

Article for special issue of the *London Review of Education* entitled
'The Psychology of Reading'

Visual factors in reading

Chris Singleton and Lisa-Marie Bull
Department of Psychology
University of Hull

Address for correspondence:

Dr Chris Singleton
Department of Psychology
University of Hull
Hull, HU6 7RX, UK
Email: c.singleton@hull.ac.uk

Visual factors in reading

Abstract

This article reviews current knowledge about how the visual system recognises letters and words, and the impact on reading when parts of the visual system malfunction. The nature of the physiological apparatus that conveys visual information to the brain places important constraints on word recognition; the efficient organisation of the components of the visual system is not inherent but largely dependent on the experience of learning to read. Although studies have reported that many children with severe reading difficulties have problems with controlling the visual fixation of words, in this context the concept of ‘visual dyslexia’ remains controversial. However, evidence that a significant proportion of children with dyslexia have impairment of the magnocellular component of visual system (which responds to contrast and movement) has led to alternative theories challenging the phonological deficit model of dyslexia. Deficits in the magno system have also been proposed as an explanation for the symptoms of visual stress which many people experience when reading, and to account for the alleviation of these symptoms by use of coloured overlays or tinted lenses. However, a competing theory that posits cortical hypersensitivity to pattern glare as the cause of visual stress is generally more favoured at the present time. Our scientific understanding of reading would be greatly improved if visual factors were better integrated into theories that at the present focus almost exclusively on linguistic factors, and some progress towards this is currently being made.

The visual system and reading

Reading involves the complex integration of visual and auditory information. In the last quarter of a century the reading research field has been dominated by work focusing on the latter, to the extent that anyone perusing the research literature may be forgiven for overlooking the fact that without first receiving and processing visual input there can be no such thing as reading at all (in any conventional sense). Human visual processing is normally so swift and efficient it is usually taken for granted by

all except psychologists and vision scientists who are curious about how, exactly, information in the form of light becomes coded in the brain. Most reading researchers are equally indifferent to what goes on in the visual system – at least, until some aspect of reading goes wrong and language-based theories fail to provide totally convincing explanations. Recent work, however, has brought visual factors back into the research spotlight and is promoting a more balanced scientific understanding of reading.

For the purposes of this article, ‘the visual system’ encompasses all aspects of the reading process that take place before information is passed from the visual centres of the cortex to other parts of the brain. We are therefore concerned here not only with the mechanisms of the eyes and how they move, the optic nerves and how they transmit information, and the visual cortex and how it recognises stimuli, but also with perceptual characteristics of print that can impact on these processes. The cornea and the lens of the eye focus light on the photo-sensitive cells in the retina at the back of the eye. These cells are more densely packed at the fovea so that visual acuity is highest when directly looking at a target, such as a word on a page. Signals generated in the photo-sensitive cells are transmitted via the optic nerves to the brain, but just before entering the brain the optic nerves cross so that each visual half-field is represented in the opposite hemisphere of the brain. This partition is very precise and means that when a word is fixated at its midpoint, the letters to the left of the fixation point will initially be registered in the right visual cortex and the letters to the right of the fixation point will be registered in the left visual cortex. Given that the left hemisphere of the brain is specialised for language and hence is responsible for word recognition (see Cohen et al, 2002), information about letters to the left of the fixation point need first to be conveyed from the right hemisphere to the left hemisphere via the corpus callosum, which connects the two hemispheres. The human visual system has not evolved for the purposes of reading and we must assume that this apparently convoluted process has advantages for visual perception generally, probably because it enables a reasonably equitable division of labour between the hemispheres (for discussion see Shillcock & McDonald, 2005). There are two types of cells in the visual pathways, differentiated by size and function. Magnocells are large and code information about contrast and movement, while parvocells are smaller and code information about detail and colour. These two systems work together, the magno

system inhibiting impulses in the parvo system while the eyes are moving. This enables us to perceive a stationary image when we move our eyes across a scene. In fact, the eyes do not move smoothly but in a series of very quick jumps (saccades) in order to fixate successive locations of the scene, between which the brain interpolates to build a complete picture. When reading, this saccadic process is activated so that (usually) each individual word is rapidly fixated in turn, each fixation (ideally) giving us a clean, clear image that is stored in working memory.

The simplified account given above does not address some of the most important questions that currently beset the field, which include (1) How does the visual system enable us to recognise letters and words? (2) What happens to reading when parts of the visual system malfunction? (3) How do the visual components of reading interact with the auditory and semantic components of the process? This article will review current psychological knowledge about these three questions and consider educational implications.

Visual processing of text

Word recognition begins with visual coding of letters. Sensitivity to the position of local characters in a word-like string of letters predicts reading ability in children and word recognition in adults (Pammer et al, 2004). This suggests that readers are sensitive to the internal visual characteristics of words and that effective reading depends on learning to encode the letters within words (Pammer & Vidyasager, 2005). This view is supported by evidence from neuro-imaging studies (e.g. Tarkiainen et al, 1999), and the fact that this coding process has been found to be deficient in dyslexic readers (Salmelin et al, 1996). There are several theoretical models of word recognition (see Lupker, 2005 for a review) but the most widely respected are variants of an interactive activation model first proposed by McClelland and Rumelhart (1981). The basic principle behind these models is that features of letters are first detected by the visual system, with activation ‘cascading’ to a letter detection stage, and finally to a word detection stage. However, when sufficient features of a letter become activated for that letter to be recognised, feature recognition is inhibited, and when sufficient letters of a word become activated for that word to be recognised, letter recognition is then inhibited. This feedback restrains the system from further (wasteful)

identification of features or letters when the next stage is satisfied with what has already been identified. Interactive activation models (e.g. Coltheart et al 2001; Grainger & Jacobs, 1996; Seidenberg & McClelland, 1989; Whitney & Cornelissen, 2005) also provide explanations for many of the psychological characteristics of word recognition, such as word frequency effects (more common words are recognised faster) and semantic effects (e.g. when words within a category, such as ‘animals’, are expected, these words are recognised faster than other words).

