difficult. Even though the task was more difficult, context advantage values were greatest in this condition. In particular, it appears that difficulty with the task is reflected in the slowing of the word reading speeds specifically. Subjects who had most difficulty with the task had the slowest word reading speeds and therefore the largest context advantage values. This can be seen from Figure 8.1a) and b) by the wide spread of values in both of the nasal random word conditions.

The increased context advantage in the nasal field relative to the fovea and the inferior field, is not consistent with comparisons of eccentrically fixating patients with central field loss to normally sighted controls using their foveae. All of the patients in Fine & Peli (1996) had central field loss due to AMD. It was therefore assumed, although fixation was not measured in the study, that most of them were using an area of retina to either the left of their scotoma (Schuchard & Fletcher, 1994; Sunness et al., 1996). In Fine and Peli's study, the context advantage values for the CFL patients (2.0±0.22) were not significantly different from the context advantage values for the normally sighted observers (2.3±0.13) reading with foveal fixation.

One critical difference between the current study and that of Fine & Peli (1996) is that the patients in Fine and Peli's experiment were able to move their eyes relative to the text they were reading. Rubin & Turano (1994) reported that, unlike normally sighted people, patients with central field loss do make eye movements within words when reading RSVP. It has been hypothesised that RSVP benefits reading comprehension because the lack of requirement for eye movements reduces the visual difficulty of the task. If the visual difficulty is reduced, the cognitive capacity available for comprehension is therefore increased (Chen, 1986). According to Chen's hypothesis (Chen, 1986), making eye movements within words should reduce the possible context advantage because cognitive resources that would otherwise be used for comprehension of meaningful text must be devoted to the planning and execution of eye movements. In agreement with this, Fine et al. (1997) showed that the ratio of reading rates for sentences to random words (there called sentence-gain) was reduced when the subjects read with simulated cataracts that severely reduced their acuity and presumably increased the requirements for cognitive resources.

Chen's hypothesis could explain why context advantage values were not greater for the patients in Fine and Peli's study (Fine & Peli, 1996) relative to their normally sighted subjects. However, it does not explain why context advantage was much greater in the nasal field than the inferior field in the study described in this chapter. One would have expected the context advantage values in the nasal field to be reduced relative to the inferior field, where subjects found fixating in the voluntary fixation condition easier. Also, in the inferior field, most of the letters in each word were closer to the fovea than they were in the nasal condition also making reading easier than with the nasal field. Indeed, conflicting arguments exist as to the effect of task difficulty on the ability to use context. Baldasare & Watson (1987) hypothesised that vision impaired readers would be less efficient at using context because a large proportion of their finite processing capacity is required for decoding the visually degraded stimulus. In support of this theory, Patberg et al. (1981) found that poor readers were able to use context less effectively than good readers. It was considered that so much of the poor reader's processing capacity was directed at letters and words, that they were unable to use contextual information effectively. In contrast, Whittaker & Lovie-Kitchin (1993) have proposed that vision impaired readers should use context at least as much, if not more than normally sighted readers. This is because visually degraded text increases the importance of context in helping the reader determine the stimulus.

Despite the conflicting data, one possible reason for the increased context advantage observed in the nasal field may be due to the difficulty the subjects had maintaining fixation when they read random words in the voluntary fixation condition. This may have specifically decreased their reading rate for the random words, thereby increasing context advantage.

The results of this study also did not indicate reduced context advantage in the inferior field that has been reported in previous studies (Latham & Whitaker, 1996b; Chung et al., 1998; also see Chapter 9). In the study by Latham & Whitaker (1996b), average context advantage was reported to be 2.9 at fovea and 1.1 at 5 degrees inferior visual field. In the study by Chung et al. (1998), average context advantage was 2.4 at fovea and about 1.3 at 5 degrees. The context advantage values at the fovea in these studies are similar to those in Fine & Peli (1996) (2.3) and (Fine et al. (1997) (2.5 combined across the older and younger subjects), as well as the current study (2.6). The fact that context advantage values at the fovea are similar across studies suggests that the difference in stimuli or methods cannot account for the different findings in the inferior field. The potential reasons for this conflicting finding are discussed in Chapter 9, where context advantage was found to reduce with eccentricity.

8.6 CONCLUSIONS

The results of the study show no effect of the need to maintain fixation on context advantage. This chapter is unable to reconcile the differences in context advantage in the inferior and nasal visual fields relative to past studies (Latham & Whitaker (1996b) and Chung et al. (1998) for the inferior field and Fine & Peli (1996) for the nasal field). However, context appears to be an important factor in determining reading rates regardless of where the text is imaged on the retina. It is clear that patients with central field loss have difficulty reading, and that their reading rates rarely match those of normally sighted readers or readers with other visual impairments that do not affect the fovea (Legge et al., 1992). However, from the results of this study, it is not possible to say that the ability to use the context available from the text is the limiting factor.

Chapter 9

READING WITH LONG-TERM CENTRAL FIELD LOSS

9.1 INTRODUCTION

The previous chapters (Chapters 7 and 8) investigated the fact that rapid serial visual presentation (RSVP) reading speed for normally sighted subjects is slower when text is presented in the periphery than when presented at the fovea. This is the case even when peripherally presented text is appropriately magnified (Latham & Whitaker, 1996b; Chung et al., 1998). Some studies have found that this reduction in reading speed has a greater effect on the reading speeds for meaningful text than those for random words. As a result, some studies have found context advantage (CA) values (the ratio of text reading speeds to random word reading speeds) to be greater at the fovea than the periphery in normally sighted observers (Latham & Whitaker, 1996b; Chung et al., 1998). The ability of normally sighted observers to utilise context when reading therefore appears to be specifically suited to foveal fixation. As such, this may provide a reason for the reduced text reading speeds of individuals with central field loss (CFL). This hypothesis however is not supported by Fine & Peli (1996) who asked CFL and normally sighted subjects to read both words and text using RSVP. Although their CFL subjects read slower than the normally sighted subjects there was no significant difference in context advantage (there called sentence-gain) between their normally sighted subjects using central fixation and the CFL subjects using eccentric fixation. The study described in Chapter 8 also found no difference in context advantage values for normally sighted subjects reading text foveally and stabilised at 5 degrees inferior visual field.

Studies and clinical experience have shown that the visual system is able to adapt to loss of central field by choosing one or more preferred retinal loci (PRL) to use as a 'pseudo-fovea' (Cummings et al., 1985; Timberlake et al., 1986; Guez et al., 1993; Lei & Schuchard, 1997), and Chapter 7 has suggested that the best position for this PRL is in inferior field. Unfortunately this new retinal locus does not automatically achieve visual function similar to that of the fovea (Timberlake et al., 1987). It is therefore important to understand to what extent, if at all, the PRL of the observer with CFL can actually adapt to become more like the fovea.

A minimum level of adaptation with loss of central field does occur, as patients with CFL can be trained to use a new retinal locus for fixation. Nilsson et al. (1998) used a computer and video display system to determine the most suitable retinal location for reading and the magnification needed in subjects with dense central scotomata. A relatively small number of training hours produced a significant increase in text reading speed as well as an improvement in fixation stability using the eccentric retinal locus. Whittaker & Cummings (1986) found abnormal eye-movement patterns in subjects with CFL, including hypometric (undershooting) saccades and inter-saccade fixations. However, eye movements of their subject with long-term field loss were more typical of a normal, foveate individual. As part of the same study, the authors created an artificial scotoma in a normally sighted subject. The subject's eye movements were then trained so that a peripheral retinal locus became a 'pseudo-fovea' with stable fixation and the accurate endpoint of saccades. At least as far as eye movements are concerned, results of these studies suggest some level of plasticity of the visual system in order that adaptation to central field loss can occur.

Although, as seen above, eye movements and fixation ability can be trained to improve visual performance, the evidence for functional adaptation is less clear. It is however a common clinical observation that patients can recover neurological functions after brain injury and in fact neurogenesis has been demonstrated in the adult human brain (Goldman &

Plum, 1997; Witte, 1998). Studies have also shown re-organisation of neuronal connectivity in the target brain area after focal retinal lesions in adult mammals (Kaas et al., 1990; Gilbert & Wiesel, 1992). Changes have also been shown in receptive field properties of neurons in adult mammal visual cortex (Pettet & Gilbert, 1992; McLean & Palmer, 1998) following conditioning with a stimulus that produced a central field loss. Thus, evidence of plasticity within the adult brain exists that would suggest adaptation of the visual system is possible.

9.2 AIMS

Considering the evidence cited above for functional adaptation, this study investigates how long-term use of eccentric field in CFL patients affects reading performance as compared with normals using eccentric retina. It is hypothesised that in long-term CFL there will be an increase in context advantage more similar to that used by normals when reading with their fovea. This would enable improved ability to use context and indicate functional adaptation of the PRL over time. Such evidence of plasticity of retinal function would reinforce the usefulness of training to maximise reading performance in addition to the benefits of stabilising eye movement function. A similar or reduced context advantage in long-term CFL compared to normal peripheral vision would indicate no functional adaptation of the PRL and at least partially explain the reduced reading performance seen with CFL patients. Although this result suggests that no functional improvement of the peripheral point will occur, training of subnormal fixation and eye movements using a suitable PRL would still be beneficial.

9.3 MATERIALS AND METHODS

9.3.1 Subjects

Seven normally sighted subjects (age range 21-36 years; mean = 26.0±4.9 years) with no ocular or systemic disease participated in the study. Viewing was monocular, using the dominant eye. Visual acuity of the recorded eye for each of these subjects was better than or equal to 0.0 logMAR. Eight subjects (age range 28 – 54 years; mean = 39.0±10.0 years) with bilateral central field loss (CFL) were also recruited. All subjects had been diagnosed with Stargardt's disease and had documented bilateral central field loss for a minimum of 3 years. Bilateral CFL ensured that eccentric fixation was habitually used in the dominant eye tested in this study. Suitable subjects were chosen from patient records of the Birmingham & Midland Eye Centre and the Coventry & Warwickshire Hospital. Details of the subject's ocular history were obtained from the hospital notes and confirmed by direct questions prior to the commencement of the experiment. None of the subjects reported having received any formal training in eccentric fixation. Ethical committee approval was received from Aston University and from the hospitals from which the subjects were recruited. All subjects gave informed consent and were compensated for their time.

9.3.2 Visual Acuity and Visual Fields

High contrast distance visual acuity was recorded following subjective refraction for all subjects in each eye using an internally illuminated EDTRS chart at 3 metres. Near visual acuity was measured using a Bailey-Lovie near word acuity chart at 25 cm with appropriate working distance correction if required. The remaining tests were carried out using the dominant eye with the other eye patched. Visual fields were measured for the CFL subjects using a Bjerrum Screen and a 3 mm white target at 1 metre. This provided an estimated measurement of the central scotoma size and location. The subjects used their PRL for fixation, resulting in the scotoma being offset with respect to the fixation point. The foveal position was estimated by comparison to the blind-spot position and the eccentricity of the

PRL relative to the fovea was noted. Fixation was defined in terms of the location of the PRL relative to the fovea in one of 4 visual field quadrants, i.e. superior, inferior, left or right. Eccentricity was approximated by dividing the visual field into annuli. These were centred around the assumed foveal position and separated at 5 degree intervals such that a fixation eccentricity of 5 degrees was within an annulus ranging from 2.5 to 7.5 degrees and an eccentricity of 10 degrees was within an annulus ranging from >7.5 to 12.5 degrees. These annuli enabled the eccentricity of fixation to be approximated to the nearest 5 degrees by examination of the visual field plots. Table 9.1 gives a summary of the visual acuity and fixation characteristics of the CFL patients.

9.3.3 Stimuli

Oral reading speeds were measured using single sentences and lists of random words. A list of 600 sentences was used which were 5-7 words in length. The sentences consisted of words within the top 10,000 most frequent words in written English (Hofland & Johansson, 1982) and each word was a maximum of 7 letters long. For each trial, one sentence was presented from the pool of sentences, and a subject read each sentence only once. A list of 300 nouns, adjectives and adverbs (3-7 letters long) also within the top 10,000 most frequent words in written English (Hofland & Johansson, 1982) was also compiled. These words were presented at random in groups of five and no words were repeated within a group. All subjects had an educational standard that exceeded the level of the text ensuring that reading speed measures were not compromised by difficulty in comprehension of the text. These stimuli were also used in the study described in Chapter 8.

The sentences and random words were presented using the RSVP paradigm (Chapter 2.4.3). There was no inter-stimulus interval. Text was presented in centred Times New-Roman font and in reverse polarity (white on black) on an EIZO TS62-T 17 inch colour monitor using a Visual Stimulus Generator 2/3 (Cambridge Research Systems). The monitor measured 33 cm horizontally and 24.5 cm vertically and displayed 640 x 480 pixels. The screen refresh rate of the monitor was 100 Hz which limited stimulus durations to multiples of 10 ms. Stimulus durations and the inter-stimulus interval were confirmed with a photocell and oscilloscope. Letters were presented at a luminance of 93 cdm^{-2} on a background of luminance 2.4 cdm^{-2}, providing a Weber contrast of approximately 97%. These values were measured with a Minolta CS 100 photometer.

Subject	PRL location in visual field	Eccentricity of fixation (degrees)	Age (years)	Bilateral CFL (years)	HCVA dominant eye (logMAR)	HCVA other eye (logMAR)	Near VA (logMAR) (at 25cm)	Near VA other eye (logMAR) (at 25cm)
JD	Right (right eye)	10	36	4	0.82	0.82	1.2	1.2
DB	Left (left eye)	5	54	3	0.22	1.8	0.6	1.1
MG	Inferior (left eye)	10	46	9	1.02	1.1	1.3	1.2
VB	Left (left eye)	25	49	42	1.5	1.5	1.2	1.2
SL	Inferior (right eye)	5	29	23	1.0	0.96	1.1	1.1
SA	Inferior (left eye)	5	30	15	0.86	0.86	1.1	1.1
HJ	Left (right eye)	15	39	14	1.3	1.34	1.6	1.6
CG	Inferior (left eye)	5	28	21	0.98	1.2	0.9	1.2

Table 9.1. Fixation characteristics, ages and distance and near visual acuities of the CFL subjects.

9.3.4 Procedure

All subjects read the words and sentences with their dominant eye whilst the other eye was patched. Viewing distance was maintained by means of a chin rest. Normally sighted subjects read aloud text that was presented at the fovea, and also at 5 and 10 degrees inferior visual field whilst they fixated a central white spot target. The presentation location was defined from the centre of the word for all locations. The fixating eye was monitored using a video camera. This ensured that the normally sighted observers fixated accurately such that the text was presented at the intended eccentricity. A loss of fixation was shown as a vertical eye movement, which was easily detected. If this occurred, the current trial was discarded. However, this was necessary only 3 times throughout the study. CFL subjects used their PRL to read aloud the same words and sentences as the normally sighted subjects.

The largest possible print size was 5.0 degrees when the viewing distance was 40 cm (or 4.0 degrees when the viewing distance was 50 cm). This maximum size allowed the longest words in the list to fit within the size constraints of the screen without resorting to working distances less than 40 cm. The first sizes presented were 2.5 degrees for the CFL subjects and the normally sighted subjects reading at 5 and 10 degrees, and 0.57 degrees for the normally sighted subjects when reading with their fovea. Threshold reading speeds for print sizes ranging from 2.5 degrees down to acuity threshold were determined using the method of limits. The procedure used for the determination of these thresholds is described below.

