Visual Factors in Reading

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Summary

Visual factors are often ignored in theoretical accounts of reading and overlooked in the classroom. This article reviews recent research on the role of vision in reading, focusing mainly on cognitive processes involved in word recognition and scanning text, the impact of anomalies of the visual system, and the identification and treatment of visual stress in reading. These different lines of research all converge on the key role of practice in text reading, which is essential to discipline eye movements, to attain fluency in decoding and to provide a sound basis for competent reading comprehension. Visual factors that can disrupt such practice will inevitably hinder the development of skilled reading and consequently vigilance by teachers and educational psychologists is necessary to spot visual problems and initiate effective solutions.

Visual Factors in Reading

Reading involves the complex integration of visual, phonological and semantic information but in the research literature on the subject the first of these aspects is conspicuous by its neglect. If one did not know better one might easily imagine that reading had little, if anything, to do with vision. Even in the substantial, authoritative, and frequently quoted review of reading research edited by Snowing and Hulme (2005) only two of 27 chapters have a major focus on visual factors. The paucity of research on visual factors, in comparison with the dominance of studies on language (particularly on phonology) in the reading research can easily lead to an underestimation of the significance of visual factors. In turn, there is serious risk of reading problems caused by visual factors being overlooked by educational psychologists and teachers and consequently left untreated.

The purpose of this article is to review a number of seminal lines of recent research on visual factors in reading in an effort to redress the balance. The intention is not to argue that linguistic factors, such as phonology, are unimportant but, rather, that our understanding of the processes of reading in general, and of reading difficulties, in particular, is likely to progress better if knowledge from both linguistic and visual fields of research are combined.

The visual system and reading

The cornea and the lens of the eye focus light on the photosensitive 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 photosensitive 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, 2004), 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 cooperation between the two systems enables us to perceive a stationary image when we move our eyes across a scene or a page of text. 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'). The eyes do not move smoothly but in a series of very quick jumps (saccades) in order to fixate successive portions of the text. During saccades, vision is suppressed as a result of activation of the magnocellular system. When reading, this saccadic process is activated so that (usually) each individual word is rapidly fixated in turn, each fixation (ideally) giving a clean, clear image that can be stored in working memory. Fixations last for an average of about 200–250 milliseconds, while saccades are much quicker: typically about 20–40 milliseconds. Regressions – i.e. movements of the eyes backwards to previous parts of the text – are made occasionally, but in skilled readers only about 10–15% of fixations are regressions.

Visual processing of text

Recognising text begins with visual coding of letters. Although the external shape of the word can influence its perception (Beech & Mayall, 2005), there is substantial evidence that readers are sensitive to the internal visual characteristics of words and

that effective reading depends on learning to encode the letters within words. Good readers are more proficient at recognising and responding to the internal configurations of letter-like strings (Pammer et al, 2004; Pammer & Vidyasager, 2005). Neuroimaging studies also indicate that neural processing of letters precedes word recognition (Tarkiainen et al, 1999; Tarkiainen, Cornelissen & Samelin, 2002), but in dyslexic readers this early visual coding process has been found to be deficient (Salmelin et al, 1996), supporting the view that it is intrinsic to effective reading.

Explanatory models of how the visual system progresses from coding letters to recognising words are many and varied. However, the most widely respected models of word recognition are variants of an interactive activation model first proposed by McClelland and Rumelhart (1981). The basic principles are that firstly, the visual system detects features of letters (lines and curves), whereupon neural activation 'cascades' to the next stage (letter detection), and finally to word detection. Critical to these models, however, is the interactive feedback that increases the efficiency of the system. 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 inhibited. Feedback restrains the process from continuing to identify features or letters when the next stage is already satisfied. Interactive activation models (e.g. Coltheart et al 2001; Grainger & Jacobs, 1996; Seidenberg & McClelland, 1989; Whitney & Cornelissen, 2005) can also account for many of the psychological characteristics of word recognition, such as word frequency effects (more common words being 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). For a review of models of word recognition see Lupker (2005).

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, experienced readers (Kelly et al, 2004).