Fixations – that is, periods during reading when the eyes are relatively stable and taking in information from the text – last for an average of about 200–250 milliseconds. Saccades – that is, the movement of the eyes between fixations, during which vision is suppressed – are fairly brief, typically about 20–40 milliseconds. When reading English (or in any language where print goes from left to right across the page) the eyes mostly move along the lines of text from left to right and then across to the beginning of the next line (the ‘return sweep’). About 10–15% of fixations by skilled readers are regressions: i.e. movements of the eyes backwards to previous parts of the text. Eye movements are influenced by the reader’s proficiency: skilled readers tend to make shorter fixations, longer saccades and fewer regressions (Rayner, 1998). In beginning readers, average fixation duration is 50% longer than in adult readers and twice as many fixations and regressions are made. Because children with reading difficulties also show shorter saccades, longer and more fixations, and more regressions than normal readers it has sometimes been suggested that faulty eye movements are a cause of poor reading. However, the weight of evidence does not support this view, rather it implies that efficient eye movements are disciplined during normal reading development and consequently if reading development is abnormal then eye movements will tend to lack efficiency (Hyönä & Olson, 1995; Kulp & Schmidt, 1996; Olson et al, 1983; Rayner, 1998). An alternative view is that the alternation of saccades and fixations during reading requires a rapid switching of attention between what Fischer and Weber (1990) term ‘engaged’ and ‘disengaged’ forms. In the engaged attentional state saccades are inhibited so that the person can fixate a target. When attention is disengaged the inhibition of saccadic eye movements is removed. These authors reported evidence of unstable fixations in more than half the dyslexic children in their sample. Subsequent studies suggested that this

weakness of fixation could be improved by practice (see Fischer & Hartnegg, 2000) but it is unclear whether this improvement benefits reading skills.

Eye movements are also a function of the difficulty and informativeness of the text. When making saccades proficient readers often skip function words (prepositions, conjunctions, articles and pronouns) and spend more time fixating content words (nouns, verbs, adjectives and adverbs), especially if these are unusual. In skilled readers the decision *when* to move the eyes during reading appears to be related to high level factors such as the lexical and syntactic complexity of the text, and regressions are usually a response to comprehension failure (Kennedy et al, 2003). The decision *where* to move the eyes seems to be more a function of low level factors such as word length. However, explaining exactly how the brain controls eye movements in reading is no easy task, given the speed at which several complex processes are being executed (for review see Rayner et al, 2005). For example, how do we know (without looking) that a function word is coming up and hence we may be free to skip it? Part of the explanation seems to lie in the fact that when reading the perceptual span extends beyond the fixated word, and a limited amount of information is available about the text that falls within that span. The extent and direction of the perceptual span is partly determined by the nature and complexity of the writing system. In English the perceptual span extends from about 3-4 letters to the left, to 14-15 letters to the right, of the fixation point. In informationally dense writing systems, such as Chinese and Japanese, the perceptual span is smaller than in English. In languages read from right to left the perceptual span extends asymmetrically to the left of the fixated word, i.e. opposite to that found in languages read from left to right. However, the perceptual span is also partly a function of learning to read and beginning readers have smaller perceptual spans than more experienced readers. Although the information about words immediately to the right of the currently fixated word (the 'parafoveal zone') is limited this could be enough to enable us to skip 'unimportant' words or highly predictable words, demonstrating top-down control over the bottom-up components of the word recognition process (see Rayner, 1998, for a review). Hence the experience of reading itself enables children to develop greater fluency and increased speed not only by practising word recognition skills but also by learning to exert top-down control over eye movements so that patterns of fixation can become more efficient.

Because of the differential density of receptor cells in the retina, when a word is fixated not all letters are equally visible to the reader. Visual acuity drops off sharply either side of the fixation point so we usually find it quite difficult to recognise words either side of the word we are fixating – without moving our eyes, that is. The letter that is fixated is the most visible and the visibility of other letters in the word will depend on the distance from the fixation point and whether these letters are inner or outer letters in the word. Words are more rapidly recognised when readers fixate the centre letters of a word rather than the outer letters. However, word beginnings are usually more informative than word endings (see Shillcock, Ellison & Monaghan, 2000) so the outcome is that the ideal place to end a saccade is between the beginning and the middle of the word. This has been called the ‘optimal viewing position’ (OVP) (Brysbaert & Nazir, 2005). One interesting effect of OVP is that relatively more letters in the word are transmitted directly to the language-advantaged left hemisphere, leaving the right hemisphere to deal with fewer letters to convey to the left hemisphere. Thus the effort involved in word recognition is divided between the hemispheres, but not entirely equally; again, we must presume that this conveys advantages in processing speed and efficiency. It is also presumed that OVP is learned in the process of reading acquisition and consequently novice readers, who usually read word by word, are more likely to be susceptible to anomalies in viewing position. Indeed, there is evidence that in children with dyslexia or impaired reading, fixation position and behaviour is different to that seen in more competent readers (Kelly et al, 2004).

In short, studies of word recognition lead to two main conclusions. First, that the nature of the physiological apparatus which conveys visual information to the brain and enables words to be identified (the ‘hardware’), places several constraints on the process. Second, that the efficient organisation of the various components of the system (the ‘software’) is not inherent but comes about as a result of the experience of learning to read. This underlines the educational requirement for adequate and appropriate practice in text reading in order to attain fluency.