Two or three trials were presented at the largest text size as practice trials. These trials were started at very slow presentation times, and then duration was reduced in 0.1 log unit steps until a threshold value was determined. Threshold was defined as an error being made in reporting words. To be deemed correct, words in the sentences and word lists had to be read verbatim. The data from these trials was not included in the analysis. At the largest size used, three trials were then commenced at 0.4 log units slower than the threshold value determined in the practice trials. The presentation time was then reduced in 0.1 log unit steps until the subject was unable to read the word list or sentence without errors. The recorded threshold reading speed was the fastest presentation time that the subject was able to read without errors. Three trials were then commenced 0.4 log units faster than the threshold value determined in the practice session, and the presentation time was increased until the subject was able to read the word list or sentence without errors. As before, the recorded threshold reading speed was the fastest presentation time that the subject was able to read without errors. At the fast presentation times, the monitor refresh rate limited the minimum presentation time to 10 ms. For the fastest normally sighted readers this meant that the initial presentation time was sometimes less than 0.4 log units faster than their threshold presentation times. However, the fastest threshold recorded for any subject was 30 ms or 2000 wpm, which was still 0.2 log units slower than the fastest possible presentation time. When six threshold values had been obtained, the print size was reduced by 0.1 log units, and the procedure described above was repeated. The initial presentation time for these second and subsequent trial sets was the same as the first trial set (i.e. 0.4 log unit steps slower or faster than the initial threshold estimate), thus providing, when possible, at least 4 presentation speeds above or below threshold. A trial was discarded if the subject reached threshold reading speed after less than two sentence or word list presentations within a particular trial. As threshold speeds reduced, this initial value was reduced by an equivalent amount in order to maintain a minimum number of random word/sentence presentations within each trial before threshold was reached. The process was repeated until a text size was reached where the subject was unable to read the sentences or random words without errors. At large print sizes, threshold reading speeds remained constant over a number of print sizes, thus resulting in a plateau of maximum reading speed. The plateaus for each subject are depicted by the solid lines in Figure 9.1. If less than 3 plateau reading speed values were obtained, text was then presented at 3.2 or 4.0 degrees, and if necessary 5.0 degrees by decreasing the working distance to 40 cm.

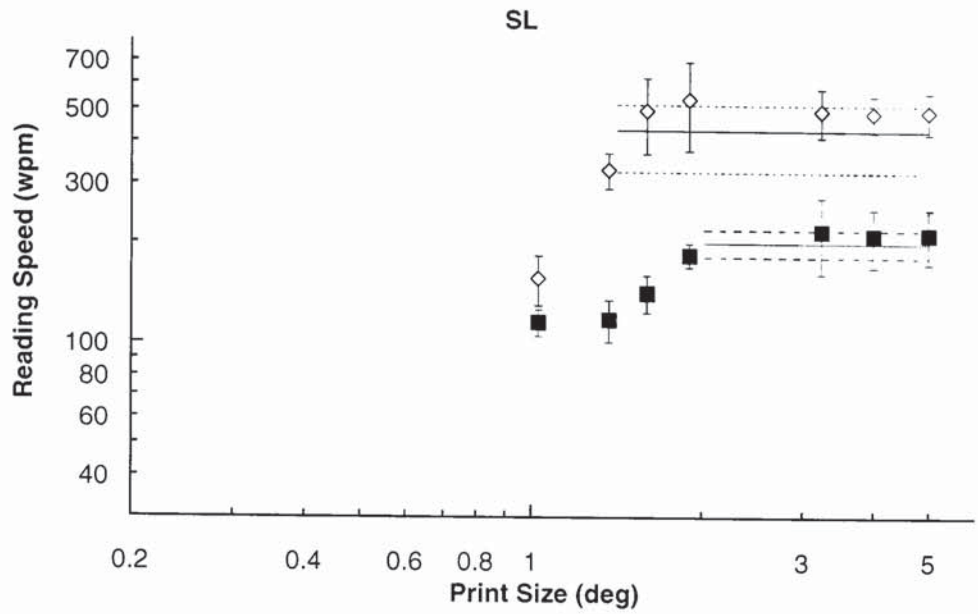
The working distance was 50 cm for all normally sighted subjects when reading print sizes 10 point (0.27 degrees) or larger. The working distance was increased to 1 m and then 2 m to obtain image sizes less than 0.27 degrees and 0.14 degrees respectively. This enabled an angular subtense as small as 0.09 degrees to be obtained whilst maintaining image quality with a minimum point size of 10 point. The minimum print size read by any of the subjects however, was 0.12 degrees. The working distance for CFL subjects was also 50 cm. However, for three subjects (HJ, VB and MG) the viewing distance was reduced to 40 cm to enable 5.0 degree text to be presented. Subjects wore their distance correction and those who habitually wore spectacles for near were corrected for working distances less than 1 m.

9.4 RESULTS

The presentation duration times were recorded in milliseconds (ms) and converted to words per minute (wpm) using the following equation:

Reading Speed (wpm) = 60000/presentation duration per word (ms) Equation 9.1.

For each subject and each condition, reading speeds (wpm) were plotted as a function of print size in degrees. Data for the CFL subjects are shown in Figure 9.1. The data were analysed using an algorithm developed by (Mansfield et al., 1996). The advantages of using this type of analysis are explained in Chapter 2.5.2. The algorithm calculates a maximum reading speed (MRS) and critical print size (CPS), both with 95% confidence intervals. The MRS values are shown by the solid lines in Figure 9.1, and the CPS is the smallest print size that lies along each MRS plateau line. The dashed and dotted lines show the 95% confidence intervals for the MRS and CPS values. Figure 9.2 a) and b) are plots of the data for the normally sighted subjects reading sentences and random words respectively with each fixation condition. For clarity, only the MRS values with 95% confidence intervals are shown for the normally sighted subjects. The average CPS values for the normally sighted subjects reading random words and sentences are shown in Figure 9.3. Figures 9.1 and 9.2 show that reading speeds for sentences are consistently faster than those for random words. Reading speeds for both normally sighted and CFL subjects increase with increasing print size and level out at larger print sizes to form a plateau of reading speeds.



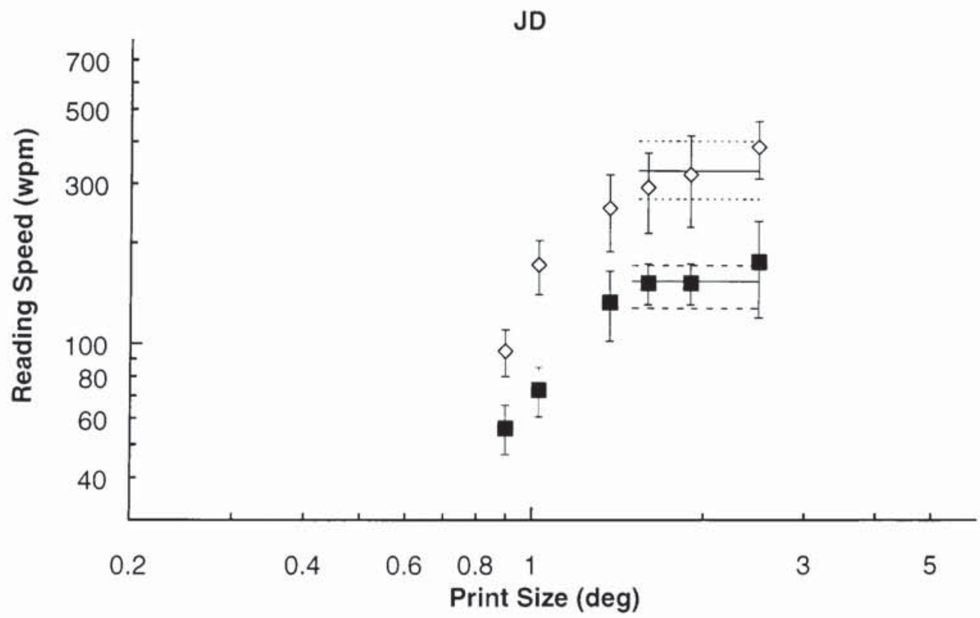
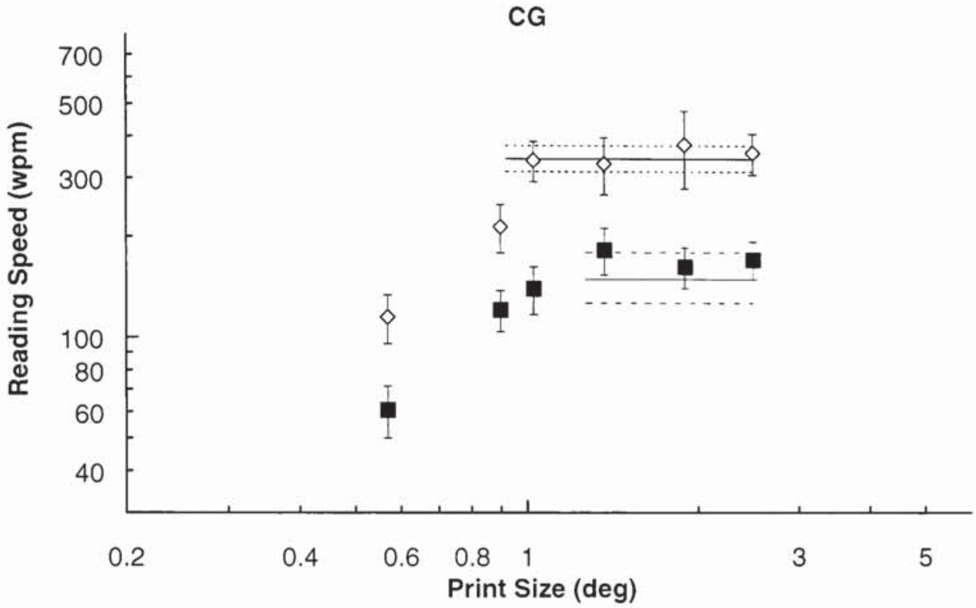
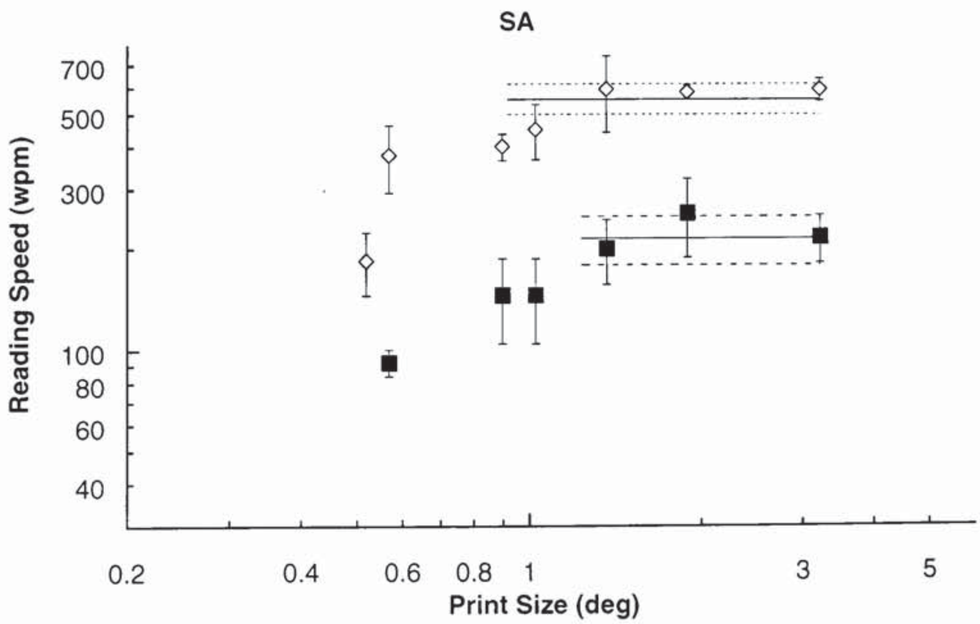


Figure 9.1. Reading speed (wpm) plotted as a function of print size (degrees) for the 8 CFL subjects, reading both random words and sentences with their preferred retinal locus (PRL). Words = closed squares; Sentences = open diamonds. The solid lines are the maximum reading speeds (MRS) calculated using the algorithm developed by Mansfield (1996). The dotted and dashed lines are the 95% confidence intervals for the MRS values. The CPS is the smallest print size along the MRS line. Error bars are ±1SD.





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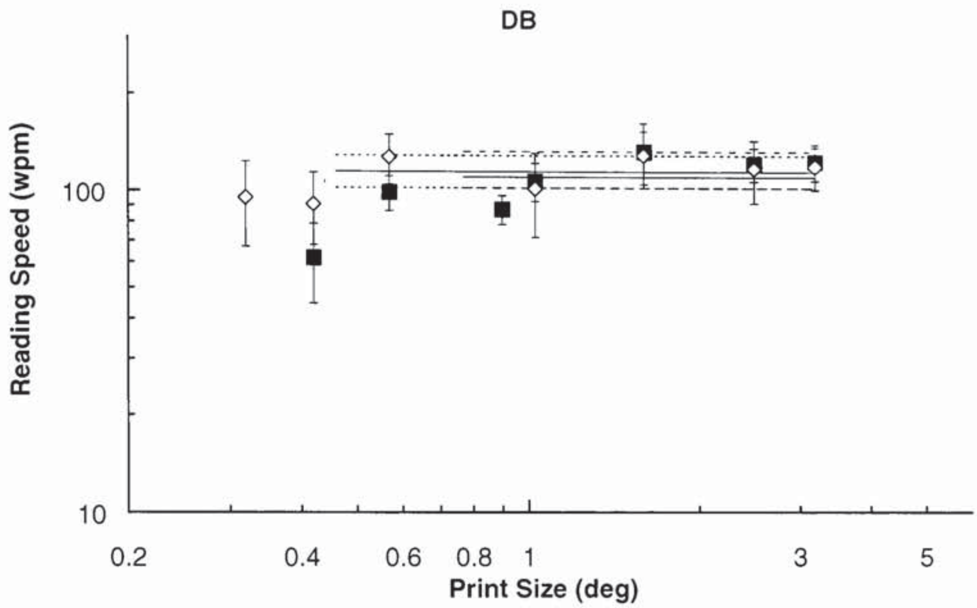

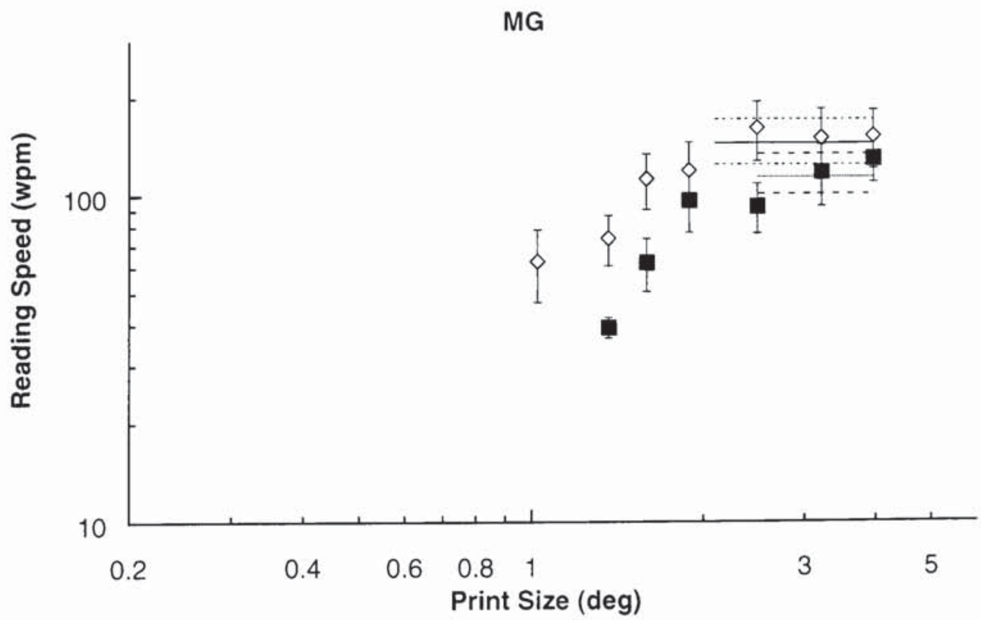

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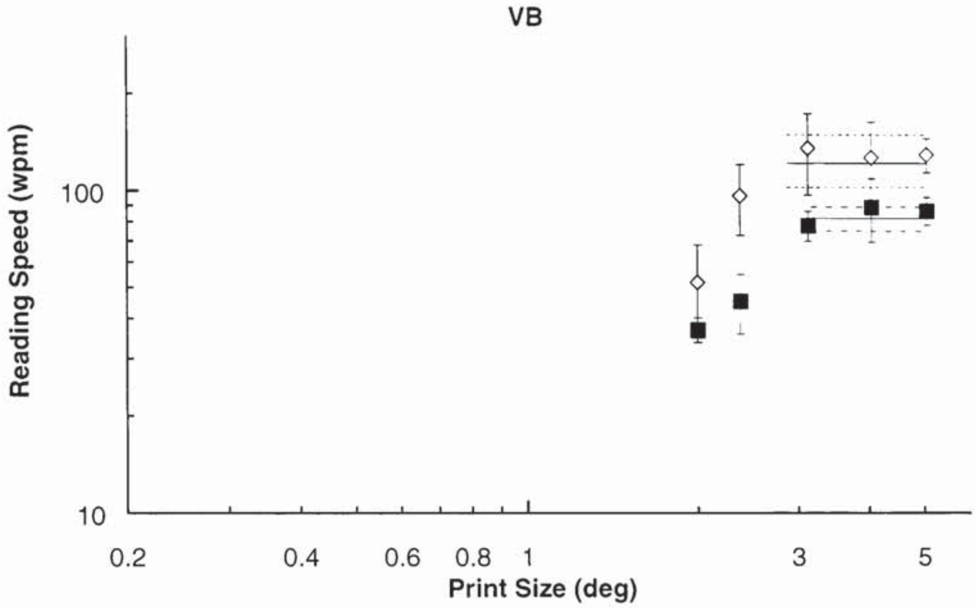