Eye movements during reading

Eye movements during reading are a function of the proficiency and experience of the reader (for reviews see Rayner, 1998; Rayner, Juhasz & Pollatsek, 2005). Older and more skilled readers tend to make shorter fixations, longer saccades and fewer regressions. Average fixation duration is 50% longer in beginning readers than in adult readers and the former make twice as many fixations and regressions. Children with reading difficulties also make more saccades over shorter distances, have longer and more fixations, and more regressions than normal readers. During the 1980s it was suggested that, for the above reasons, faulty eye movements could be a cause of poor reading. On the whole, however, 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).

The average adult reader reads at a speed of approximately 250 words per minute, fixating (almost) every word for an average of about a quarter of a second.

However, eye movements are also a function of the complexity of the text, evidencing top-down control over the bottom-up components of the word recognition process. Proficient readers often skip function words (prepositions, conjunctions, articles and pronouns) and spent 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. Regressions are usually made when there is a problem understanding part of the text (Kennedy et al, 2003). On the other hand, the decision *where* to move the eyes to seems to be more a function of low-level factors such as word length. But herein lies a puzzle: how do we know (without first looking) that a function word is coming up and hence we can skip it? It appears that a limited amount of information is available to the reader about the text a short distance to the right of the currently fixated word (the 'parafoveal zone'), which is what probably enables us to skip 'unimportant' words or highly predictable words.

Vision and reading difficulties

Over 20% of schoolchildren have vision problems that are likely to impact on reading acquisition unless corrected by spectacles (Evans, 2001; Lightstone & Evans, 1995; Thomson, 2002). When the lenses of the eye cannot focus properly various types of refractive error arise. The most common is myopia (short-sightedness), which affects about 10% of children. Also common are hypermetropia or hyperopia (long-sightedness), affecting about 5% and astigmatism (a condition in which the eyeball is not spherical, causing lack of clarity in some aspects of vision), also affecting about 5%. The ability of the eye to accommodate to near and far images 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.

Visual dyslexia?

The weight of evidence on the causes of dyslexia supports an underlying deficit in phonological processing (Farmer & Klein, 1995; Ramus, 2001; Ramus, Rosen, Dakin, Day, Castellote, White & Frith 2003; Snowling, 2000; Vellutino, Fletcher, Snowling & Scanlon, 2004), but there is evidence that low-level visual processing abnormalities may also be a feature of dyslexia in some cases (e.g. Stein & Walsh, 1997; Livingstone, Rosen, Drislane, & Calaburda 1991). For example, various studies have reported findings of poor control of fixation in children with dyslexia (e.g. Eden et al, 1994; Fischer & Weber, 1990), and over half of a large sample of children with poor reading studied by Stein and Fowler (1982) were reported to lack 'ocular motor dominance' because they did not have a stable or fixed 'reference eye' in tests of convergence or divergence such as the Dunlop Test. Stein and Fowler (1985), who called this condition 'visual dyslexia', subsequently claimed that monocular occlusion of one eye facilitated the development of a fixed reference eye as well as improvements in reading. Cornelissen and colleagues also 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). However, these findings were not always replicated (see Bigelow & McKenzie, 1985; Newman et al, 1985) and discrepancies may well have been due to the unreliability of the methods employed to assess vergence control (see Bishop, 1989; Stein & Fowler, 1993). 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. In summary, it seems unlikely that poor vergence control is a significant cause of reading difficulties and hence the concept of 'visual dyslexia' remains highly controversial (see Beaton, 2004, and Evans, 2001, for reviews.).

Nevertheless, a proportion of children and adults with dyslexia do seem to show low-level visual impairment affecting the magnocellular visual system (Conlon et al., 2000; Cornelissen et al., 1995; Demb et al., 1997; Evans, 1997; Stein & Walsh, 1997; Talcott et al., 2000). There are four main types of evidence that point to this conclusion. Firstly, dyslexics have been found to have a reduced ability to detect

flicker (Evans et al., 1994). Secondly, although dyslexics can detect fine detail as well as others, they are typically poor at detecting coarse detail (Livingstone et al., 1991). Thirdly, dyslexics are more inclined to show prolonged persistence of the visual image causing masking of vision on successive fixations (Slaghuis & Ryan, 1999). Fourthly, dyslexics have a decreased ability to detect fine motion (Cornelissen et al., 1995). Anatomical support for the magno deficit was provided by Livingstone et al. (1991), who found that the magno cells in the brains of deceased dyslexics post mortem were 30% smaller and more disorganised than in normal brains.