Vision and reading difficulties

If the lenses of the eye do not focus properly various types of refractive error arise, such as short-sightedness (myopia), long-sightedness (hypermetropia or hyperopia) and astigmatism (a condition in which the eyeball is not spherical, causing lack of clarity in some aspects of vision). About 10% of schoolchildren are short-sighted, 5% long-sighted and 5% have some degree of astigmatism; without correction by spectacles these problems can impact on reading acquisition (Evans, 2001). The automatic focussing of the eye to retain a clear image (accommodation) can also be subject to a number of anomalies that may respond to eye exercises. Accommodation problems are sometimes noticed when a child has to change focus rapidly, e.g. from the classroom board to a book. Conditions in which the two eyes do not move together synchronously are known as binocular incoordination (found in about 5% of schoolchildren), the most common types being strabismus ('lazy eye') and decompensated heterophoria. The latter can cause various undesirable symptoms when reading, including headaches, eyestrain and blurred vision. Uncorrected refractive errors or strabismus can result in one eye being significantly weaker than the other (amblyopia), which should be treated before the age of eight. Given how common refractive and orthoptic problems are, and the detrimental effects they can have on learning to read, it is essential that children's vision is checked when starting school and that children who display anomalies or symptoms at any time should be referred for full eye examination (see Lightstone & Evans, 1995; Thomson, 2002).

A number of studies have reported findings of poor control of fixation in children with dyslexia (e.g. Eden et al, 1994; Fischer & Weber, 1990). More than half of a large sample of children with reading difficulties studied by Stein and Fowler (1982) were reported not to have a stable or fixed 'reference eye' when given tests that required either convergence or divergence of the eyes. They claimed this demonstrated these children had failed to establish 'ocular motor dominance' and called the condition 'visual dyslexia'. Stein and Fowler (1985) further reported that monocular occlusion of one eye frequently led to both a development of a fixed reference eye and improvement in reading. However, subsequent studies (e.g. Bigelow & McKenzie, 1985; Newman et al, 1985) did not always replicate these findings, and this field has been the subject of fierce debate (see Bishop, 1989; Stein

& Fowler, 1993). The discrepancies in the findings could be due to different samples of children used and to the unreliability of the methods employed to assess vergence control. Subsequently, Cornelissen and colleagues reported that the type of errors children made in reading and spelling were a function of whether or not they had a stable reference eye (Cornelissen et al, 1991, 1994). These authors argued that visual confusion is likely to make it difficult for children to learn the visual pattern of words, and so such children would have to rely more on a phonologically-based strategy, even when the words are irregular and hence not susceptible to phonological analysis. More recently, Stein (Stein, 2001; Stein & Walsh, 1997) has linked ideas about eye movement control in reading difficulties to the magnocellular deficit theory of dyslexia (see below), arguing that an impaired magno system could destabilize processes of binocular fixation. However, Goulandris et al (1998) did not find that orthoptic tests discriminated between dyslexic and reading-age matched controls, and Everatt et al (1999) found that poor vergence control was not common in adult dyslexics. The concept of ‘visual dyslexia’ thus remains highly controversial and although not ruling out the contribution of orthoptic factors to reading altogether, it seems unlikely that poor vergence control is a very significant cause of reading difficulties (see Beaton, 2004, and Evans, 2001, for reviews).

Magnocellular deficit theory of reading difficulties

Research to date is consistent with the position that a proportion of individuals with dyslexia have a low-level visual impairment affecting the magno visual system (Cornelissen et al., 1995; Stein & Walsh, 1997; Talcott et al., 2000) that persists beyond childhood (Conlon et al., 2000). In fact, 75% of dyslexics have been found to have a magno deficit compared to only 8% of the normal population (Evans, 1997). The magno system is important for directing visual attention, control of eye movements, and visual search – three skills having key roles in reading (Edwards et al, 1995). Thus, if one part of the system is dysfunctional it is not unreasonable to anticipate problems in smooth and efficient processing of text.

Evidence for the magno deficit comes from four main types of psychophysical study. (1) Dyslexics have a reduced ability to detect flicker (e.g. Evans et al., 1994). (2) Dyslexics often have reduced ability to detect coarse detail, but a normal ability to

detect fine detail (Livingstone et al., 1990). (3) There tends to be a prolonged persistence of the visual image causing masking of vision on successive fixations (e.g. Slaghuis & Ryan, 1999). (4) There is a decreased ability to detect fine motion (e.g. Cornelissen et al., 1995). Anatomical support for the magno deficit was provided by Livingstone, Galaburda and colleagues, who found that the magno cells in the brains of deceased dyslexics post mortem were 30% smaller and more disorganised than in normal brains. Weaker evidence for the magno deficit is also provided by electrophysiological studies (e.g. Demb et al., 1997).

A magno deficit may be better conceptualised as a functional deficit in the early stages of the dorsal visual stream. The dorsal stream (in which magno cells dominate) has a key role in the early mediation of guided visual search and spatial selection (Vidyasagar, 1999, 2001). This information is fed back to the visual cortex on to the ventral stream (in which parvo cells dominate) to allow for detailed examination of a selected object. Thus the dorsal stream acts as the control of an attentional ‘spotlight’ (Pammer & Vidyasagar, 2005; Vidyasagar 1999, 2001). If the former is impaired then it is reasonable to assume that difficulties would emerge when attempting to identify and assemble a target from its local features, particularly in cluttered visual scenes, such as a page of text (Vidyasagar, 1999). Further support for this theory is provided by the left mini-neglect theory of dyslexia, i.e. a disadvantage of the left visual field in selecting and processing visual information (Hari et al., 2001). Left mini-neglect reflects an impairment of the right posterior parietal cortex (rPPC) since this region is involved with visually guided movement, spatial attention and eye movements. Left mini-neglect is related to the magno deficit theory since magno input is important for rPPC function via the dorsal visual stream (Merigan & Maunsell, 1993). The dorsal stream of dyslexics may receive weaker magno input (Eden et al., 1996) and impair visuospatial attention allocation, in particular in the left visual field (contralateral to the rPPC) (Facoetti et al., 2003).