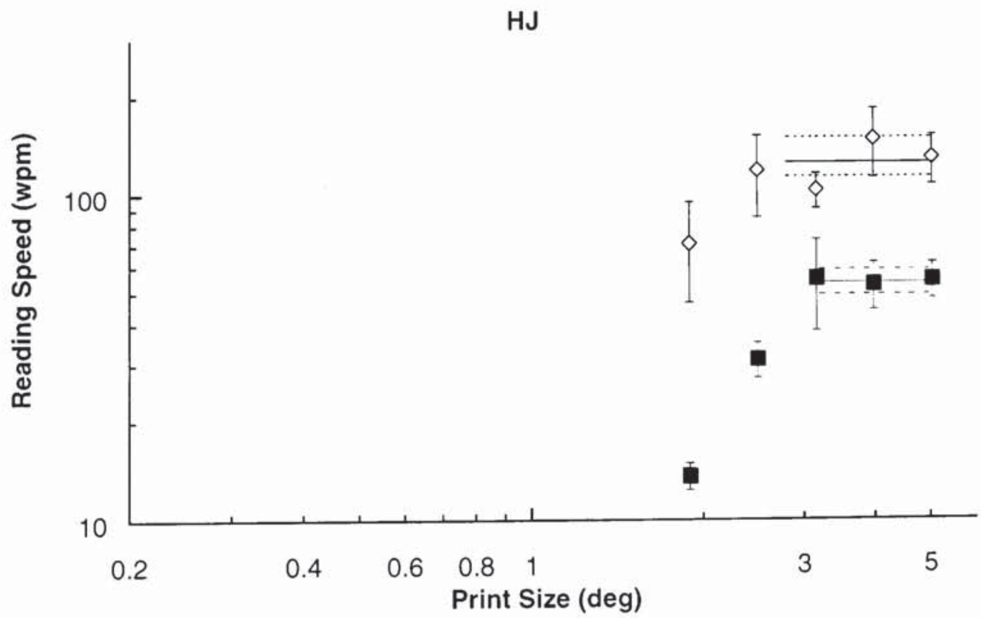
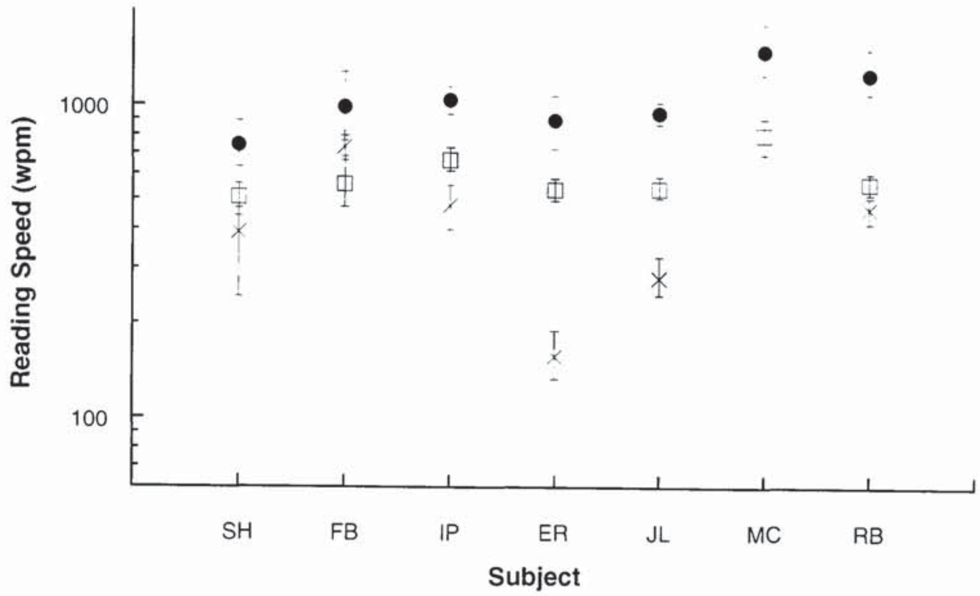


Figure 9.1 continued.

a)



b)

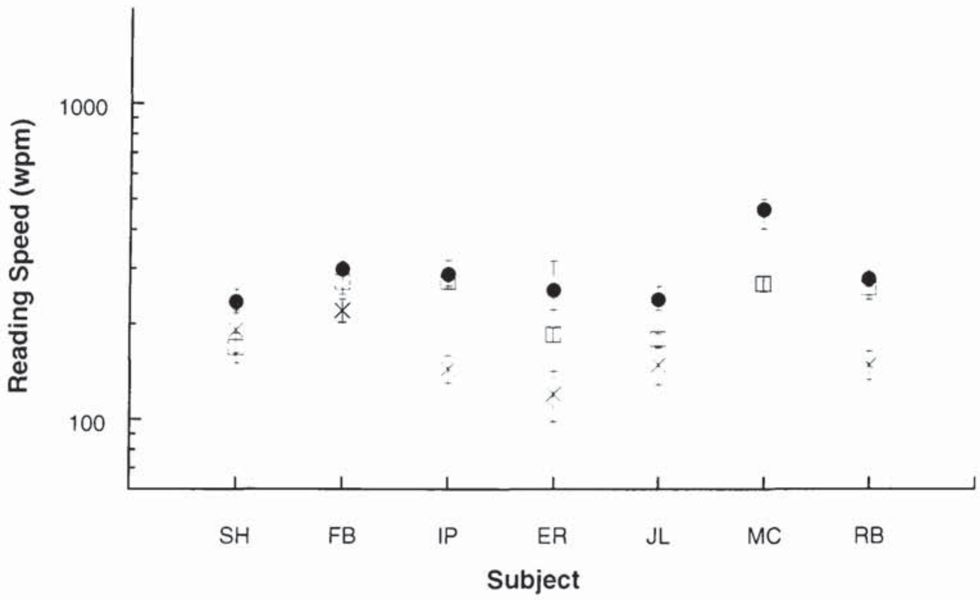


Figure 9.2. Plots showing the maximum reading speeds (wpm) for a) sentences and b) random words for each of the 7 normally sighted subjects reading foveally, at 5 degrees and 10 degrees inferior fixation. Fovea = closed circles; 5 degrees = open squares; 10 degrees = X's. Error bars are the 95% confidence intervals for the maximum reading speeds. No 10 degree data was obtained for subject MC because he was unable to complete the study.

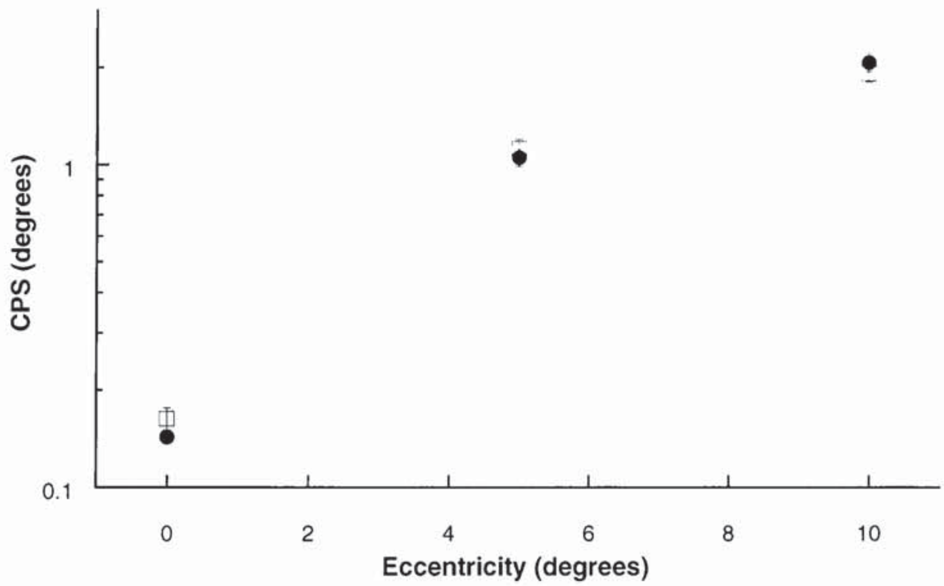


Figure 9.3. Plot showing the critical print sizes (degrees) for sentences and random words averaged for the 7 normally sighted subjects reading foveally, at 5 degrees and 10 degrees inferior fixation. Random words = closed circles; Sentences = open squares. Error bars are ±1SEM. No 10 degree data was obtained for subject MC because he was unable to complete the study.

9.4.1 Reading Speed

Figure 9.4 shows maximum reading speeds (wpm) for the sentence and random word conditions for the normally sighted subjects combined, and for the CFL subjects individually. Considering the normally sighted subjects, analysis of variance shows a significant effect of eccentricity on reading speed ($F(2,34)$ 24.1, $p<0.001$), and post-hoc analyses (Scheffe, 5% level) show that reading speeds for foveal fixation are significantly faster than those at 5 degrees eccentricity (mean difference = 267 wpm) and 10 degrees eccentricity (mean difference = 393 wpm). Although reading speeds for 5 degrees eccentricity are on average 125 wpm faster than those for 10 degrees eccentricity, this difference is not significant at the 5% level. There is also a greater reduction in the sentence reading speed than the random word reading speed with eccentricity (Foveal sentence - 10 degree sentence: mean difference = 574 wpm; foveal words - 10 degree words: mean difference = 104 wpm).

The CFL subjects read sentences slower than the normally sighted subjects at the fovea ($t(13)$ -7.1, $p<0.001$) and at 5 degrees ($t(13)$ -4.4, $p<0.01$) but they were not significantly different to the normally sighted subjects reading at 10 degrees ($t(12)$ -1.5, $p=0.16$). Similarly, the CFL subjects also read random words slower than the normally sighted subjects at the fovea ($t(13)$ -4.6, $p<0.001$) and at 5 degrees ($t(13)$ -3.5, $p<0.01$), but were not significantly different to normally sighted subjects reading at 10 degrees ($t(13)$ -1.0, $p=0.33$). However, the CFL subjects fall into two clear groups: those who read sentences faster than 330 wpm and those who read sentences slower than 150 wpm (Figure 9.1 or Figure 9.4). The fast group of CFL subjects read significantly faster than the slow group for both words ($t(6)$ 4.1, $p<0.01$) and sentences ($t(6)$ 5.6, $p<0.001$). In comparison to the normally sighted subjects, the fast CFL subjects read sentences at a similar rate to the normally sighted subjects at 10 degrees ($t(8)$ -0.03, $p=0.98$) and words at a similar rate to normals at 5 degrees ($t(9)$ -1.8, $p=0.11$) and 10 degrees ($t(8)$ 0.8, $p=0.45$). The slow CFL subjects read both sentences (t(8) -2.9, p=0.02) and words (t(8) -3.3, p=0.01) slower than the normally sighted subjects at 10 degrees.

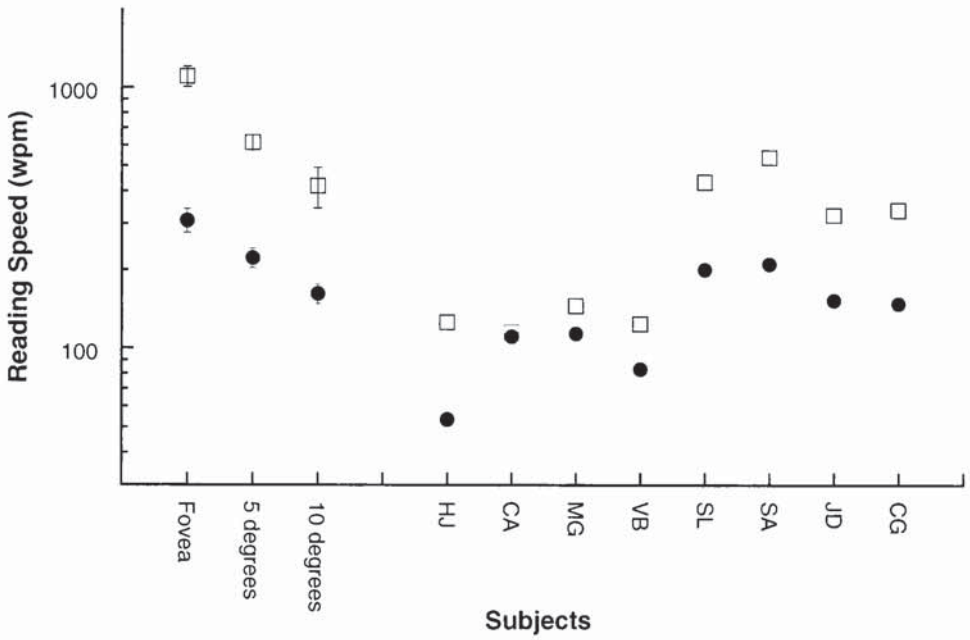


Figure 9.4. Maximum reading speeds for words (closed circles) and sentences (open squares). Mean values (±1SEM) for normally sighted subjects under all conditions are shown and are compared with each CFL subject shown individually.

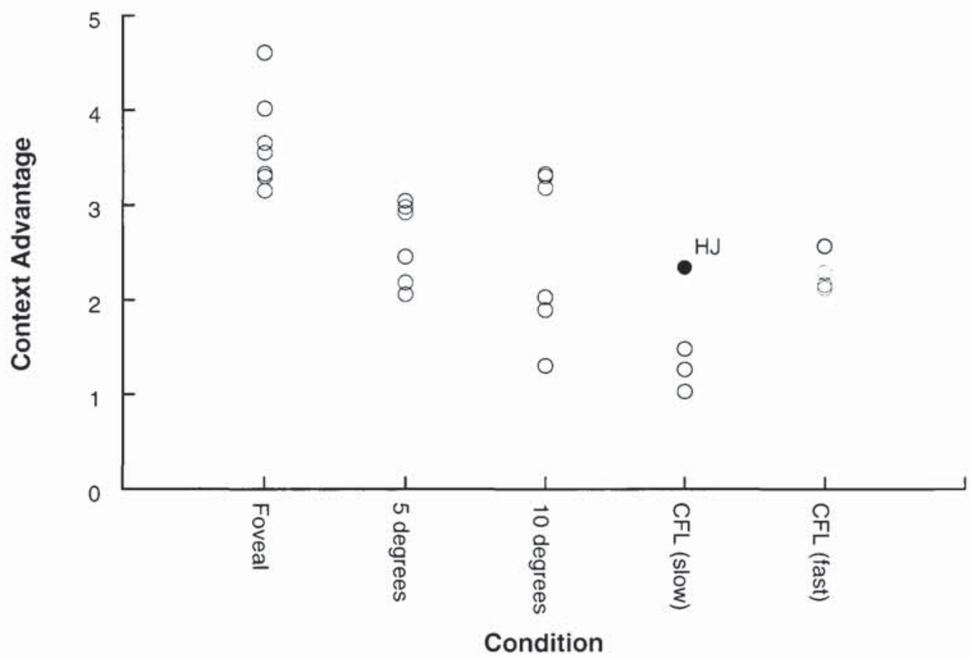


Figure 9.5. Context advantage values shown for both normally sighted (foveal, 5 degrees and 10 degrees fixation) and for both the slow and fast CFL subjects.