The magno system is crucial is directing visual attention, controlling eye movements, and in visual search. Since all these skills have central roles in reading (Edwards et al, 1995), then it follows that if the magno system is dysfunctional, problems in smooth and efficient processing of text are likely to result (Stein et al., 2000). However, the magno impairments in dyslexia are extremely subtle and have 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 is unclear how impaired pronunciation and manipulation of isolated words and non-words, hallmarks of dyslexia, could be caused by magno deficits (Hayduk et al., 1996). It has also been suggested that the magno deficit may reflect a more generalised deficit in attention (Stuart et al., 2001) or that only a sub-group of dyslexics have a magno deficit (Borsting et al., 1996.). Finally, a satisfactory explanation of how, exactly, the magno system causes dyslexic-type difficulties has yet to be put forward (for various discussions on this subject, see Eden et al., 1996; Facoetti et al., 2003; Hari et al., 2001; Merigan & Maunsell, 1993; Pammer & Vidyasagar, 2005; Stein, 2001, 2003; Stein & Walsh, 1997; Vidyasagar, 1999, 2001, 2004).

Visual stress

The observation that some individuals experience perceptual distortions and other unpleasant visual effects when reading printed text was first reported by Meares (1980) and Irlen (1983). Both of these individuals noted that these symptoms can

frequently be alleviated by using coloured overlays (sheets of transparent plastic that are placed upon the page). Although this condition has been known by several labels (e.g. 'Meares-Irlen syndrome', 'visual discomfort'; 'scotopic sensitivity syndrome'), term 'visual stress' is increasingly recognised as being the most appropriate. The symptoms of visual stress fall into two broad categories: asthenopia (sore, tired eyes; headaches; photophobia), and visual perceptual distortions (illusions of shape, motion, and colour; transient instability; diplopia). Prevalence rates vary, depending on the criteria used, but are commonly reported in the range 5-34% for the general population, but somewhat higher amongst people with dyslexia (Evans & Joseph, 2002; Kriss & Evans, 2005; Wilkins et al., 2001).

Visual stress interferes with the ability to read for long duration and consequently children who suffer from visual stress tend to lack the practice essential for the development of rapid and accurate decoding of text (reading fluency) and reading comprehension (Tyrell et al., 1995). Visual stress occurs in good readers but is more often observed in poor readers (Kriss & Evans, 2005) and is quite common in dyslexics (Cornelissen et al., 1994; Singleton & Henderson, 2007b; Stein & Walsh, 1997). If visual stress is not identified early in childhood serious negative consequences for educational attainment and psychosocial wellbeing are probable (Wilkins, 2003).

The symptoms of visual stress can be alleviated by various techniques, including enlargement of print or use of a typoscope (a reading mask that covers the lines of text above and below the lines being read) (Hughes & Wilkins, 2000). However, the most widely used treatment is that of coloured tints, either in the form of acetate overlays or tinted lenses (Wilkins, 2003). Irlen was the first to use this technique systematically but until the 1990s members of the medical, psychological and educational professions remained sceptical. However, following the landmark studies of visual stress in the 1990s by Wilkins and colleagues, it is now generally accepted that coloured tints can reduce symptoms of visual stress and improve reading speed, fluency, accuracy and comprehension. Rigorous double-masked randomised placebo-controlled trials supported the treatment of visual stress with individually prescribed coloured lenses and demonstrated that the benefit from coloured lenses is idiosyncratic and specific (Wilkins et al., 1994; Evans et al., 1994, 1996). Accurate

specification for optimal tints for lenses can be determined using the Intuitive Colorimeter (Wilkins et al., 1992). Precision tinted lenses are usually found to afford the greatest benefits because they are easier to use (e.g. with white boards and when writing) and because the colour can be precisely prescribed from the full range of possible colours. Alternative systems offering limited ranges of tints (e.g. Chromagen and Harris filters) are used by some optometrists, but the effectiveness of these in comparison with precision tints has yet to be properly determined and they have been criticised by Wilkins (2003). The Society for Coloured Lens Prescribers [www.s4clp.org] supplies details of practitioners in the UK who subscribe to a professional code of conduct in the assessment and supply of coloured lenses.