Stein (2003) argues that boosting magno performance using yellow filters or training eye fixation can significantly improve reading performance. Indeed, it has been suggested that the beneficial effect from coloured filters in dyslexia might be a perceptual consequence of the magno deficit. Further, impaired magno function may cause the binocular instability often seen in dyslexia; dyslexics make fewer visual reading errors if they read with one eye (monocular occlusion) (Stein & Walsh, 1997). Monocular occlusion relieves the confusion caused by two images moving around

independently. This treatment is not as effective in older children, but it shows that the ocular motor consequences of the magno deficit are reversible if treatment is given early enough (Stein & Walsh, 1997).

The magno deficit theory has been criticised for failing to provide a clear explanation for how impaired pronunciation and manipulation of isolated words and non-words, hallmarks of the dyslexic phenotype, could be caused by magno deficits (e.g. Hayduk et al., 1996). However, two different research groups have found that dyslexic people who have a phonological impairment also have the magno deficit (Lovegrove, 1991; Witton et al., 1998). A more generalised version of the magno deficit theory may explain this finding; magno temporal processing deficits may result in visual *and* auditory processing impairments. Impaired low level auditory transient processing would lead to a reduced sensitivity to detect rapidly changing auditory stimuli, and entail problems with phonological decoding (Stein, 2001; Talcott et al., 2000), thus linking the magno deficit with a phonological decoding deficit (Demb et al., 1997; Eden et al., 1996).

The magno impairment in dyslexia is subtle and has been disputed (see Skotton, 2000). Hulme (1988) argued that if there is a direct relationship between visual impairments and reading difficulties, then dyslexic children should have more problems in reading prose rather than single words; this is seldom the case. It has also been suggested that the magno deficit may reflect a more generalised deficit in attention (Stuart et al., 2001). The conflicting findings may reflect that only a subgroup of dyslexics have a magno deficit (Borsting et al., 1996). However, most researchers now concede that the main visual difference between good and poor readers is in their magno function because the balance of evidence from a wide variety of techniques strongly supports this view (Stein et al., 2000).

Visual stress

Meares (1980) and Irlen (1983) observed that some individuals experience perceptual distortions when reading printed text that can be alleviated by using coloured overlays (sheets of transparent plastic that are placed upon the page). Often called ‘Meares-Irlen syndrome’, this condition has also been known by several other labels (e.g. ‘visual discomfort’; ‘scotopic sensitivity syndrome’), and it will be referred to here as ‘visual stress’. The symptoms can be described in general terms as asthenopia (sore,

tired eyes; headaches; photophobia) and visual perceptual distortions (illusions of shape, motion, and colour; transient instability; diplopia). Prevalence rates range from 5-34% for the general population depending on the criteria used (Evans & Joseph, 2002; Kriss & Evans, 2005; Wilkins et al., 2001).

Visual stress can interfere with the ability to read for long periods and so is likely to hinder reading development, since the rapid and accurate decoding of text promotes reading fluency (Tyrell et al., 1995). Although visual stress can occur in good readers it is more commonly observed in poor readers (Kriss & Evans, 2005) and often reported by dyslexics (Cornelissen et al., 1994; Stein & Walsh, 1997). Thus, if visual stress is not identified early in childhood there may be serious negative consequences for educational attainment and psycho-social well-being (Wilkins, 2003). The symptoms of visual stress can be alleviated by enlarging print (Hughes & Wilkins, 2000; Wilkins, 2003), and by using a typoscope (a reading mask which covers the lines of text above and below the lines being read). However, the condition is most commonly and successfully treated by the use of coloured overlays (Wilkins, 2003). Until the 1990s, when Wilkins and colleagues (Wilkins et al., 1994; Evans et al., 1995, 1996) began to investigate visual stress using highly controlled studies, the credibility of treatment using coloured overlays was still met with scepticism within the medical and educational profession. However, it is now known that coloured overlays can reduce symptoms of visual stress and improve reading fluency, accuracy and comprehension (Robinson & Foreman, 1999).

People with visual stress almost invariably report more benefit from precision tinted lenses than from coloured overlays because they are easier to use (e.g. with white boards and when writing) and because the colour can be precisely prescribed. The Intuitive Colorimeter is an instrument which allows accurate determination of the optimal specification for tinted lenses and it is used to prescribe tinted spectacles (Wilkins et al., 1992). Rigorous double-masked randomised placebo controlled trials now support the treatment of visual stress with individually prescribed coloured lenses and demonstrate that the benefit from coloured lenses is idiosyncratic and specific (Wilkins et al, 1994).

Visual stress is often defined and diagnosed as a condition that is "...alleviated by the use of individually prescribed coloured filters" (Evans, 1997). The typical protocol starts with a screening test using coloured overlays, which is usually administered by a teacher or optometrist. If children express a preference for a coloured overlay then this is evaluated by measuring improvement in reading speed with the overlay and/or the voluntary sustained use of the overlay for at least half of a school term. The Wilkins Rate of Reading Test (WRRT) was devised to test for immediate benefit in rate of reading: this assesses visual factors in reading and is relatively unaffected by cognitive factors. The test uses small, closely spaced, randomly ordered text and consists of high frequency words. Reading rate with and without an overlay is calculated. Studies using WRRT have shown that reading rate is faster with an overlay in children who show sustained voluntarily use of their overlay (Wilkins et al., 2001).