9.4.2 Context Advantage

Context advantage (CA) is the ratio of sentence reading speed to that for random words (Figure 9.5). The average CA values (±1SEM) for the normally sighted subjects reading foveally, and at 5 and 10 degrees inferior visual field are 3.7±0.2, 2.7±0.2 and 2.5±0.3 respectively. Analysis of variance shows a significant effect of eccentricity on context advantage ($F(2, 17)$ 6.8, $p<0.01$) and post-hoc analyses (Scheffe, 5% level) show that CA values for foveal fixation are significantly larger than those at both 5 degrees (mean difference = 0.99) and 10 degrees eccentricity (mean difference = 1.15). Although CA values for 5 degrees eccentricity are on average 0.16 units larger than those for 10 degrees eccentricity, this difference is not significant at the 5% level.

The fast CFL subjects have significantly larger CA values than the slow CFL subjects ($t(6)$ 2.53, $p=0.05$). Only one subject (HJ) who reads slowly has a CA similar to those reading more quickly (Figure 9.5; closed circle). The average CA values (±1SEM) for the slow, fast and combined CFL group are 1.5±0.3, 2.3±0.1 and 1.9±0.2 respectively.

The fast CFL subjects also have CA values that are smaller than the normal fovea ($t(9)$ -5.1, $p<0.001$) but are not significantly different to the normally sighted subjects reading with their peripheral retina at 5 degrees ($t(9)$ -1.6, $p=0.14$) or 10 degrees ($t(8)$ -0.5, $p=0.65$). The slow CFL subjects have significantly smaller CA values than the normally sighted subjects at the fovea ($t(9)$ -6.4, $p<0.001$) and 5 degrees ($t(9)$ -3.8, $p<0.01$) but not at 10 degrees ($t(8)$ – 2.0, $p=0.09$). If the CFL group are considered as a whole, their CA values are significantly smaller than the normally sighted subjects reading with their fovea ($t(13)$ –6.22, $p<0.001$) or at 5 degrees eccentricity ($t(13)$ -2.86, $p=0.013$). They are not significantly different to normally sighted subjects reading at 10 degrees eccentricity ($t(12)$ –1.55, $p=0.15$).

9.4.3 Critical Print Size

The critical print size (CPS) is the smallest print size at which reading speed reaches its maximum rate (Figure 9.3). Analysis of variance for the normally sighted subjects shows a significant effect of eccentricity on CPS ($F(2,34)$ 268, $p<0.001$) but there is no significant effect of stimulus type ($F(2,34)$ 0.16, $p=0.7$). Therefore, for the purposes of the analysis, word and sentence CPS values are combined. Post-hoc analyses (Scheffe, 5% level) show that the CPS at the fovea is significantly smaller than the CPS at 5 degrees eccentricity (mean difference = 0.94 degrees). The CPS at 5 degrees eccentricity is also significantly smaller than that at 10 degrees (mean difference = 0.95 degrees). The average CPS values (±1SEM) for the normally sighted subjects reading at the fovea, 5 degrees and 10 degrees eccentricity are 0.15±0.01, 1.1±0.1 and 2.1±0.1 degrees respectively.

The CPS values for words and sentences for the CFL subjects are also not significantly different ($t(7)$ 2.17, $p=0.07$). Therefore, for the purposes of the analysis, these values are combined. The average CPS values (±1SEM) for the slow CFL subjects (2.2±0.4 degrees) are significantly larger than those for the fast CFL subjects (1.4±0.1 degrees), ($t(14)$ –2.2, $p<0.05$). The CPS values for the fast CFL subjects are significantly larger than the normally sighted subjects reading foveally, and at 5 degrees eccentrically, but significantly smaller than the normally sighted subjects reading at 10 degrees ($t(18)$ –4.5, $p<0.001$). The CPS values of the slow CFL subjects, are statistically similar to those of the normally sighted subjects reading at 10 degrees eccentricity ($t(18)$ 0.6, $p=0.56$).

9.5 DISCUSSION

None of the CFL subjects are able to use context as well as the normally sighted subjects fixating foveally. The hypothesis that with long-term CFL adaptation occurs within the visual system that improves the ability of the periphery to use context to levels seen in the normal fovea can therefore be rejected. A regeneration and re-organisation similar to what is seen to occur within the neural system following optic nerve damage (Sabel et al., 1997) and retinal lesions (Kaas et al., 1990; Gilbert & Wiesel, 1992) may play a part in the formation and improved control of the PRL chosen after central field loss. However, this adaptation is not able to completely recreate the unique functional characteristics of the normal fovea. Even so, the context advantage (CA) values of the fast CFL subjects are not significantly different to the normally sighted subjects fixating at 5 degrees or 10 degrees. Considering that the fast CFL subjects have PRL's located between 5 and 10 degrees eccentricity (Table 9.1), this may suggest a slight improvement in their ability to use context over what would be expected of a normally sighted subject at the same eccentricity of fixation. However, a more accurate method of determining fixation location, such as with a scanning laser ophthalmoscope, would be required before this finding could be pursued further.

The results also show that the CFL subjects can be separated into two significantly different groups depending on their reading performance. To investigate the reason for this, the differences between the fast and slow CFL readers were investigated more closely.

In terms of reading speed the faster CFL readers have a similar reading performance to the normally sighted subjects at 10 degrees and the slow CFL readers are slower than the normals under all conditions examined. Context advantage values show that fast CFL readers utilise context to a similar extent to the normals at 5 and 10 degrees peripherally, whilst the slow readers are similar to the normals only at 10 degrees. The fast CFL readers also have significantly larger CA values compared to the slow readers. RSVP sentence reading speeds and CA values have been shown to decrease with eccentricity in normally sighted observers (Latham & Whitaker, 1996b; Chung et al., 1998), suggesting that the slower CFL readers are fixating at a greater eccentricity than the faster readers. Although analysis of variance shows that eccentricity of fixation is not statistically different between the two groups of CFL readers ($F(3)$ 1.92, $p=0.30$), three of the four slow CFL readers are reading at eccentricities greater than or equal to 10 degrees. This is in contrast to the fast CFL readers where only one subject has a PRL as peripheral as 10 degrees. Therefore, there is a tendency for the slow readers to read with a more eccentric PRL than the fast readers. In fact, if subject DB, who is the one slow CFL reader with a PRL less than 10 degrees, is removed from the analysis, eccentricity of fixation is statistically different between the two groups ($t(5)$ –2.62, $p=0.05$). Furthermore, the CPS data shows that the average CPS values for the fast CFL readers are significantly smaller than those for the slow CFL readers ($t(14)$ –2.23, $p<0.05$). Making the logical assumption that the magnification required relates to the eccentricity of fixation (Chung et al., 1998), these results would suggest that the slow CFL readers are fixating at a more eccentric locus than the fast readers. Therefore, it is the greater eccentricity of fixation that makes them perform worse.

Another possible explanation for reduced reading performance of the slow CFL readers compared with the fast CFL readers, is reduced visual acuity. For the fixating eye, the visual acuities of the fast CFL readers were not significantly different to the visual acuities of the slow CFL readers for both distance ($t(6)$ -0.33, $p=0.75$) and near ($t(6)$ -1.10, $p=0.31$). However, without subject DB, a slow CFL subject whose visual acuity was higher than her reading speed would predict, the data for the near visual acuities between the two groups tends towards significance ($t(5)$ –2.2, $p=0.08$), and the fast CFL readers have significantly better distance visual acuities than the slow CFL readers ($t(5)$ –2.8, $p<0.05$). Since VA reduces with increase in fixation (Weymouth, 1958), this finding is in agreement with the fixation data, which shows a tendency for the slow readers to read with a more peripheral PRL.

As seen above, subject DB needs to be excluded from the analysis in order to show significant differences between the fast and slow CFL readers in terms of CA and eccentricity of fixation values. It is unclear why subject DB reads as slowly as she does, because she has better visual acuities and a smaller eccentricity of fixation than the other slow CFL readers. Studies have reported however, of subjects with CFL using different PRL for different stimuli (Guez et al., 1993; Lei & Schuchard, 1997). Subject DB may be using a more eccentric PRL for reading than she is for the visual acuity and visual field tasks. However, subjects were asked to be aware of the location of the PRL they were using during the testing and to report any differences in PRL used between the tasks. Although all subjects were aware of fixating eccentrically, none reported being aware of using more than one PRL.

The results of subject HJ also appear to contradict the general findings. She is a slow CFL reader, but shows a context advantage of 2.4, which is more similar to the fast CFL readers. The larger than expected context advantage value is due to the slower than average word reading speeds compared with the other slow CFL readers. Although she is the subject with the worst visual acuity, none of the fixation characteristics are able to provide a suitable explanation.

Studies have shown that variability in reading performance depends on the location of the PRL within the visual field as well as the eccentricity of fixation. Normally sighted subjects have shown faster reading speeds when subjects used the inferior visual field for fixation compared with the lateral visual field (Cummings & Rubin, 1992; Nilsson et al., 1998) (also see Chapter 7). In this study, the two groups of CFL subjects do not differ significantly in their fixation location as estimated from the Bjerrum plots. However, three of the four fast CFL readers use a PRL inferior to their scotoma in visual field space compared with only one slow CFL reader. The other subjects use a lateral fixation position. This suggests a tendency for the fast CFL readers to use their inferior visual field for fixation and the slow CFL readers to use their lateral visual field.

Studies have also shown that CFL patients with juvenile macular degeneration read faster than those with CFL secondary to ARMD (Legge et al., 1992; Sunness et al., 1996). Although the location of the PRL's developed by these two groups has been shown to be different (Guez et al., 1993; Sunness et al., 1996; Fletcher & Schuchard, 1997) it is also possible that the age difference between them is a factor. Non-specific changes in alertness and attention that occur with age could reduce reading speed and a younger subject may also have more motivation to adapt to the situation as they have a potentially large part of their working life ahead of them. Latham & Hazel (1999) have shown RSVP reading speeds in normally sighted older subjects (76.3±2.5 years) to be significantly slower than in young subjects (26.0±4.9 years) for both foveal and 5 degree fixation. The results for the study described here show that the fast CFL readers are significantly younger than the slow CFL readers ($t(6)$ -4.498, $p<0.01$). However, psychophysical and electrophysiological studies of aging have indicated that visual function declines only slightly or not at all until age 50-60 years (Johnson & Choy, 1987). Only one subject in the Stargardts group is older than 50 years and the mean age of the group is 38.9±8.9 years. Therefore, age is unlikely to be a contributory factor to optimum reading performance in this group of subjects.

With regards to the normally sighted subjects, the reading speed results reinforce previously published findings (Latham & Whitaker, 1996b; Chung et al., 1998). Even when print size is not the limiting factor, maximum text reading speeds are still lower in the periphery than in central vision.

The CA findings of this and previous studies (Latham & Whitaker, 1996b; Chung et al., 1998), would appear to conflict with Fine & Peli (1996) as well as with the results of the study described in Chapter 8 of this thesis. In this study, CA values for normally sighted subjects are 3.7 at the fovea and 2.7 at 5 degrees eccentricity. Latham & Whitaker (1996) investigated the effect of fixation eccentricity on RSVP reading speed using 5-6 word sentences and lists of 5 random words matched in length and frequency to the words in the sentences. For their two subjects, they found an average CA of 2.9 at the fovea, which reduced to 1.1 at 5 degrees eccentricity. Using a similar paradigm, Chung et al. (1998) also found that context advantage was less in the periphery. Their average CA values reduced from 2.4 at the fovea to 1.3 at 5 degrees eccentricity. In contrast, Fine & Peli (1996) found no significant difference in CA between their normally sighted subjects reading RSVP foveally (2.3) and their CFL subjects reading with their PRL (2.0). The study in Chapter 8 also found no significant difference in CA values for normally sighted subjects reading text foveally (2.6) and stabilised at 5 degrees inferior visual field (2.7).

There are a number of factors to consider when attempting to explain the differences between these two groups of studies. Firstly, there are difficulties in comparing results between studies where the stimuli differ. Fine & Peli (1996) used MNRead sentences of 9-14 words and random word lists of eight words. In comparison, the sentences and random word lists used in the study described here are shorter, being 5-7 words and 5 words in length respectively. Although the CA values for Fine & Peli's CFL subjects are similar to those in the study described here, the CA values for the normally sighted subjects are much lower (2.3±0.13) than those of the normally sighted subjects in this study. Fine & Peli's low average CA value for their normally sighted subjects can be attributed to low average sentence reading speeds (386.8±24.1 wpm) compared to those recorded in this study (1072.4±100.1 wpm) as well as others (Rubin & Turano, 1992; Latham & Whitaker, 1996b; Chung et al., 1998). For example Rubin & Turano (1992) recorded average foveal RSVP reading speeds of 1171 wpm for single sentences presented at a size 8 times acuity. Similarly, Latham & Whitaker (1996b), using single sentences of 5-6 words and Chung et al. (1998), using single sentences of 8-14 words, recorded average plateau reading speeds of

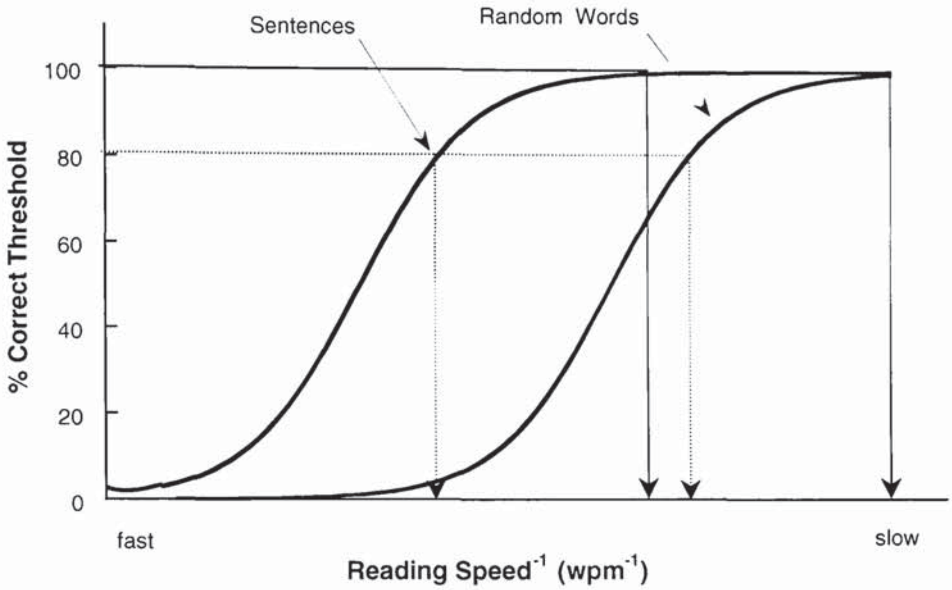
1340 wpm and 807 wpm respectively. Slower average normal reading speeds in Fine & Peli's study could be considered a result of the longer and more complex sentences. According to a hypothesis by Chen (1986), increasing the visual difficulty, such as by making the sentences longer and more complex, increases the cognitive capacity required to process the text. This results in a reduction in the spare capacity available to utilise context and therefore a reduction in sentence reading speed. However, in the study by Fine & Peli (1996) reading speed thresholds were measured at 78% performance compared with the 100% performance measure used in the study described here. The lower performance threshold required in Fine & Peli's study would produce relatively faster reading speeds than if a 100% threshold measure was used, thus reducing any effect of the more complex sentences. Also, as cited above, Chung et al. (1998) used sentences of a similar length to Fine & Peli also with an 80% correct threshold and reported far greater average reading speeds.