If tinted lenses are not appropriate then coloured overlays, in either A4 or A5 sizes, to place over the page of text usually offer the next best solution. Various makes are available, including IOO (Institute of Optometry) [www.ioosales.co.uk], Cerium Visual Technologies [www.ceriumvistech.co.uk] and Crossbow Education [www.crossboweducation.com]. Although these systems differ slightly, all include a representative range of around 10 colours that can be used singly or in combination, each providing in total up to about 30 different colour options. The most effective colour (or combination of colours) for reducing symptom can be determined subjectively by systematic pair-wise comparison (both IOO and Cerium produce screening sets of overlays for this purpose). The benefits of coloured overlays in reducing the symptoms of visual stress have been well demonstrated (e.g. Robinson & Foreman, 1999; Tyrell et al, 1995; Wilkins et al, 2001). The effectiveness of the chosen colour can be measured by use of Wilkins Rate of Reading Test comparing reading rate with and without the selected overlay (Wilkins et al, 1996). Over 20% of unselected children read at least 5% faster using a coloured overlay and about 5% read as much as 25% faster (Wilkins, 2003). Amongst children with reading difficulties, these figures are considerably higher; e.g. Kriss & Evans (2005) found that 45% of children with dyslexia read at least 5% faster using a coloured overlay.

When unselected children are given overlay screening, about 50% report that a colour or combination of colours improves clarity or comfort for reading, and about half of these children will continue to use their chosen colour when reading for several months (Smith & Wilkins, 2007). Recently a range of inexpensive small

overlays called ‘Reading Rulers’ has been introduced by Crossbow Education, which are 200mm wide by 60 mm high, with a black horizontal stripe across the middle to assist keeping on the line of text. These rulers are used singly and are not suitable for use in combination. Smith & Wilkins (2007) compared Reading Rulers with conventional overlays and found that children with visual stress did not show any significant increase in reading speed using Reading Rulers whereas using the conventional overlays they did. This effect was not due to the smaller size of the Reading Rulers but, rather, to the limited range of colours in the set which dramatically reduced the chances of coming close to the optimal tint for any given child. As a direct result of this research, Crossbow Education has now increased the range of colours available in Reading Rulers. However, there remain concerns about the way in which these rulers may be used in the classroom, as children are often permitted to select colours by idiosyncratic preference on a day-by-day basis rather than by systematic pair-wise comparison in a screening situation so that the teacher can ensure that the most effective colour is being used by the child. There is a real danger that children may decide that colour, *per se*, does not help their reading when they have not had a proper opportunity to determine the most effective colour.

Causes of visual stress

There are two competing theories regarding the causes of visual stress. Wilkins and colleagues maintain that visual stress is caused by pattern glare, i.e. a general over-excitation of the visual cortex due to hypersensitivity to contrast (see Evans, 2001; Wilkins, 1995, 2003). Geometric repetitive patterns (e.g. stripes), which create square-wave on-off neural signals in the visual cortex, can cause headaches in migraineurs and can trigger seizures in people with photosensitive epilepsy (Wilkins, 1995). Such patterns can also produce perceptual distortions in normal individuals as a result of neural ‘overload’ (Wilkins, 2003). Fluorescent lights, which flicker at 100 times a second, and CRT computer monitors, which often have a refresh rate of less than 70 Hz, have similar neural effects and can also trigger the same symptoms (Wilkins, 1995). Text can resemble a pattern of stripes with visually stressful characteristics, which explains why it can provoke perceptual distortions and cause headaches. Children who were helped by coloured tints were twice as likely to have

migraine in the family as control children (Maclachan et al, 1993). Wilkins (1995, 2003) suggests that because the wavelength of light is known to affect neuronal sensitivity, the use of colour could redistribute cortical hyperexcitability, thus reducing the perceptual distortions and headaches.