Symptom questionnaires (e.g. Irlen, 1991; Conlon & Hine, 2000) are frequently used to give an initial clue as to whether a child suffers from visual stress and may benefit from an overlay. They can successfully indicate susceptibility to visual stress in adults (e.g. Evans & Joseph, 2002; Singleton & Trotter, 2005); in children, however, their use is controversial because questioning children about suspected visual perceptual symptoms could result in misleading and subjective responses. Hence in such cases diagnosis by evaluation of the child's response to using an overlay may be argued to be the next best thing. Unfortunately, at present there is no completely objective diagnostic test for visual stress, but screening for visual stress in reading using a new computerised reading-like visual search task has recently shown to be an educationally promising development (Singleton & Bull, submitted).

There are two competing theories as to the cause of visual stress. The first is provided by Wilkins and colleagues (see Evans, 2001; Wilkins, 1995, 2003) who maintain that visual stress is caused by pattern glare, i.e. a general over-excitation of the visual cortex due to hypersensitivity to contrast. Geometric repetitive patterns that can evoke seizures in people with photosensitive epilepsy and trigger migraines can produce perceptual distortions in normal individuals as a result of neural 'overload' (Wilkins, 1995; Wilkins, 2003). Depending on its layout, text can resemble a pattern

of stripes with stressful characteristics and provoke distortions and even seizures, similar to those provoked by stripes. Maclachan et al (1993) found that children who find colour helpful are twice as likely to have migraine in the family. Wilkins (1995, 2003) speculates that since the wavelength of light is known to affect neuronal sensitivity and alter the pattern of neural activity (Zeki, 1983) the use of colour could redistribute the cortical hyperexcitability, thus reducing the perceptual distortions and headaches.

The second theoretical explanation is the magnocellular deficit hypothesis (Stein, 2001; Stein & Walsh, 1997; Livingstone et al, 1991). The role of the magno system in reading (reviewed above) suggests a convenient model for linking dyslexia with anomalies of eye movement control (Evans et al., 1996; Stein & Talcott, 1999). Some researchers have gone further suggesting visual stress could be encompassed within this theoretical framework (e.g. Livingstone et al, 1991). Stein (2001) argues that boosting magno performance using yellow filters can improve reading performance by increasing contrast and motion sensitivity. Yellow filters cut out the short wavelength blue light, implying that blue light may inhibit magno function in visual stress (Stockman et al., 1991). However, Wilkins (2003) dismisses the magno deficit theory of visual stress, arguing that it is unable to account for the idiosyncrasy and specificity in optimal colour for reading. Wilkins also regards visual stress as independent of dyslexia, even though in some individuals the two conditions may be seen to have symptoms in common.

Given the relatively high prevalence rates of visual stress, it is somewhat surprising that teachers, other educational professionals, and eye care specialists still show little awareness of the condition (Wilkins, 2003). Furthermore, the majority of reading tests and other reading materials for young readers are printed in text that is too small and has visually stressful characteristics for some children, hence these materials may not only cause discomfort which discourages interest in reading but may also result in underestimation of children's reading competence (see Wilkins et al, 2004). Hence it is vital that teachers and educational professionals are aware of the condition of visual stress and of the beneficial effects that coloured overlays and filters can have. It is also important to develop an objective screening tool that is easy to use in schools, to facilitate more widespread (and early)

identification of children who experience this problem. In particular, susceptibility to visual stress in a dyslexic child is likely to be a critical factor mediating the efficacy of any traditional educational intervention.

Conclusions

Cornelissen (2005) has observed that the field of reading research has tended to split into 'language researchers' and 'vision researchers', the former group being the larger and more conspicuous of the two. Arguably, the paucity of communication between these camps has obstructed the development of a full understanding of reading. Recent psychological research, often supported by evidence from brain-scanning studies, seems to be generating wider respect for the role of vision in reading, but we are still a long way from achieving a satisfactory theory that properly integrates visual factors with the other cognitive processes involved in reading. Although it is recognised that the first stage of reading must involve carrying out visual analysis of information about words on the page, it is still somewhat contentious that characteristics of print can interact with individual differences (or even deficits) in the visual system such that the experience of reading can be uncomfortable and reading development is hindered. However, the notion that severe reading difficulties, such as dyslexia, could arise as a result of visual problems, remains highly controversial. The phonological deficit theory of dyslexia has attained the status of orthodoxy (for reviews see Ramus, 2001; Snowling, 2000) and, to date, attempts to integrate visual factors (such as magnocellular deficits) into that perspective (e.g. Stein, 2001) have not been particularly successful. This mantle has recently fallen on a small vanguard of vision researchers, who are putting forward theoretical models that seriously attempt to integrate visual and phonological factors (e.g. Pammer and Vidyasager, 2005; Whitney & Cornelissen, 2005). These models are too complex to summarise here, but it is interesting to consider their implications for dyslexia as this is so often the chief battleground between the opposing camps. Pammer and Vidyasager (2005) have suggested that deficiencies in the dorsal visual stream resulting in 'spatial jitter', with consequent difficulties in reliable identification and assembly of visual features, could lead to problems in early readers acquiring the alphabetic code (i.e. grapheme-phoneme correspondence rules). In the early stages of learning to read it is essential to

associate a consistent visual symbol (e.g. 'ch') with a phoneme or sound (/ch/). If early visual coding is inadequate it will be much more difficult to learn this association. Whitney & Cornelissen (2005) suggest that reading acquisition might break down (e.g. in dyslexia) if, when the child is learning to fixate and process words sequentially letter-by-letter, the formation of grapho-phonemic representations is not as robust as usual. This could be due to magnocellular dysfunction generating attentional difficulties that affect the visual system (see Cornelissen et al, 1998; Vidyasagar, 2001, 2004). These new theoretical models remain to be tested but they do offer prospects for an integration of visual factors into our understanding of the processes of reading and are evidence of progress towards more a balanced theoretical perspective in the field as a whole.