Another possible cause for the slower than normal reading speeds is that both the normally sighted and low vision subjects in Fine & Peli's study were 55 years or older. This is older than the average age of the normally sighted subjects in this study (26.0±4.9 years). Johnson & Choy (1987) have reported a significant decline in psychophysical and electrophysiological functions after the age of 60 years. In addition, it has been reported that the effect of age on RSVP reading rates is to slow sentence reading rate and reduce context advantage (Latham & Hazel, 1999). However, Latham & Hazel (1999) reported foveal CA values for their elderly (76.3±2.5 years) group of subjects to be 2.6. Although this value is significantly lower than the CA value of 3.7 determined for their young (26.0±4.9 years) subjects in the same study, it is still higher than the normal older foveal values reported by Fine & Peli. Therefore, this data cannot support the suggestion that the older age of the subjects in Fine & Peli's study contributes to the discrepancies seen between the two studies.

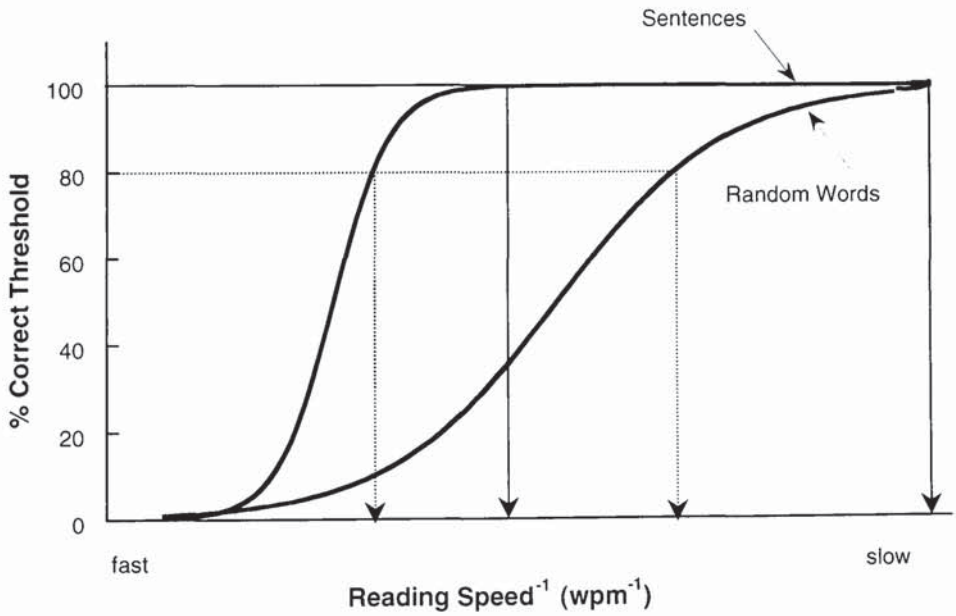
Nevertheless, these differences also do not explain the discrepancies between the study described here and the results of the study described in Chapter 8. Both studies used normally sighted young subjects as well as the same lists of sentences and words as stimuli. One difference between this study and the one described in Chapter 8 is the method for determining the reading speed thresholds. In this study, a method of limits was used which determined the threshold for maximum reading speed of 100% performance. In contrast, the study described in Chapter 8 used a staircase method with unequal step sizes that resulted in a threshold of 78% performance. If the psychometric functions of the word and sentence stimuli have different slopes, then using a different point on the function as threshold might change the relationship between word and sentence thresholds at different percentage correct measures. This would result in changes in CA for these different threshold measures. Despite this, one would still expect the thresholds determined using the 78% correct performance measure to be consistently faster than those determined using the 100% threshold for both words and sentences (Figure 9.6 a) and b)). When comparing the average reading speeds determined with the two thresholding methods however, the thresholds determined in Chapter 8 are faster than those reported in this chapter for foveal words (mean difference = 53.5 wpm), peripheral (5 degrees) sentences (mean difference = 16.29 wpm) and peripheral (5 degrees) words (mean difference = 8.9 wpm). In contrast, they are slower for foveal sentences (mean difference = 201.2 wpm). This data suggests that the slopes of the psychometric functions for the different thresholding methods cannot explain the differences in the results between the two studies.

Another difference in the two different thresholding methods is the number of data points used to obtain the thresholds. In the study described in Chapter 8, a list of 18 stimuli (sentences or word lists) were read by the subjects, and the thresholds were determined from the mean of the staircase reversals (usually 7-10 reversals in any given run). In contrast, in the study described here, 6 thresholds were determined at each print size, each from an average of 5 stimuli. These 6 thresholds were then averaged to determine the threshold reading speed for that print size. The data for all the print sizes were then analysed using an algorithm developed by Mansfield et al. (1996), to determine the maximum reading speed. Hence, this method used a far greater number of data points than the staircase method to determine the final threshold. The staircase method could therefore result in more variable data, which would be less reliable for the determination of context advantage ratios. Indeed, the standard errors in the data determined using the method of limits, are smaller than those determined using the staircase method for all conditions except foveal sentences. In this case, when the data for one subject (MC) whose reading speeds are exceptionally fast are removed from the analysis, the standard errors also become less than those determined with the staircase method.

Another possible reason for the difference in the results between the two studies is that different decision criteria may have been used to mark a sentence correct or incorrect. These criteria may have been stricter for the study described in Chapter 8 compared with the one described here. The effect on the results of this examiner bias however, would be expected to be similar for both the foveal and peripheral data. As explained above, the differences in average reading speeds between the two studies are in fact different for the foveal compared with the peripheral data, and even different between random word and sentence conditions at the same visual field location. It is therefore unlikely that examiner bias can explain the discrepant results.



a)



b)

Figure 9.6 a) and b). A diagram showing psychometric functions for words and sentences, where the slopes of each function are a) equal and b) different. When the slopes of the psychometric functions for words and sentences are equal, the CA values determined for the 100% threshold are the same as those determined for the 80% threshold. When the slopes are different, the CA values will be different depending on the level of threshold used. The reading speeds measured with the 78% correct performance however, will always be faster than those measure with the 100% correct performance regardless of the slopes of the functions.

9.6 CONCLUSIONS

In conclusion, none of the CFL subjects in this study are able to use their PRL to the same level of efficiency as the normally sighted subjects using their fovea regardless of the duration of their CFL. However, some of the subjects clearly perform better than others. Better performance is associated with a more central PRL, better visual acuity, and younger age. We can reject the hypothesis that the CA seen in subjects with long-term CFL is greater than that found in normal peripheral vision. Functional adaptation of the PRL does not occur over time to enable improved ability to use context at levels more similar to the normal fovea. Although the CA data agrees with some previously published data (Chung et al., 1998), the findings disagree with the implied findings of Fine & Peli (1996) as well as those of the study in Chapter 8. A careful investigation of the differences in the methodologies used in the studies however, was not able to fully explain the discrepant results.

Chapter 10

THE EFFECT OF ECCENTRICITY ON VISUAL SPAN SIZE

10.1 INTRODUCTION

The visual span in reading is the number of characters that can be recognised at each fixation (O'Regan et al., 1983; O'Regan, 1990; Chapter 2.5.2). O'Regan et al. (1983) reported the foveal visual span to be 10 letters for letters of 0.33 degrees in size, when a 90% correct recognition level was used. More recently, Legge et al. (1997a) used the RSVP method to measure reading speeds of 3, 6, 9 and 12 letter words, presented as lists of 4 words. From this data they determined the foveal visual span to be 10.6 letters for letters subtending 1 degree and 5.3 letters for letters subtending 6 degrees. The visual span however, differs from the concept of the perceptual span. Rather than being defined as specifically character recognition, the perceptual span is defined in terms of the functional demands of reading, including detection of word length and spacing as well as the utilisation of context. Functionally it is the region of the visual field that influences eye movements and fixation times in reading (Rayner & Pollatsek, 1989). It is estimated by Rayner & McConkie (1976) to be 15 characters to the right of fixation and 4 characters to the left. For the purposes of this thesis, studies that require the subject to read static text using page navigation can be considered to be measuring perceptual span, whilst studies using RSVP format text or letter strings are measuring the visual span.

This chapter investigates the hypothesis that the reduction in reading speed in peripheral vision, despite magnification (Latham & Whitaker, 1996b; Chung et al., 1998), is due at least in part to a reduction in the size of the visual span. Legge et al. (1997a) termed this the 'shrinking visual span hypothesis'. This hypothesis states that it should take longer to recognise words that are wider than the visual span because more than one fixation will be required to 'see' all of the word. This theory suggests that it is the need for additional fixations, not a reduction in processing speed that reduces reading speeds with increasing eccentricity of fixation. As word length increases, more fixations are required before the entire word will be seen and is able to be recognised. A reduced visual span in peripheral vision would therefore be indicated by an increased dependence of word recognition time on word length with increasing eccentricity. The 'shrinking visual span hypothesis' is in contrast to the 'prolonged viewing hypothesis', which states that the speed at which words can be processed reduces with increase in eccentricity of fixation regardless of word length. Increasing eccentricity therefore increases the fixation time required to process each word. Slower reading at increased eccentricities would not show a stronger dependence of word-recognition time on word length because the recognition of all words would slow down by a similar amount. The difference in reading speed between two different eccentricities would be constant for all word lengths.

Legge et al. (1997a) have previously examined the interaction between contrast and word length and their effect on reading times. They investigated whether slow reading in low vision (from a loss of effective contrast or contrast reserve) and slow reading in normal vision (with low contrast text) was due to a reduction in the visual span – 'shrinking visual span hypothesis', or the longer viewing time required to recognise the low contrast letters – 'the prolonged viewing hypothesis'. For the normally sighted subjects, they found a reduction in visual span size with increasing contrast attenuation of the text, and only weak support for a prolonged viewing hypothesis. In addition, 6 out of 7 of their low vision subjects, most of whom had cloudy media, showed a pattern of results consistent with a reduced visual span. These findings suggest that a reduction in the visual span could be a reason for why reading slows when contrast is low in normal vision, and why vision impaired readers read slowly with reduced contrast reserve. Indeed, it is possible that these findings could be extrapolated to other forms of vision impairment such as central field loss (CFL).

10.2 AIM

To determine whether the prolonged viewing hypothesis or a reduction in visual span can explain the reduced reading speed of normal peripheral retina as compared to that at the fovea.

10.3 MATERIALS AND METHODS

10.3.1 Subjects

Four normally sighted subjects (age range 21-30 years; mean = 25±3.7 years) with no ocular or systemic disease participated in the study. Subjects viewed the text monocularly using their dominant eye. Visual acuity of the recorded eye for each of these subjects was better than or equal to 0.0 logMAR. Aston University Ethics Committee approval was obtained, and all subjects gave informed consent.

10.3.2 Stimuli

Oral reading speeds were measured using lists of random words of three, six or nine letters in length. The word list for each word length consisted of 400 words within the top 15,000 most frequent words in written English (Hofland & Johansson, 1982). For each word length, words were presented at random in groups of five and no words were repeated within a group. All subjects had an educational standard that exceeded the level of the text ensuring that reading speed measures were not compromised by difficulty in comprehension of the text.

The word lists were presented using the RSVP paradigm (Chapter 2.4.3), with no inter-stimulus interval. Text was presented as described in Chapter 9 on an EIZO TS62-T 17 inch monitor using a Visual Stimulus Generator 2/3 (Cambridge Research Systems).

10.3.3 Procedure

All subjects read the words with their dominant eye whilst the other eye was patched. A viewing distance of 50 cm was maintained by means of a chin rest. For each trial, subjects could choose to read each word orally as it was presented or wait until all five had been displayed. All four subjects read from word lists of the three different length words, with the order of presentation being randomised between subjects. For each word length, the subject read the words when they were presented at the fovea, and also at 5 and 10 degrees inferior visual field whilst they fixated a central white spot target. The fixating eye was monitored using a video camera. This ensured that the observers fixated accurately such that the text was presented at the intended eccentricity. A loss of fixation was shown as a vertical eye movement, which was easily detected. If this occurred the current trial was discarded, although this was only necessary on three occasions throughout the study.

For each word length and location, the text was presented at a number of text sizes from largest (a size capable of supporting maximum reading speed) to smallest (acuity limit) in 0.1 log unit steps. For the foveal condition, the largest text size was 0.64 degrees (measured as the vertical height of a lower-case 'x'). For the 5 degree and 10 degree locations, the largest text sizes used were 2.5 degrees and 3.2 degrees respectively. Due to the size limitations of the monitor, the largest text size possible at the working distance used was 3.2 degrees. This ensured that all of the nine letter words fitted within the horizontal constraints of the screen.

The foveal condition was examined first. A number of trials were presented at the largest text size as practice trials. These trials were started at very slow presentation times, which were reduced in duration by 0.1 log unit steps until a threshold value was determined. A presentation was marked correct if all five words were read correctly, although errors of order were allowed. After correct reporting of a presentation, the presentation times were reduced until a threshold value was determined. The data from these practice trials was not included in the analysis. At the largest text size used, three trials were then commenced at 0.4 log units slower than the threshold value determined in the practice trials. As before, after each correct report of a presentation, the presentation time was reduced until the subject was unable to read the word list without errors. The threshold reading speed was the fastest presentation time for which no errors were made. Three trials were then commenced 0.4 log units faster than the threshold value determined in the practice session, and the presentation time was increased until the subject was able to read the word list without errors. As before, the threshold reading speed was the fastest presentation time for which no errors were made. When six threshold values had been obtained, the print size was reduced by 0.1 log units and the procedure described above was repeated. The initial presentation time for these second and subsequent trial sets was the same as the first trial set (i.e. 0.4 log unit steps slower or faster than the initial threshold estimate). As threshold speeds reduced, this initial presentation time was reduced by an equivalent amount in order to maintain a minimum number of random word presentations within each trial before threshold was reached. The process was repeated until a text size was reached where the subject was unable to read the random words without errors.

The working distance was 50 cm for all subjects when reading print sizes of 0.27 degrees or larger. The working distance was increased to 1 m and then 2 m to obtain image sizes less than 0.27 degrees and 0.14 degrees respectively. This enabled an angular subtense as small as 0.09 degrees to be obtained whilst maintaining image quality. This did not affect the results as the minimum text size read by any of the subjects was 0.12 degrees. Subjects wore their distance correction for all working distances.

10.4 RESULTS

Threshold presentation duration times were recorded in milliseconds (ms) and converted to words per minute (wpm) using Equation 9.1 (Chapter 9). For each print size within each condition, the six presentation times were averaged. Figure 10.1 shows reading speeds (wpm) plotted as a function of print size in degrees. The shape of these graphs is the same as the reading speed plots described in Chapter 2.5.1. They show the maximum reading speed (MRS) and critical print size (CPS) values for each condition. The 95% confidence intervals are not shown for clarity.

Visual span was estimated using the same method as Legge et al. (1997a). First, the plateau reading speeds were converted to reading time in msec/word and reading time was plotted as a function of word length. These plots are shown in Figure 10.2 for all four subjects. The regression lines in Figure 10.2 show the relationship between reading time, T (msec), and word length, L (characters):

$$T = A + BL \qquad \text{Equation 10.1}$$

where A and B are word length dependent y-intercept and slope parameters respectively. Table 10.1 lists the slopes, intercepts, and r^2 values for each subject. With the exception of subject CB, there is an obvious increase in slope of the regression lines (B) with increase in eccentricity of fixation. This increase in slope reflects an increased dependence of word recognition time on word length with increasing eccentricity. There is also a varying amount of vertical shift (change in A) of the curves with increase in eccentricity, reflecting a prolonged viewing time per word required.

The size of the visual span was estimated as follows. The slopes of the regression lines in Figure 10.2 have units of time per character (i.e. time per word divided by the number of characters per word). The reciprocal of the slope is therefore the number of characters identified in a unit of time (or characters per msec). If it is assumed that words are only identified during fixations, then the unit of time could be a fixation and the reciprocal of the slope could be an estimate of the number of letters identified per fixation, or the visual span. Assuming that the average fixation time in reading is 250 msec (Rayner & McConkie, 1976), the visual span was therefore calculated as the reciprocal of the slope from the regression lines in Figure 10.2, multiplied by 250 msec. These values are also shown in Table 10.1. Figure 10.3 shows the calculated visual span values (in characters) for each subject plotted as a function of eccentricity. This figure shows that there is a reduction in the size of the visual span with increasing eccentricity. The average visual spans (±1SEM) for central, 5 degree and 10 degree fixation are 14.9±2.0, 8.3±1.4 and 4.9±1.6 characters respectively.