The second theoretical explanation attributes visual stress to a deficit in the magnocellular system (Stein, 2001; Stein & Walsh, 1997; Livingstone et al, 1991). The role of the magno system in reading provides a theoretically attractive link between dyslexia and anomalies of eye movement control (Evans et al., 1996; Stein & Talcott, 1999), and several researchers have suggested that visual stress could be encompassed within this theoretical framework (e.g. Livingstone et al, 1991). Stein (2001) argues that use of highly saturated yellow or blue filters ('Oxford filters') can compensate for a magno deficit and improve reading performance by increasing contrast and motion sensitivity. Yellow and blue are complementary colours that will cancel each other out to give white, so Stein's theory suggests that either colour is somehow capable of inhibiting magno function and thus use of the complementary colour may redress the balance. However, the efficacy of Oxford filters has yet to be widely demonstrated, and 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.

Identification of visual stress

There are three alternative approaches to the identification of visual stress: symptom questionnaire, overlay screening, and visual search, of which only the last is objective. Although symptom questionnaires (e.g. Irlen, 1991; Conlon & Hine, 2000) can often indicate susceptibility to visual stress in adults (Evans & Joseph, 2002; Singleton & Trotter, 2005), their use with children is controversial because questioning children about suspected visual perceptual symptoms can result in misleading and subjective responses (Northway, 2003). Overlay screening, although widely used, is also not without shortcomings. In the first place, overlay screening depends on the person's subjective judgment, which is not an ideal situation for a screening device. Furthermore, while colour is an effective treatment for most people with visual stress,

it does not work for all (Evans & Joseph, 2002; Singleton & Trotter, 2005), so not everyone with visual stress will be detected in an overlay screening. The use of greater than 5% increase in reading speed with an overlay as a criterion for diagnosis is limited in applicability because of interaction with reading accuracy. Children with average or above average reading accuracy often show increases of less than 5% with an overlay despite suffering from visual stress (Singleton & Henderson, 2007a). In summary, overlay screening can result in unacceptably large numbers of false positives and false negatives.

Singleton and Henderson (2007a, 2007b) have researched an objective method of screening for visual stress based on visual search. There is evidence that individuals with visual stress are impaired by visually stressful stimuli during visual search (Conlon et al, 1998; Conlon & Hine, 2000; Tyrell et al, 1995). In the task devised by Singleton and Henderson, individuals were required to locate a randomly generated three-letter word in a matrix of distractor three-letter words presented on a computer screen. The background on which the matrix is superimposed is either visually unstressful (grey) or visually stressful (alternating black/white horizontal stripes). In various studies with children from age 7 upwards and adults it was found that if there is a significant difference between search times in the visually unstressful and the visually stressful conditions, this is a strong predictor of visual stress. Using this method, called ViSS (Visual Stress Screener), to screen unselected samples of children, it was found that those classified as having high susceptibility to visual stress had significantly larger increases in reading rate with a coloured overlay compared with those classified by ViSS as having low susceptibility to visual stress (Singleton and Henderson, 2007a). Individuals classified by ViSS as having susceptibility high visual stress also reported more symptoms, although there were indications that reports of symptoms were less reliable in the younger age group.

ViSS has the advantage that it is an easy-to-deliver computerised system that is entirely objective and is not significantly influenced by reading ability. Singleton and Henderson (2007b) showed that ViSS was equally capable of identifying susceptibility to visual stress in children with dyslexia. In this study, visually stressful stimuli were found to cause significantly more disruption of visual search in the dyslexic sample than in the control sample, but on visually unstressful stimuli there

were no differences between the groups. This not only demonstrates the effectiveness of ViSS for screening for visual stress in dyslexic as well as non-dyslexic children, but also indicates that ViSS is not simply measuring other cognitive abilities, such as memory or attention, which are clearly required for visual search but which may also be deficient in dyslexia.

The relationship between visual stress and dyslexia

In the dyslexics studied by Singleton and Henderson (2007b) the incidence of high visual stress (41%) was found to be almost twice that found in the reading-age controls (23%), figures that are comparable with those reported by Kriss and Evans (2005), in which 34% of the dyslexic group and 22% of the control group met their criteria for visual stress. These results suggest that visual stress is much more common amongst people with dyslexia than amongst people who do not have dyslexia. The findings that dyslexic children showed significantly higher susceptibility to visual stress on ViSS, had significantly higher increases in reading rate with an overlay, and also reported significantly more critical symptoms of visual stress compared to reading age controls all imply a relationship of some sort between dyslexia and visual stress (see also Singleton & Trotter, 2005).