References

- Beaton, A.A. (2004) *Dyslexia, reading and the brain*. New York: Psychology Press.
- Bigelow, E. R. & McKenzie, B.E. (1985) Unstable ocular dominance and reading ability. *Perception*, 14, 329-335.
- Bishop, D.V.M. (1989) Unfixed reference, monocular occlusion, and developmental dyslexia – a critique. *British Journal of Ophthalmology*, 73, 209-215.
- Borsting, E., Ridder, W.H., Dudeck, K., Kelley, C., Matsui, L. & Motoyama, J. (1996). The presence of magnocellular defect depends on the type of dyslexia. *Vision Research*, 36, 1047-53.
- Brysbaert, M. & Nazir, T. (2005) Visual constraints on written word recognition: Evidence from the optimal viewing-position effect. *Journal of Research in Reading*, 28, 216-228.
- Cohen, L., Lehericy, S., Chochon, F., Lemer, C., Rivaud, S. & Dehaene, S. (2002). Language-specific tuning of visual cortex? Functional properties of the Visual Word Form Area. *Brain*, 125, 1054-1069.
- Coltheart, M., Rastle, K., Perry, C., Langdon, R. & Ziegler, J. (2001) DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, 108, 204-256.

- Conlon, E. & Hine, T. (2000). The influence of pattern interference on performance in migraine and visual discomfort groups. *Cephalgia*, 20, 708-713.
- Conlon, E.G., Lovegrove, W.J., Chekaluk, E. & Pattison, P.E. (2000) Measuring visual discomfort. *Visual Cognition*, 6, 637-63.
- Cornelissen, P. (2005) Editorial (Visual factors in reading). *Journal of Research in Reading*, 28, 209-215.
- Cornelissen, P., Bradley, L., Fowler, S. & Stein, J.L. (1991) What children see affects how they read. *Developmental Medicine and Child Neurology*, 33, 755-762.
- Cornelissen, P., Bradley, L., Fowler, S. & Stein, J.L. (1994) What children see affects how they spell. *Developmental Medicine and Child Neurology*, 36, 716-727.
- Cornelissen, P., Hansen, P., Gilchrist, I., Cormack, F., Essex, J., Frankish, C. (1998), Coherent motion detection and letter position encoding. *Vision Research*, 38, 2181-2191.
- Cornelissen, P., Richardson, A., Mason, A. & Stein, J.F. (1995). Contrast sensitivity and coherent motion detection measured at photopic luminance levels in dyslexics and controls. *Vision Research*, 35, 1483-1494.
- Cornelissen, P.L., Richardson, A.R., Mason, A., Fowler, M.S. & Stein, J.F. (1994). Contrast sensitivity and coherent motion detection measured at photopic luminance levels in dyslexics and controls. *Vision Research*, 34, 1483-94.
- Demb, J.B., Boynton, G.M. & Heeger, D.J. (1997), Brain activation in visual cortex predicts individual differences in reading performance. *Proceedings of the New York Academy of Sciences*, 94, 13363-13366.
- Eden, G.F., Stein, J.F., Wood, H.M. & Wood, F.B. (1994) Differences in eye movements and reading problems in dyslexic and normal children, *Vision Research*, 34, 1345-1358
- Eden, G.F., VanMeter, J.W., Rumsey, J.W., Maisog, J. & Zeffiro, T.A. (1996). Functional MRI reveals differences in visual motion processing in individuals with dyslexia. *Nature*, 382, 66-69.

- Edwards, V.T., Hogben, J.H., Clark, C.D. & Pratt, C. (1995). Effects of a red background on magnocellular functioning in average and specifically disabled readers. *Vision Research*, 36, 1037-1045.
- Evans, B.J.W. (2001). *Dyslexia and Vision*. London: Whurr.
- Evans, B.J.W. (1997) Assessment of visual problems in reading. In J.R. Beech and C.H. Singleton (Eds.) *Psychological Assessment of Reading*. London: Routledge, pp. 102-23.
- Evans, B. J. W., Busby, A., Jeanes, R. & Wilkins, A. J. (1995). Optometric correlates of Meares–Irlen Syndrome: a matched group study. *Ophthalmic & Physiological Optics*, 15, 481–487.
- Evans, B.J.W., Cook, A., Richards, I.L. & Drasdo, N. (1994). Effect of pattern glare and coloured overlays on a simulated reading task in dyslexics and normal readers. *Optometry & Vision Science*, 71, 619-28.
- Evans, B.J.W. & Joseph, R. (2002). The effect of coloured filters on the rate of reading in an adult student population. *Ophthalmic & Physiological Optics*, 22, 535-545.
- Evans, B. J. W., Wilkins, A. J., Brown, J., Busby, A., Wingfield, A. E., Jeanes, R. & Bald, J. (1996). A preliminary investigation into the aetiology of Meares–Irlen Syndrome. *Ophthalmic & Physiological Optics*, 16, 286–296.
- Everatt, J., Bradshaw, M.F. & Hibbard, P.B. (1999) Visual processing and dyslexia. *Perception*, 28, 243-254.
- Facoetti, A., Lorusso, M.L., Paganoni, P., Cattaneo, C., Galli, R. & Mascetti, G.G. (2003). The time course of attentional focusing in dyslexic and normally reading children. *Brain and Cognition*, 53, 181-184.
- Fischer, B. & Hartnegg, K. (2000) Effects of visual training on saccade control in dyslexia. *Perception*, 29, 531-542.
- Fischer, B. & Weber, H. (1990) Saccadic reaction times of dyslexic and age-matched normal subjects. *Perception*, 19, 805-818.