Figure 10.4 is a plot of average plateau reading speed (wpm) ±1SEM as a function of eccentricity (degrees). This figure shows that there is a reduction in plateau reading speed with increasing word length at each eccentricity. There is also a small reduction in plateau reading speed with increase in eccentricity, with a tendency for a larger difference between central and 5 degrees eccentricity (mean difference = 135.8 wpm) than between 5 and 10 degrees eccentricity (mean difference = 50.5 wpm). This reduction in reading speed can also be seen from Figure 10.1.

The CPS is the smallest letter size required to achieve maximum reading speed. Figure 10.5 is a plot of CPS (degrees) (±1SEM) as a function of word length for foveal, 5 degree, and 10 degree fixation. This figure shows that the CPS increases with eccentricity. It also shows that CPS is not dependent on word length. Therefore, approximately the same magnification of text is required to reach plateau reading speed, regardless of word length. One limitation on this assertion however, is that only one of the subjects was able to read the 9 letter words at 10 degrees eccentricity. Therefore, it could be assumed that the other subjects would have required much bigger print in order to reach their plateau reading speeds under these conditions. As such, the true CPS would be bigger than is suggested from the data. The data enable us to say however, that CPS is independent of word length up to at least 9 characters at 5 degrees eccentricity.

Subject	**Eccentricity (degrees)**	***A***	***B***	r^2	**Visual Span (characters)**
AC	0	155	18.3	1.00	13.6
	5	124	39.9	0.97	6.3
	10	129	45.4	0.82	5.5
AT	0	96.3	18.7	0.83	13.4
	5	169	28.0	0.77	8.9
	10	129	75.6	1.00	3.3
CB	0	111	21.2	0.93	11.8
	5	224	21.0	0.69	11.9
	10	375	27.3	1.00	9.2
KL	0	93.4	12.0	0.86	20.9
	5	107	42.3	0.76	5.9
	10	-98.6	158	1.00	1.6

Table 10.1. A and B are y-intercepts and slopes respectively for the regression fit $T = A + BL$; where T is the reading time in msec/word, and L is word length in characters. Visual span = $250/B$ in characters.

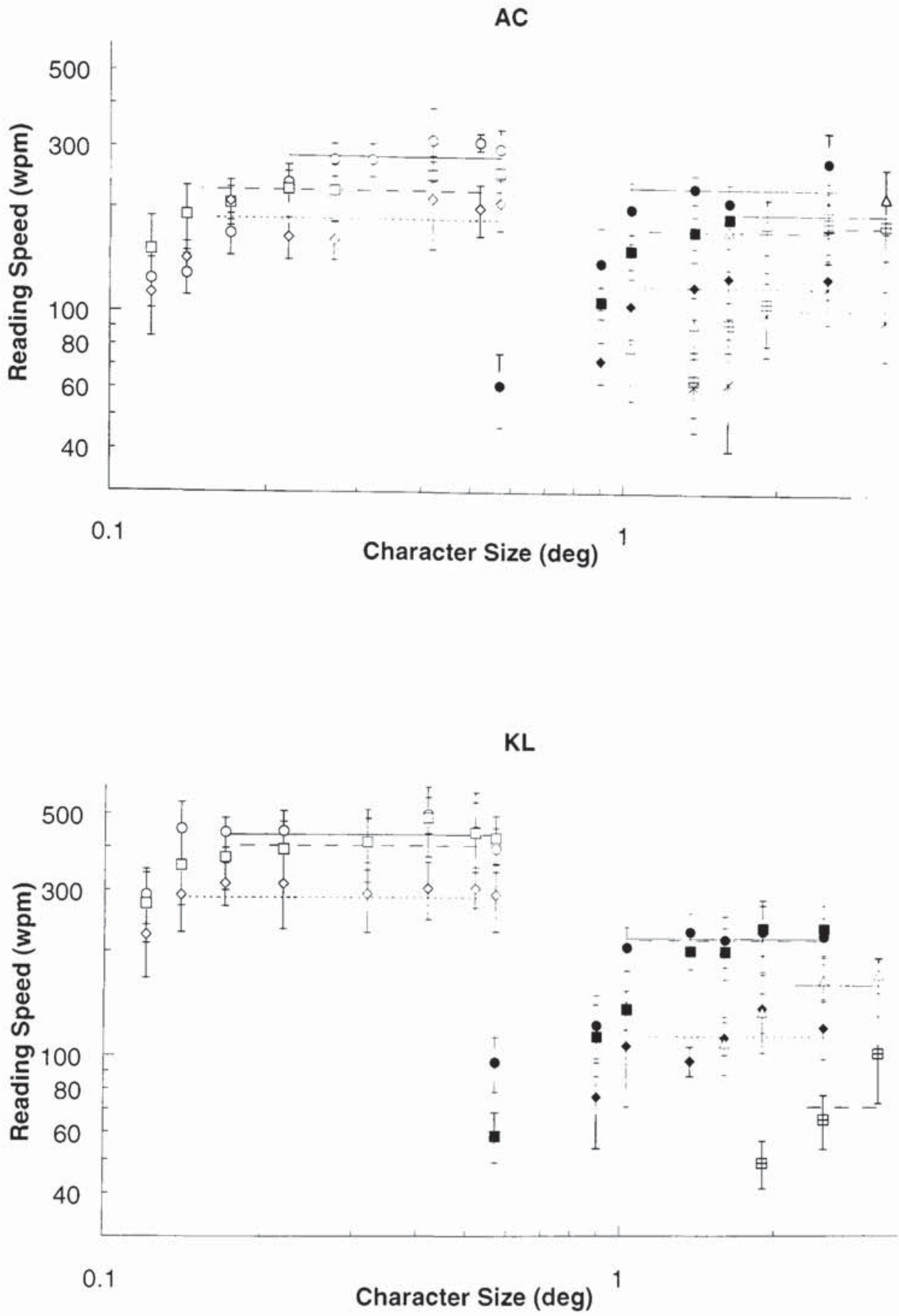
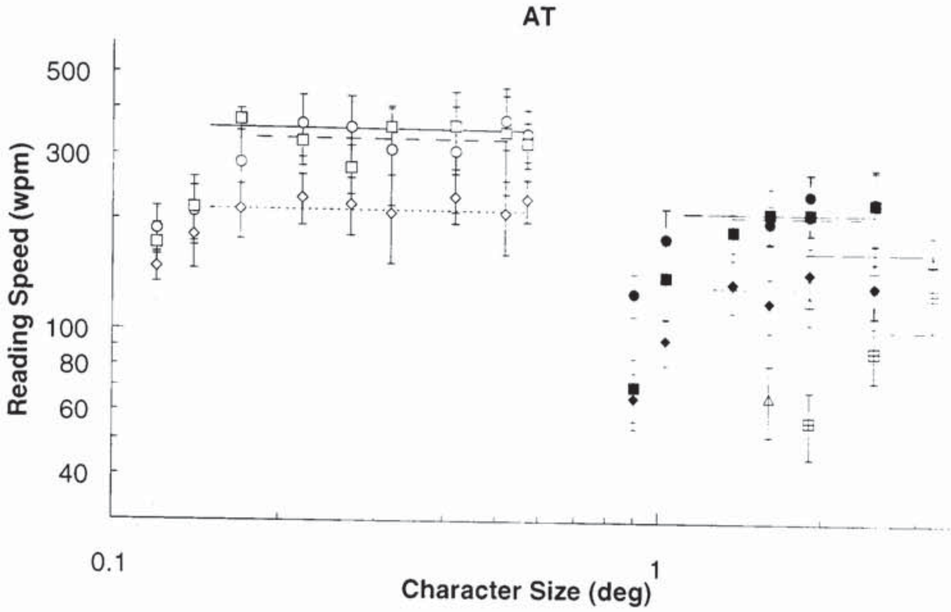


Figure 10.1. Reading speed (wpm) plotted as a function of character size (degrees) for the four subjects. Foveal fixation: Open circles = 3 letter; open squares = 6 letter; open diamonds = 9 letter. 5 degree fixation: Closed circles = 3 letter; closed squares = 6 letter; closed diamonds = 9 letter. 10 degree fixation: Open triangles = 3 letter; Crossed squares = 6 letter; X's = 9 letter. Only subject AC was able to read the 9 letter words at 10 degrees fixation. The other subjects were unable to read these words correctly at the largest size available. Horizontal lines are the plateau reading speeds for each condition. Solid line = 3 letter; Dashed lines = 6 letter; Dotted lines = 9 letter. The smallest print size included in the maximum reading speed range is the critical print size (CPS). Error bars are ±1SD.



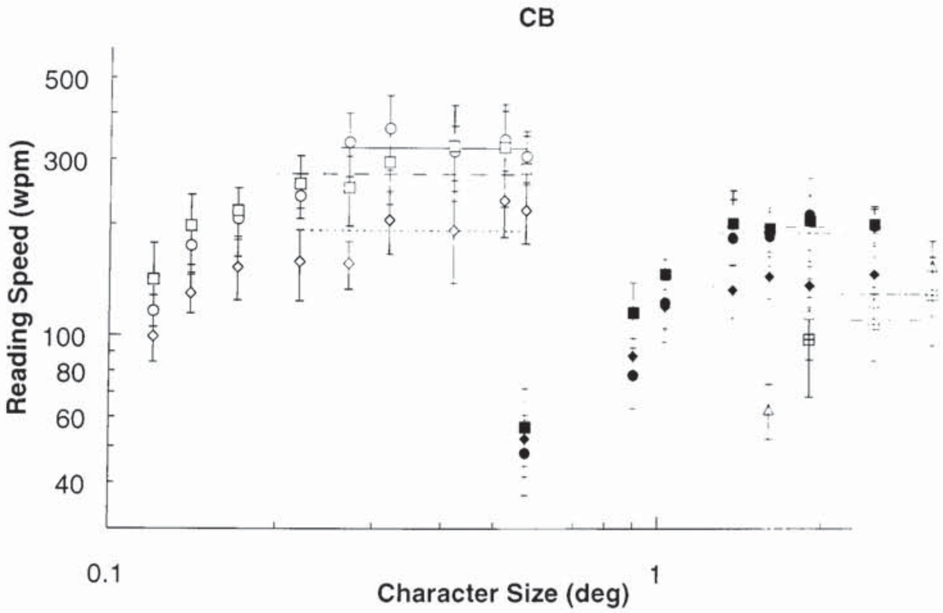


Figure 10.1 continued.

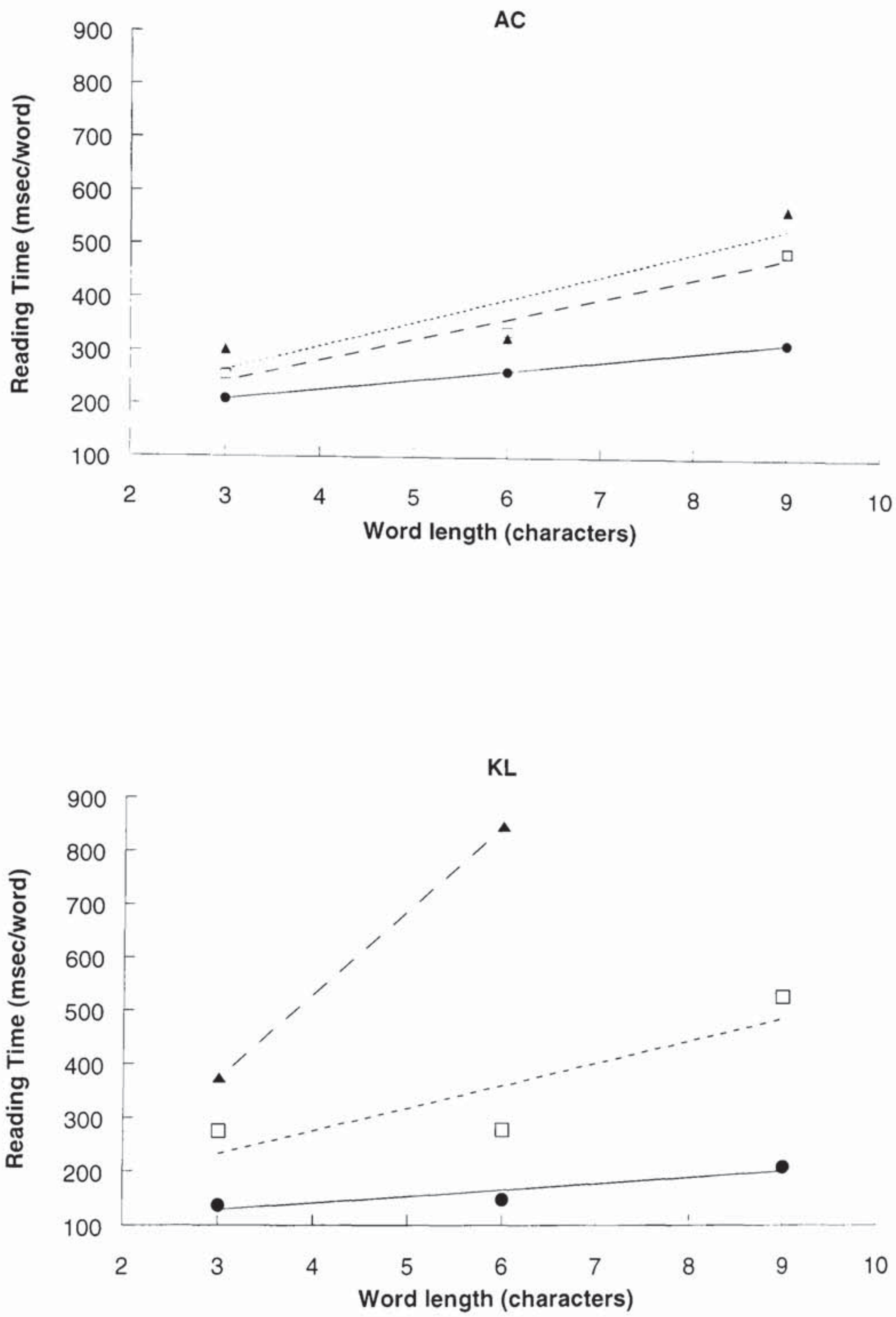


Figure 10.2. Plateau reading time (msec/word) as a function of word length for 3 letter, 6 letter and 9 letter words. Values apply to character sizes greater than the critical print size (CPS). Closed circles = foveal presentation; open squares = 5 degree presentation; closed triangles = 10 degree presentation.