The magnocellular deficit hypothesis offers one explanation for these findings. Traditionally, the magnocellular deficit hypothesis (Stein and Walsh, 1997) and the phonological deficit hypothesis (Snowling, 2000) have been seen as competing explanations of dyslexia, although Stein (2001) has speculated about how the two might be connected. More recently, however, Pammer and Vidyasagar (2005) have attempted a more detailed integration, which starts from the assumption that the cortical network subserving reading incorporates visual, auditory, and phonological elements. The visual sub-component, which is responsible for the accurate spatial encoding of letters, words and text, may be impaired in dyslexia. These authors argue that adequate early sensory coding is intrinsic to phonological awareness and subsequent reading ability, but in dyslexics the visual system fails to provide the feedback necessary for detailed examination of a selected location in the visual field, particularly in cluttered visual scenes as in visually stressful text.

On the other hand, the link between dyslexia and visual stress may not necessarily be causal. Since visual stress discourages motivation to practice reading, this will progressively widen the gap between good and poor readers as a function of differences in reading experience (a trend called the 'Matthew effect' by Stanovich, 1986). It is likely that the dyslexic person's lack of automaticity in word recognition (caused by underlying deficits in phonology or memory, for example) necessitates them adopting a technique for processing text (e.g. detailed scrutiny of individual 'problem' words) that increases their sensitivity to the physical characteristics of the print, which, in turn, will naturally tend to exacerbate any symptoms or effects of visual stress. Susceptibility to visual stress is a characteristic that varied from person to person; the majority of the population is only mildly susceptible (but under certain conditions can nevertheless experience visual stress), while people who suffer from photosensitive epilepsy or from migraine tend to be highly susceptible. This explanation might be called 'threshold shift' because the hypothesised impact of dyslexia is to shift the threshold for visual stress, increasing the person's susceptibility, in much the same way that migraineurs, for example, tend to be more sensitive to adverse visual factors and are more likely to have high susceptibility to visual stress. On the basis of this hypothesis it would be predicted that non-dyslexic poor readers who lack automaticity in word recognition should also show increased symptoms of visual stress when reading comparable with those found in dyslexic readers. It would also be predicted that dyslexics, when compared with non-dyslexics, should <u>not</u> show increased symptoms of visual stress in situations where reading is <u>not</u> involved. The latter prediction suggests that dyslexics (unlike most persons with high susceptibility to visual stress) would not have increased sensitivity to visual flicker (e.g. from fluorescent lighting or computer monitors). These predictions have yet to be tested but, if confirmed, would be consistent with widely-reported evidence of <u>impaired</u> flicker detection in dyslexics (e.g. Buchholz & McKone, 2004; Evans, Drasdo & Richards, 1994; Floyd, Dain & Elliott, 2004; Martin & Lovegrove, 1987; Talcott et al., 1998).

Conclusions

Research on visual factors in reading points to several important conclusion of educational relevance. The physiological apparatus that conveys visual information to the brain places constraints on the cognitive processes involved in reading. The efficient organisation of the various components of the cognitive system 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 discipline eye movements, attain fluency in decoding and provide a sound basis for competent reading comprehension. Visual factors that can disrupt the reading process, either directly (such as problems of visual acuity) or indirectly (such as visual stress), will have detrimental effects on the development of fluency and comprehension. Refractive and orthoptic problems are common in childhood and thus 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 eye examination. There is also a strong case for screening for visual stress, which is a much more common problem than any other adverse visual factor. The availability of objective computer-based screening now makes this a realistic proposition and a variety of effective treatments using coloured tints are readily available. Although research on visual factors in reading has often advanced in isolation of research on linguistic factors, recent discoveries that visual stress is much more common in people with dyslexia has propagated fresh attempts to integrate visual and phonological explanations of dyslexia, which in due course may lead to a more comprehensive understanding of how we read.

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