- Goulandris, N., McIntyre, A., Snowling, M.J., Bethel, J.-M. & Lee, J.P. (1998) A comparison of dyslexic and normal readers using orthoptic assessment procedures. *Dyslexia*, 4, 30-48.
- Grainger, J. & Jacobs, A. M. (1996) Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review*, 103, 228-244.
- Hari, R., Renvall, H. & Tanskanen (2001). Left mini neglect in dyslexic adults. *Brain*, 124, 1373-1380.
- Hayduk, S., Bruck, M. & Cavanagh, P. (1996). Low-level visual processing skills of adults and children with dyslexia. *Cognitive Neuropsychology*, 13, 975–1015.
- Hughes, L.E. & Wilkins, A.J. (2000) Typography in children's reading schemes may be suboptimal: Evidence from measures of reading rate. *Journal of Research in Reading*, 12, 314-324.
- Hulme, C. (1988). The implausibility of low-level visual deficits as a cause of children's reading difficulties. *Cognitive Neuropsychology*, 5, 369-74.
- Hyönä, J. & Olson, R.K. (1995) Eye fixation patterns among dyslexic and normal readers: effects of word length and word frequency. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 21, 1430-1440.
- Irlen, H. (1991). *Reading by the colours*. New York: Avery.
- Kelly, M. L., Jones, M. W., McDonald, S. A. & Shillcock, R. C. (2004). Dyslexics' eye fixations may accommodate to hemispheric desynchronisation. *NeuroReport*, 15, 2629-2632.
- Kennedy, A., Brooks, R., Flynn, L. & Prophet, C. (2003) The reader's spatial code. In J. Hyönä, R. Radach & H. Deubel (Eds.) *The mind's eye: Cognitive and applied aspects of eye movement research*. Oxford, Elsevier, pp. 192-212.
- Kriss, I. & Evans, B.J.W. (2005). The relationship between dyslexia and Meares-Irlen syndrome. *Journal of Research in Reading*, 28, 350-364.
- Kulp, M.T. & Schmidt, P.P. (1996) Effect of oculomotor and other visual skills on reading performance. *Optometry and Vision Science*, 73, 283-292.

- Lightstone, A. & Evans, B. J. W. (1995). A new protocol for the optometric management of patients with reading difficulties. *Ophthalmic & Physiological Optics*, 15, 507-512.
- Livingstone, M., Rosen, G.D., Drislane, F. & Galaburda, A. (1991). Physiological evidence for a magnocellular deficit in developmental dyslexia. *Proceedings of the New York Academy of Science*, 88, 7943-7.
- Lovegrove, W. (1991). Spatial frequency processing in normal and dyslexic readers. In J.F. Stein (Ed.) *Vision and Visual Dysfunction, Vol 13, Visual Dyslexia*. London: Macmillan.
- Lupker, S. J. (2005) Visual word recognition: Theories and findings. In M.J.Snowling & C. Hulme (Eds.) *The Science of Reading: A handbook*. Oxford: Blackwell, pp. 39-60.
- McClelland, J. L. & Rumelhart, D. E. (1981) An interactive activation model of context effects in letter perception. Part 1: An account of basic findings. *Psychological Review*, 88, 375-407.
- Maclachan, A., Yale, S. & Wilkins, A.J. (1993). Open trials of precision ophthalmic tinting: 1-year follow-up of 55 patients. *Ophthalmic & Physiological Optics*, 13, 175-178.
- Mearns, O. (1980). Figure/ground brightness contrast and reading disabilities. *Visible Language*, 14, 13-29.
- Merigan, W. & Maunsell, J. (1993). How parallel are the primate visual pathways? *Annual Review of Neuroscience*, 16, 36-402.
- Newman, S.P., Wadsworth, J.F., Archer, P. & Hockly, R. (1985) Ocular dominance, reading, and spelling ability in schoolchildren. *British Journal of Ophthalmology*, 69, 228-232.
- Olson, R.K., Kliegl, R. & Davidson, B.J. (1983) Dyslexic and normal readers' eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, 9, 816-825.
- Pammer, K., Hansen, P.C., Kringelbach, M.L., Holliday, I., Barnes, G., Hillebrand, A., Singh, K.D. & Cornelissen, P.L. (2004). Visual word recognition: the first half second. *Neuroimage*, 22, 1819-1825.

- Pammer, T. & Vidyasagar, T.R. (2005) Integration of the visual and auditory networks in dyslexia: a theoretical perspective. *Journal of Research in Reading*, 28, 320-331.
- Ramus, F. (2001) Outstanding questions about phonological processing in dyslexia. *Dyslexia*, 7, 197-216.
- Rayner, K. (1998) Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372-422.
- Rayner, K., Juhasz, B. J. & Pollatsek, A. (2005) Eye movements during reading. In M.J.Snowling & C. Hulme (Eds.) *The Science of Reading: A handbook*. Oxford: Blackwell, pp. 79-97.
- Robinson, G.L. & Foreman, P.J. (1999). Scotopic sensitivity/Irlen Syndrome and the use of coloured filters: a long-term placebo-controlled and masked study of reading achievement and perception of ability. *Perceptual & Motor Skills*, 88, 35-52.
- Samelin, R. Service, E., Kiesilä, P., Uutela, K. & Salonen, O. (1996) Impaired visual word processing in dyslexia revealed by magnetoencephalography. *Annals of Neurology*, 40, 157-162.
- Seidenberg, M.S. & McClelland, J.L. (1989) A distributed, developmental model of word recognition. *Psychological Review*, 96, 523-568.
- Shillcock, R., Ellison, T.M. & Monaghan, P. (2000). Eye-fixation behaviour, lexical storage and visual word recognition in a split processing model. *Psychological Review*, 107, 824–851.
- Shillcock, R.C. & McDonald, S. (2005) Hemispheric division of labour in reading. *Journal of Research in Reading*, 28, 244-257.
- Singleton, C.H. & Bull, L.M. (submitted) Computerised screening for visual stress in reading.
- Singleton, C.H. & Trotter, S. (2005). Visual stress in adults with and without dyslexia. *Journal of Research in Reading*, 28, 365-378.
- Skottun, B.C. (2000). On the conflicting support for the magnocellular-deficit theory of dyslexia. *Trends in Cognitive Science*, 4, 211-212.