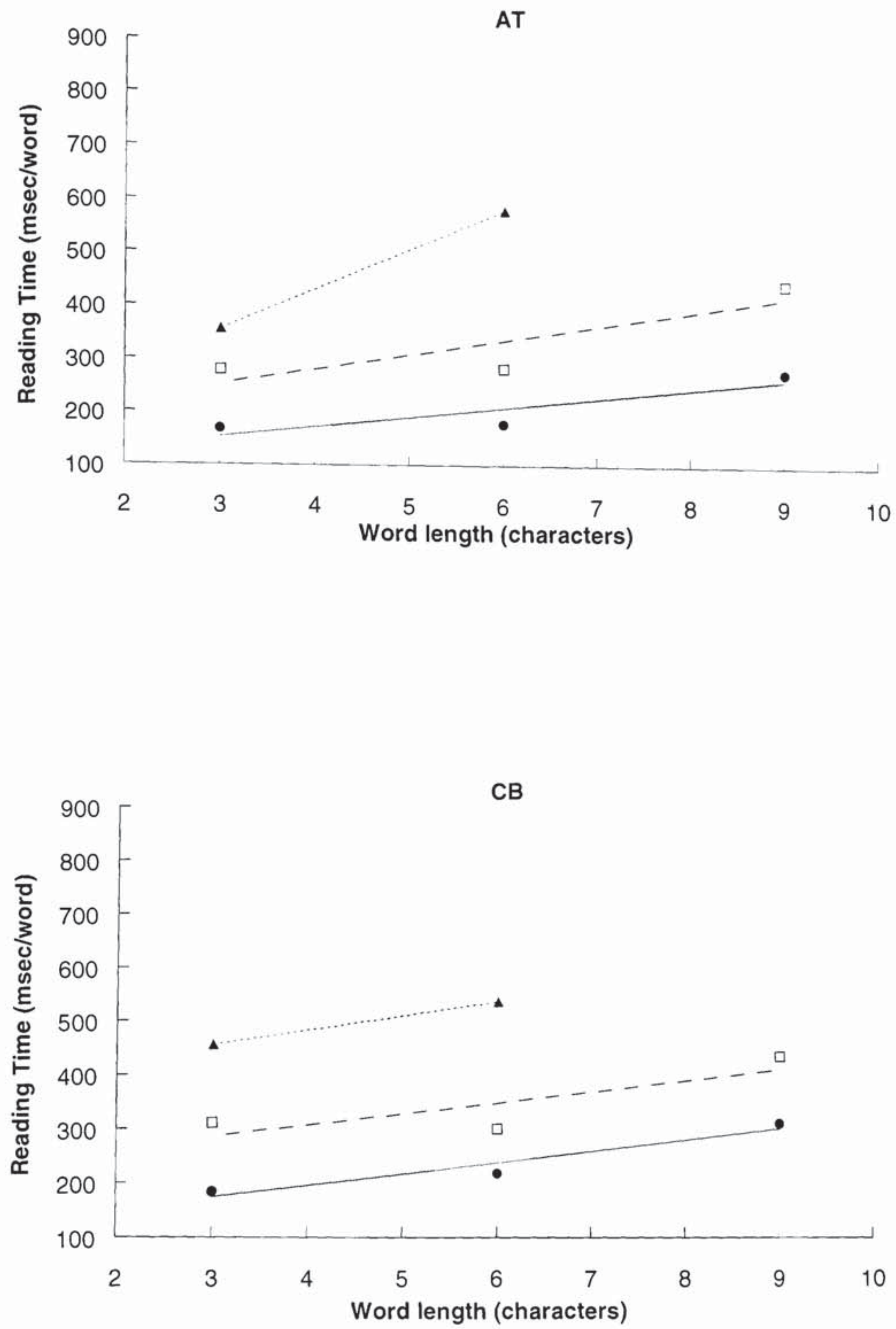


Figure 10.2 continued.

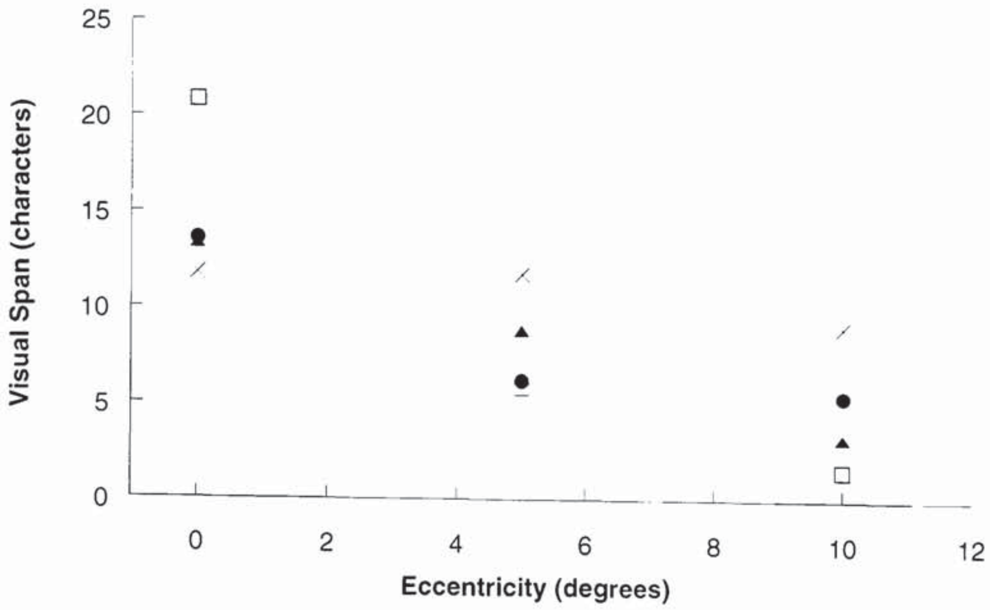


Figure 10.3. Visual span (characters) plotted as a function of eccentricity (degrees) for all 4 subjects. Open squares = KL, closed circles = AC, closed triangles = AT and X's = CB.

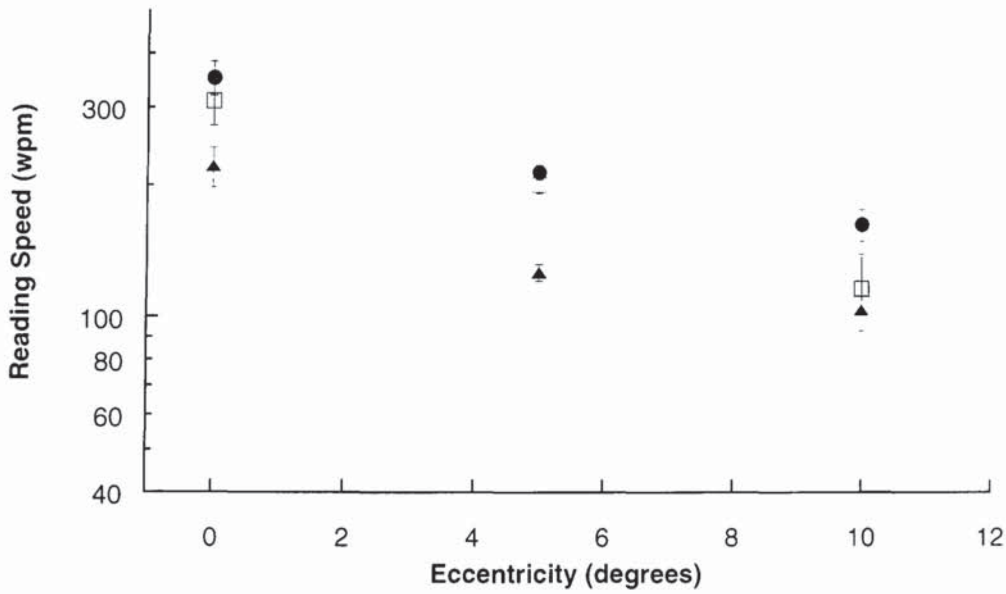


Figure 10.4. Plateau reading speed (wpm) averaged for the four subjects and plotted as a function of eccentricity (degrees) for the three word lengths used. Closed circles = 3 letter words; open squares = 6 letter words; closed triangles = 9 letter words. Note that only one subject (AC) was able to read the 9 letter words at 10 degrees eccentricity. The other subjects were unable to read these words correctly at the largest size available. Error bars are ±1SEM.

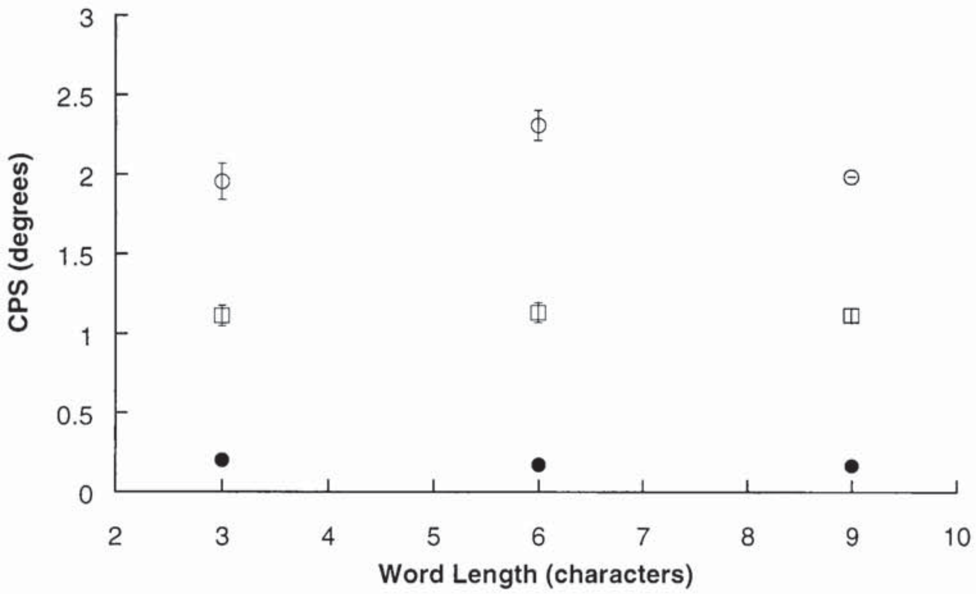


Figure 10.5. Critical print size (degrees) averaged for the four subjects and plotted as a function of word length (characters), for foveal, 5 degree, and 10 degree fixation. Closed circles = foveal fixation; open squares = 5 degree fixation; open circles = 10 degree fixation. Note that only one subject (AC) was able to read the 9 letter words at 10 degrees eccentricity. The other subjects were unable to read these words correctly at the largest size available. Error bars are ±1SEM.

10.5 DISCUSSION

The results show that the visual span, or the number of characters processed in a single fixation, reduces with eccentricity from a mean (±1SEM) of 14.9±2.0 characters at the fovea to 4.9±1.6 characters at 10 degrees eccentricity. This finding adds weight to the suggestion that one possible explanation for the decline in reading speed in peripheral vision is due to a reduction in visual span (Legge et al., 1997c).

In a conference abstract, Legge et al. (1997c) have also reported that visual span reduced with increase in eccentricity of fixation. They measured the size of the visual span for RSVP text between 0 and 15 degrees eccentricity and found a decrease from 10 characters at the fovea to 2.78 characters at 15 degrees. Legge et al. (1997c) measured reading speeds at each eccentricity with one text size of twice the CPS to represent the maximum reading speed. In the study described in this chapter however, reading speeds for each word length and at each eccentricity were measured for a range of text sizes, and the maximum reading speeds were determined from the range of plateaued reading speeds (Figure 10.1). Therefore, the calculated visual span sizes are relevant to the entire range of print sizes larger than the CPS that lie on the MRS plateau. This finding also implies therefore that at least for character sizes that lie on the reading speed plateau, it is the number of characters, not the angular subtense that is important in determining the effect on reading speed of the size of the visual span. In contrast, Legge et al. (1997a) found an effect of text size on the visual span when he measured the visual span sizes for 1 degree and 6 degree characters. He found visual span sizes of 10.6 characters and 5.3 characters for 1 and 6 degree character sizes respectively. However, in normally sighted subjects, reading speeds have only been found to plateau for text sizes up to about 3 degrees (Legge et al., 1985). For text larger than this size, reading speeds have been found to reduce with increasing text size, which could therefore have an effect on the calculated visual span values.

Fine & Rubin (1998) also looked at the effect on reading speed of the number of characters visible versus angular subtense in a study using centrally located masks covering text of random words and sentences. They matched the number of letters masked across several mask sizes whilst at the same time compensating for reduced peripheral acuity. They found that the number of letters masked from view was a better predictor of word identification time and reading speed for sentences than was the size of the mask in degrees of visual angle. The mask size in degrees had little effect on reading speed until it was 7.5 degrees and 9 letters were masked from view. The authors suggested that this finding would also help explain why patients with central scotomas require larger letters to read relative to their acuity threshold, than do either normally sighted readers or vision impaired readers without scotomas. This is because, as scotoma size increases, the number of letters blocked from view for a given letter size relative to acuity threshold also increases. This increase is greater for smaller relative sizes. Their findings also explain why reading rates decrease as scotoma size increases even if letter size is increased to be a constant size larger than acuity threshold (Cummings et al., 1985). When considering reading involving eye movements, it also reinforces the finding that saccade size increases with increasing size of the text so that an equivalent amount of text (in characters) is encompassed with each saccade (O'Regan, 1983).

Subject CB is the only subject of the four whose data do not show an increase in the slope of reading time as a function of word length with increase in eccentricity of the text. Her results also show the greatest vertical shift of the curves with increasing eccentricity of fixation. Table 10.1 shows that the intercept values (*A*) for subject CB increase consistently with increase in eccentricity. This can also be seen from Figure 10.2. The other 3 subjects do not show such consistent growth of the intercept with increasing eccentricity. In fact, the average *A* values for the 4 subjects are 113.9 msec/word (fovea), 155.9 msec/word (5 degrees) and 133.68 msec/word (10 degrees). When considering the two hypotheses of Legge et al. (1997a) described above, a vertical shift in the curves as well as the constant slope with increasing eccentricity are consistent with the prolonged viewing hypothesis. In fact, all subjects show some degree of vertical shift in the curves. Legge et al. (1997a) investigated the interaction between text contrast and word length in an RSVP reading task. Similar to the study reported here, they also found evidence of weak support for the prolonged viewing hypothesis in addition to the main affect of the shrinking visual span hypothesis. Indeed, it is possible that the two hypotheses are both correct and occurring simultaneously. A reduced visual span in the periphery, as shown by the data, will reduce reading speed. This is because, if a subject is not able to 'see' all of a word at a single glance, then a second fixation or change in location of attention within a fixation will be required, which will take time. In addition, cognitive processing in peripheral retina may indeed be slower than foveal processing, even if the text size is large enough to produce maximum reading speeds. The difference between reading speeds with foveal fixation and peripheral retina would therefore be mainly affected by the reduced peripheral visual span, however, a smaller affect of slower peripheral processing may also occur.

In this and previous (Legge et al., 1997a; Legge et al., 1997c) studies, an increase in slopes of the reading time as a function of word length graphs were taken to be indicative of a reduction in visual span. However, as suggested by (Legge et al., 1997a), it might be more expected that these graphs be in the form of stair steps rather than straight lines. For example, if the visual span was 6 characters wide, it would be expected that the reading time (T) be constant for word lengths up to 6 characters. For word lengths from 7 characters to 12 characters the reading time would be a constant time 2T and so on. The straight lines seen in the results of this study may indicate that the word length was not sampled finely enough. Alternatively, it may be possible that words of greater length, but still within the size of the visual span, may take slightly longer to process than relatively shorter words.

Figure 10.4 shows a small reduction in plateau reading speed (wpm) with increasing eccentricity. The fact that only one of the subjects could read the 9 letter words at 10 degrees fixation, suggests that limitations with regards to the monitor size may have artificially reduced the 10 degree fixation reading speeds by restricting the size of text available for presentation. However, the reduction in plateau reading speed is similar to that seen with the normally sighted subjects reading random words in the study described in Chapter 9. The average plateau reading speed values (±1SEM) reported in Chapter 9 were 294.8±29.9, 229.7±18.6 and 162.1±14.9 wpm for the foveal, 5 degree and 10 degree fixation conditions respectively. These reading speeds were not significantly different to those in the study described here for words of 3 and 6 letters in length either foveally, at 5 degrees or at 10 degrees fixation. The reading speeds for the 9 letter words were relatively slower than those for the normally sighted subjects in Chapter 9, however this only reached significance for the 5 degree fixation ($t(9)$ –4.05, $p<0.01$). The word lists used in Chapter 9 consisted of 3-7 letter words, with an average length of 5.2 letters. It is understandable therefore that the reading speeds for the 3 and 6 letter words from the study described here are more similar to those found in Chapter 9 than the reading speeds for the 9 letter words.

Figure 10.5 shows that the CPS increases with increase in eccentricity, ranging from an average (±1SEM) of 0.18±0.004 degrees at the fovea to 2.10±0.05 degrees at 10 degrees eccentricity. This agrees with previously published work of Chung et al. (1998), who also measured reading speed curves for different eccentricities. They found that average values of the critical print size increased from 0.16 degrees at the fovea to approximately 1.5 degrees at 10 degrees eccentricity. Similarly CPS values for normally sighted subjects in Chapter 9 increased from 0.15 degrees at the fovea to 2.1 degrees at 10 degrees eccentricity. Figure 10.5 also shows that CPS is independent of word length, which suggests that the reduction in maximum reading speed with increase in word length (Figure 10.4) is not due inadequate magnification of the text. As mentioned above however, only one subject could read the 9 letter words at 10 degrees eccentricity. This suggests that the true CPS for this condition could be bigger than the data implies.