- Slaghuis, W. & Ryan, J. (1999) Spatio-temporal contrast sensitivity, coherent motion, and visible persistence in developmental dyslexia. *Vision Research*, 39, 651-668.
- Snowling, M.J. (2000) *Dyslexia* (2nd edition). Oxford: Blackwell.
- Stein, J.F. (2001). The magnocellular theory of dyslexia. *Dyslexia*, 7, 12-36.
- Stein J. (2003) Visual motion sensitivity and reading. *Neuropsychologia*, 41, 1785-1793.
- Stein, J.F. & Fowler, S. (1982) Diagnosis of dyslexia by means of a new indicator of eye dominance. *British Journal of Ophthalmology*, 66, 332-226.
- Stein, J.F. & Fowler, S. (1985) Effect of monocular occlusion on visuomotor perception and reading in dyslexic children. *Lancet*, 13 July, 69-73.
- Stein, J.F. & Fowler, S. (1993) Unstable binocular control in dyslexic children. *Journal of Research in Reading*, 16, 30-45.
- Stein, J.F. & Talcott, J.B. (1999). Impaired neuronal timing in developmental dyslexia – The magnocellular hypothesis. *Dyslexia*, 5, 59-77.
- Stein, J.F., Talcott, J.B. & Walsh, V. (2000). Controversy about the visual magnocellular deficit in developmental dyslexics. *Trends in Cognitive Science*, 4, 209-11.
- Stein, J.F. & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia. *Trends in Neuroscience*, 20, 147-152.
- Stockman, A., MacLeod, D.I. & DePriest, D.D. (1991). Temporal properties of human short wavelength photoreceptors. *Vision Research*, 31, 189-208.
- Stuart, G., McAnally, K. & Castles, A. (2001). Can contrast sensitivity functions in dyslexics be explained by inattention rather than a magnocellular deficit? *Vision Research*, 41, 3205–3211.
- Talcott, J.B., Witton, C., McClean, M., Hansen, P.C., Rees, A., Green, G.G.R., & Stein, J.F. (2000.) Dynamic sensory sensitivity and children's word decoding skills. *Proceedings of the National Academy of Sciences of the United States of America*, 97, 2952-2962.

- Tarkiainen A, Helenius P, Hansen PC, Cornelissen PL, Salmelin R. (1999). Dynamics of letter string perception in the human occipitotemporal cortex. *Brain*, 122, 2119-2131.
- Thomson, D. (2002). Child vision screening survey. *Optician*, 224, 16-20.
- Tyrrell, R., Holland, K., Dennis, D. & Wilkins, A.J. (1995). Coloured overlays, visual discomfort, visual search and classroom reading. *Journal of Research in Reading*, 18(1), 10-23.
- Vidyasagar, T.R. (1999). A neuronal model of attentional spotlight: parietal guiding the temporal. *Brain Research Reviews*, 30, 66-76.
- Vidyasagar, T.R. (2001) From attentional gating in macaque primary visual cortex to dyslexia in humans. *Progress in Brain Research*, 134, 297-312.
- Vidyasagar, T. R. (2004). Neural underpinnings of dyslexia as a disorder of visuo-spatial attention. *Clinical and Experimental Optometry*, 87, 4-10.
- Whitney, C. & Cornelissen, P. (2005) Letter-position encoding and dyslexia. *Journal of Research in Reading*, 28, 274-301.
- Wilkins, A.J. (2003). *Reading Through Colour*. Chichester: Wiley.
- Wilkins, A.J. (1995). *Visual Stress*. Oxford: Oxford University Press.
- Wilkins, A.J., Evans, B.J.W., Brown, J.A., Busby, A.E., Wingfield, A.E., Jeanes, R.J. & Bald, J. (1994). Double-masked placebo-controlled trial of precision spectral filters in children who use coloured overlays. *Ophthalmic and Physiological Optics*, 14, 365-370.
- Wilkins, A.J., Huang, J. & Cao, Y. (2004) Visual stress theory and its application to reading and reading tests. *Journal of Research in Reading*, 27, 152-162.
- Wilkins, A.J., Lewis, E., Smith, F., Rowland, E. & Tweedie, W. (2001). Coloured overlays and their benefit for reading. *Journal of Research in Reading*, 24, 41-64.
- Wilkins, A.J., Nimmo-Smith, M.I. & Jansons, J. (1992). Colorimeter for the intuitive manipulation of hue and saturation and its role in the study of perceptual distortion. *Ophthalmic and Physiological Optics*, 12, 381-385.

Witton, C., Talcott, J.B., Hansen, P.C., Richardson, A.J., Griffiths, T.D., Rees, A., Stein, J.F. & Green, G.G.R. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current Biology*, 8, 791-979.

Zeki, S. (1983). Colour coding in the cerebral cortex: The responses of wavelength-selective and colour-coded cells in monkey visual cortex to changes in wavelength composition. *Neuroscience*, 9, 767-781.