10.6 CONCLUSIONS

In conclusion, the calculated visual span was found to decrease with increase in eccentricity of presentation of the text, a finding that agrees with the results of Legge et al. (1997c). There was also weaker evidence of slight decrease in processing speed with increasing eccentricity of text presentation. The results suggest that both factors contribute to the reduced reading speeds seen when reading with eccentric retina. However, the findings of the study described in this chapter show that the calculated visual span sizes are relevant to the range of print sizes that fall along the maximum reading speed plateau. Therefore, it is the number of characters in the visual span, not the size of the visual span in degrees that is important in determining reading performance.

Chapter 11

CONCLUSIONS

This thesis has investigated the detrimental effect of central field loss (CFL) on visual function and perceived visual performance. The most common cause of CFL is age-related macular degeneration (ARMD). It is the most common cause of blindness in the Western World and accounts for approximately 50% of blind registrations in the UK and North America (National Society to Prevent Blindness, 1980; Grey et al., 1989; Thompson & Rosenthal, 1989). Without foveal function a person with CFL is forced to fixate eccentrically, and thus fine detailed tasks such as reading are particularly affected. Reading is an integral part of modern living, which allows people in developed societies to communicate, socialise, learn and to educate others. This thesis has therefore specifically concentrated on the effect that CFL has on reading performance.

Clinical and research experience has shown that readers with CFL, who are forced to use an eccentric retinal locus for fixation, read slower than normally sighted subjects reading foveally, despite the use of low vision aids. In order to understand the reduced abilities of peripheral retina compared with the fovea and to maximise peripheral visual function, a clearer understanding of the visual processes of peripheral vision is necessary. In addition however, in order to improve visual performance for CFL patients, it is necessary to have reliable and valid outcome measures of rehabilitation or intervention. It is important to know that any clinical measures of visual function match the perceived visual performance of the patient. The studies in this thesis have therefore investigated two aspects of visual function with central field loss. Firstly, the success of rehabilitation or therapeutic intervention is currently measured with visual function tests. Therefore, various methods of determining visual function were compared with perceived visual performance. Secondly, potential causes for reduced peripheral reading ability were investigated using both normally sighted and CFL subjects.

High contrast distance visual acuity (HCVA) is the most common clinical measure of visual function, against which the success (or otherwise) of any form of rehabilitation or therapeutic intervention is judged. This assumes therefore that HCVA accurately reflects the perceived visual performance of the patient. Chapters 5 and 6 investigated the relationship between visual function as measured with clinical vision tests, and perceived visual performance using a quality of life questionnaire. In this way, clinical tests that most closely reflected general visual quality of life and perceived reading performance were determined for patients with acquired macular disease, without the need for any *a priori* assumptions. In Chapter 5, all tests of vision correlated highly, but low contrast measures (low contrast VA and CS) explained most of the variance in self-reported problems with reading. These results highlighted the importance of high contrast, both in the design of products (e.g. text on labels and signs) and in the design of environmental lighting to minimise glare and thus maximising effective contrast. Reading speed was found to be most important for reflecting changes in general visual quality of life. The results therefore suggested other vision tests that could be used to supplement HCVA in order to more accurately describe the perceived visual abilities of macular disease patients.

Chapter 6 also investigated both perceived visual performance and objective visual function in macular disease patients. Both types of measures were compared before and after surgery for the removal of subfoveal choroidal new vessels (CNV). The results of the study suggested that low contrast visual acuity was the only measure of visual function that improved as a result of the surgery for both ARMD associated and idiopathic/inflammatory CNV. This improvement was only found for the subjects with macular disease affecting only one eye. There was no significant change in perceived visual performance. Considering the poor visual prognosis of these patients, an equivocal result such as this may suggest a relative improvement in long-term results compared with natural progression. Unfortunately, the restrictions placed on the number of subjects in this study limited the statistical analysis possible and thus made it difficult to form concrete conclusions. The results do suggest however, that surgical intervention for this particular complication of macular disease is an avenue worth further investigation. In addition, anecdotal evidence obtained through the course of the study highlighted the detrimental effect that distortion has on a patient's reported visual performance. Reduction of distortion caused by sub-retinal fluid was reported to be appreciated by patients even though visual function or perceived visual performance measures showed little change. Currently there are no clinical tests available to quantify distortion perceived by patients. The development of such a test and the comparison of its measures with those of visual function tests and perceived visual performance may enable a more accurate understanding of certain individuals visual abilities.

As mentioned above, reading with an eccentric retinal locus for fixation is slower than reading with foveal fixation, despite the use of low vision aids to magnify print to an appropriate level. As discussed in Chapter 3, in theory magnification should be able to compensate for fewer retinal cells in the peripheral visual field compared to the central visual field. However, for text reading performance this does not appear to be the case, suggesting that print size is not the performance-limiting factor. Chapters 7-10 therefore investigated other potential reasons for reduced peripheral reading performance.

Chapter 7 investigated the effect on reading speed of the visual field location of the preferred retinal locus (PRL). It was considered that a possible deterrent to achieving optimum reading performance when using eccentric retina may be an unsuitable PRL location. Studies have shown that patients with juvenile macular degeneration (JMD) usually have a PRL below their scotoma in visual field space (Sunness et al., 1996), whereas patients with age-related macular degeneration (ARMD) use a PRL either below or to the left of the scotoma in visual field space. Reading performance was therefore compared for these most common PRL locations. The results showed that for normally sighted subjects reading eccentrically with rapid serial visual presentation (RSVP) text, the inferior visual field was a better position for presentation of the text. This was because faster maximum reading speeds were achieved in the inferior compared with the left visual field. The results therefore suggest that for CFL patients, using a PRL in the inferior visual field is more likely to produce optimum reading performances. Published data involving reading with eye movements and artificial scotomas (Fine & Rubin, 1999) has also found reading in the inferior field to be faster than reading in left visual field. Using RSVP text and retinally stabilised images, this study was able to show that the advantage of the inferior field is not limited to reading tasks involving eye movements, nor due to the masking of text in either location. Therefore, other factors are at least partly responsible for the higher reading speeds reported for the inferior field.

Another potential cause of reduced reading performance in peripheral retina is the reduction in the ability of the peripheral retina to utilise context or the meaning of text. Context advantage (CA), the ratio of reading speed for sentences to the reading speed for random words, has been used as a measure of the ability to process meaningful text. Published data for both normally sighted and vision impaired subjects however, has resulted in conflicting findings. Some studies using normally sighted subjects have shown a reduction in CA for eccentric retina compared with foveal fixation (Latham & Whitaker, 1996b; Chung et al., 1998). In contast, Fine & Peli (1996) found no difference in context advantage (there called sentence gain) between their CFL subjects reading with an eccentric PRL and normally sighted subjects fixating foveally. Chapter 8 attempted to reconcile these findings by comparing results using different methodologies. Text was either presented peripherally whilst the subject fixated a central target, or with the use of an eye tracker and optical image stabiliser, the text was stabilised on the subject's eccentric retina. The results of the study showed no significant difference between the results found when using the different methodologies. Therefore, whether or not a subject was required to fixate a central target could not explain the discrepancies in the previously published data. In addition, the fovea and inferior retina showed similar abilities to utilise context. The results of this study did not show that the ability to use the context available from the text is the limiting factor in the reading performances of people with CFL.

Chapter 9 also investigated the ability of peripheral retina to use context. Considering the evidence for cortical plasticity, it was hypothesised that for patients with long-term CFL, adaptation of the PRL would occur that would enable it to utilise context at levels seen in the normal fovea. Evidence of such adaptation would be evidence for the benefit of eccentric fixation training as a method of improving reading performance. The results of the study showed that none of the CFL subjects in this study were able to use their PRL to the same level of efficiency as the normally sighted subjects using their fovea regardless of the duration of their CFL. All subjects showed reduced reading speeds and reduced context advantage values compared with the normal fovea. However, some of the subjects clearly performed better than others. Better performance was associated with a more central PRL, better visual acuity, and younger age. The findings reported in this study for the normally sighted observers conflict with those reported in Chapter 8. The CA values reported in Chapter 8 were similar for foveal and inferior fixation. For the normally sighted subjects in this study however, CA values reduced with increasing eccentricity of fixation. The differences in methodologies used by the two studies were unable to fully explain the discrepancy. Indeed, the variation in reported CA values across recent published studies could not be reconciled suggesting that the measure of CA deserves further investigation. It may be that the reading speed plateau is not stable enough to be used as a ratio for determining CA.

Chapter 10 investigated the possibility that a reduction in visual span size with increasing eccentricity of fixation contributes to reduced peripheral reading performances. In agreement with the results of (Legge et al., 1997c), the calculated visual span was found to decrease with increase in eccentricity of presentation of the text. In addition however, there was weaker evidence for an increase in processing time with increasing eccentricity of text presentation. Previous data (Legge et al., 1997a) had determined the visual span by using a single large text size. In contrast, in the study described in Chapter 10, calculated visual span sizes were determined from the plateau reading speeds for each word length. The visual span sizes were therefore relevant to the range of print sizes that fell along the maximum reading speed plateau. This suggests that it is the number of characters in the visual span, not the size of the visual span in degrees that is important in determining reading performance. Indeed, previous normative data from studies that have measured reading speeds with artificial central scotomas of varying sizes, have shown that the number of characters masked is more important to reading speed than the mask size in degrees. Reading eye movement studies have also shown that average saccade sizes (in degrees) increase with increasing character size to maintain a similar number of characters per saccade.

In conclusion, a patient with CFL is more likely to show better reading performance if they have a small central scotoma, a less eccentric PRL located in inferior visual field, relatively good acuities and are young in age. Eccentric fixation training is likely to be of help for the stabilisation of fixation and the improved accuracy of fixation, but would not be able to improve reading performances to near foveal level. As well, a patient with long-term CFL is unlikely to improve reading performances above those of normally sighted subjects reading at a similar eccentricity. The reduction in visual span in the periphery compared with the fovea is likely to limit reading performance. However, it is unclear whether the ability to use context is also a limiting factor. When assessing potential reading ability in daily life, it is important to consider performance for low contrast tasks in addition to high contrast visual acuity. Also, when considering general perceived visual performance, a measure of reading speed may correlate well for patients with CFL. The effect of distortion on perceived visual performance appears to have a notable effect. Therefore for certain macular disease patients the measurement of distortion may be important to consider. Further investigation is suggested to determine potential methods for quantifying distortion.

An understanding of peripheral reading performance in patients with CFL is important if we are able to improve their reading abilities. It is clear that text size is not the limiting factor to this performance and this thesis has suggested other possibilities.

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APPENDIX: A

Publications

Journal papers

CA Hazel, K Latham Petre, RA Armstrong, MT Benson, NA Frost. Visual function and subjective quality of life compared in subjects with acquired macular disease. In press. *Investigative Ophthalmology & Visual Science.*

K Latham Petre, CA Hazel, EM Fine, GS Rubin (2000). Reading with eccentric fixation is faster in inferior field than in left visual field. *Optometry & Vision Science* **77**, pp: 34-39.

EM Fine, CA Hazel, K Latham Petre, GS Rubin (1999). Are the benefits of sentence context different in central and peripheral vision? *Optometry & Vision Science*, **76**, pp: 764-769.

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Latham K & Hazel CA. Reading performance in normal foveal and peripheral vision. Journal of Videology, in press.

Hazel CA & Latham K. Processing of text and words with long-term central field loss. Journal of Videology, in press.

Refereed Conference Abstracts

Hazel CA, Latham K, Armstrong RA & Benson MT (1999). Visual function and reading in low vision: how do optometric tests compare to perceived ability? *Ophthalmic & Physiological Optics*, **19**, pp: 523.

Hazel CA, Latham K, Fine EM & Rubin GS (1999). RSVP reading with eccentric fixation in inferior and left visual field. *Investigative Ophthalmology & Visual Science*, 40(suppl), pp:S33

Hazel CA, Latham K, Armstrong RA, Benson MT (1998). The correlation between tests of visual function and perceived visual ability in central field loss patients. *Investigative Ophthalmology & Visual Science*, 39(suppl), pp: S841.

Benson MT, Richardson PRS, Hazel CA, Nichols C. Latham K, Wild JM (1998). RPE transplantation after removal of sub-foveal CNV in AMD: changes in psycho-visual parameters. *Investigative Ophthalmology & Visual Science*, 39(suppl). pp:S391.

Patient	Age (years)	Gender	Diagnosis	Operated HCVA (logMAR)	Non-op. HCVA (logMAR)	Operated LCVA (logMAR)	Non-op LCVA (logMAR)	Operated CS (logCS)	Non-op CS (log CS)	Binoc CS (logCS)	Operated near VA (logMAR)	Non-op near VA (logMAR)	Binoc near VA (logMAR)
CL	37	Male	POHS	0.44	0.40	0.94	0.52	1.55	1.50	1.80	0.70	0.40	0.30
WB	26	Female	POHS	0.84	1.08	1.08	1.20	1.00	1.20	1.30	1.00	1.00	1.00
AW	36	Female	POHS	0.60	-0.10	1.40	0.14	1.15	1.70	1.75	0.70	0.10	0.10
CH	40	Female	POHS	1.40	-0.08	1.62	0.12	1.15	1.65	1.65	1.60	0.00	0.00
AL	36	Female	POHS	1.00	-0.08	1.20	0.10	0.95	1.65	1.65	1.20	0.10	0.10
BH	49	Female	POHS	0.76	0.24	1.14	0.44	1.05	1.65	1.65	1.00	0.10	0.00
SC	37	Female	POHS	0.64	-0.14	1.46	0.12	1.35	1.65	1.65	1.30	0.00	0.00
MB	30	Female	POHS	0.60	-0.08	0.68	0.32	1.30	1.75	1.30	0.50	0.20	0.20
IP	45	Female	POHS	0.12	-0.06	0.64	0.18	1.60	1.85	1.75	0.26	0.10	0.20
JP	48	Female	IDIO.	0.20	0.00	0.54	0.20	1.65	1.80	1.90	0.40	0.40	0.40
SC	45	Male	IDIO.	1.16	0.06	1.52	0.16	0.30	1.75	1.80	1.20	0.10	0.10
JG	77	Female	ARMD	1.14	0.46	1.44	0.92	0.90	0.90	1.05	1.40	0.70	0.60
JC	55	Female	ARMD	1.14	0.00	1.82	0.30	0.95	1.55	1.55	1.40	0.00	0.00
FB	80	Male	ARMD	0.56	1.50	1.00	1.74	1.10	0.80	1.10	0.70	1.40	0.70
HK	74	Male	ARMD	1.14	0.06	1.44	0.24	0.90	1.50	1.65	1.50	0.10	0.10
JT	83	Female	ARMD	0.62	1.18	1.10	1.38	1.20	0.70	1.35	0.60	0.60	0.60
DP	74	Male	ARMD	0.80	0.00	1.44	0.40	0.80	1.40	1.35	0.80	0.10	0.10
PN	67	Male	ARMD	1.06	0.14	1.18	0.36	1.10	1.50	1.55	1.10	0.10	0.10
DM	64	Female	ARMD	0.74	0.46	0.92	0.64	1.60	1.65	1.65	1.00	0.50	0.50
HM	78	Male	ARMD	1.46	1.68	1.50	1.80	0.75	*	0.80	1.50	*	1.50
AR	79	Male	ARMD	0.90	0.80	1.20	0.98	1.20	0.95	1.35	1.50	1.00	1.00
BS	54	Female	ARMD	0.62	-0.10	1.12	0.10	0.90	1.65	1.65	1.00	0.00	0.00
EH	71	Female	ARMD	1.14	0.76	1.40	0.90	0.90	1.35	1.35	1.40	0.90	0.90
MD	72	Female	ARMD	1.54	0.20	1.84	0.46	0.40	1.35	1.65	1.60	0.30	0.30
WP	80	Male	ARMD	1.38	1.24	1.68	1.28	0.90	0.40	0.90	1.60	1.60	1.60

Appendix B: Demographics and pre-operative measurements for the 25 subjects taking part in the study described in Chapter 6. '*' denotes vision was too poor for a measurement to be made; 'Operated' denotes measurement for operated eye; 'Non-op' denotes measurement for non-operated eye; 'IDIO.' denotes idiopathic; 'POHS' denotes presumed ocular histoplasmosis syndrome; 'ARMD' denotes age-related macular degeneration.