The selective attention functioning of the magnocellular pathway is compromised in dyslexia: evidence using a visual search paradigm.

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Submitted in partial fulfilment of the requirements
of the degree of
Bachelor of Science (Honours)
in the Division of Psychology
the Australian National University

November 1999
Word Length:10,000 (to the nearest 500)

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Acknowledgments

I would like to thank my supervisors, Drs Trichur Vidyasagar and Kristen Pammer for their guidance and encouragement throughout my Honours year, and their willingness to let me do my own thing.

I would also like to thank Dr Judy Slee for her many words of wisdom, Dr Elinore McKone for being at University on weekends, and Drs Mike Smithson and Craig McGarty for clearing the cobwebs surrounding my statistical brain.

I am also very grateful for the co-operation given to me by principals, teachers, ancillary staff and students who were involved with my study.

Thankyou also must go to my fellow Honours confederates who kept me sane through this years adventure.

Finally, I would also like to thank my husband, Ralph and daughter Rebecca, for putting up with my stress attacks, finding my missing files and fixing the computer.

Abstract

There is compelling evidence for an association between the pathology of dyslexia and a magnocellular deficit, but how such a deficit contributes to the reading disabilities exhibited is not clear. In this study, the hypothesis that the attentional spotlighting function of the magnocellular (M) pathway is compromised in dyslexia was tested. Poor readers and age-matched normal readers were compared on two different types of visual search tasks; one which required the detection of a target defined by a single feature, either size or orientation, and the other where the target was defined by a conjunction of features, namely size and orientation. Even though both these features are likely to be processed by the parvocellular dominated pathway of the visual system, an intact magnocellular pathway may be necessary for providing selective attention during the search task. No significant differences were found between the two groups on the simple feature search, however the poor readers performance was significantly lower than the normal readers in the conjunction search. Also, as the number of distractor items increased, the poor readers' performance worsened significantly. It is proposed that this lower visual search performance by poor readers arises from an attentional spotlighting function deficit, thereby providing a mechanism to link the pathophysiology of dyslexia with the reading disabilities they exhibit.

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Reading well allows one to enjoy the literary accomplishments of many writers, from science fiction to politics, according to one's interests. However, being able to read is not just a pleasure, but is also necessary for effective communication in today's world. Unfortunately, there are some individuals who, for reasons which are not obvious, have a constant struggle with the written word. These people fail to learn to read with normal proficiency despite having conventional learning opportunities, culturally adequate socio-economic backgrounds, normal intelligence, motivation and visual acuity, and freedom from brain lesions. When their reading ability is ascertained as children and found to be more than 2 years behind their peers, they are classified as "developmental dyslexics" (Hynd, Semrud-Clikeman, Lorys, Novey & Eliopoulos, 1990). It has been estimated that between three and ten percent of school aged children may be so categorised (Shaywitz, Bennett, Fletcher & Escobar, 1990).

Conventionally, the explanation given for the reading problems experienced by dyslexic children has been that of a phonological deficit (Brady & Shankweiler, 1991), in which phonological representations of words are "fuzzy" or "under specified" leading to difficulties with mapping letters onto sounds. Consequently, dyslexics have difficulty with verbal short-term memory, word and non-word repetition, and rapid automatic naming (Paulesu, Frith, Snowling, Gallagher, Morton, Frackowiak & Frith, 1996).

Dyslexics also display a variety of impairments associated with visual perceptual deficits, such as reading words backwards, for example, "was" for "saw" (Galaburda & Livingstone, 1993). They also complain that words and letters move around, blur and become merged, thus illustrating the visual confusion they experience (Stein, 1991). These impairments have been taken as evidence indicating the presence of a visual system deficit in dyslexics.

Parallel pathways of the visual system

In vision, physiological, anatomical, psychophysical (reviewed in Livingstone & Hubel, 1988) and clinical (Farah, 1990) evidence indicate that information is divided among separate channels.

Segregation of visual information into three major parallel channels, magnocellular (M), parvocellular (P), and koniocellular (K), begins at the retina. Each of these channels carry different types of visual information which they convey to different layers of the lateral geniculate nucleus (LGN) of the thalamus, and then on to different regions in the primary visual (striate) cortex (for review see Calloway, 1998). The P and M channels have been extensively studied and their importance demonstrated by the finding that they include about 90% of the axons that leave the retinas (Perry, Oehler & Cowey, 1984), and that little vision survives when both are destroyed (Schiller, Logothetis & Charles, 1990a, 1990b).

The mapping of pathways beyond the LGN is not simply one to one. There has been some evidence suggesting that the parietal pathway depends largely on M channel contributions, but also includes contributions from the P channel, and that the temporal pathway receives major contributions from both channels (Merigan & Maunsell, 1993). However, while there appears to be considerable cross-talk between these channels (DeYoe & Van Essen, 1988; Felleman & Van Essen, 1991; Ferrera, Nealey & Maunsell, 1992), it has been suggested that their contributions remain largely segregated since each is dominated by a distinct pattern of connectivity radiating from the visual striate cortex (Livingstone & Hubel, 1988). A schematic representation of these parallel channels and their interconnections is shown in Figure 1.

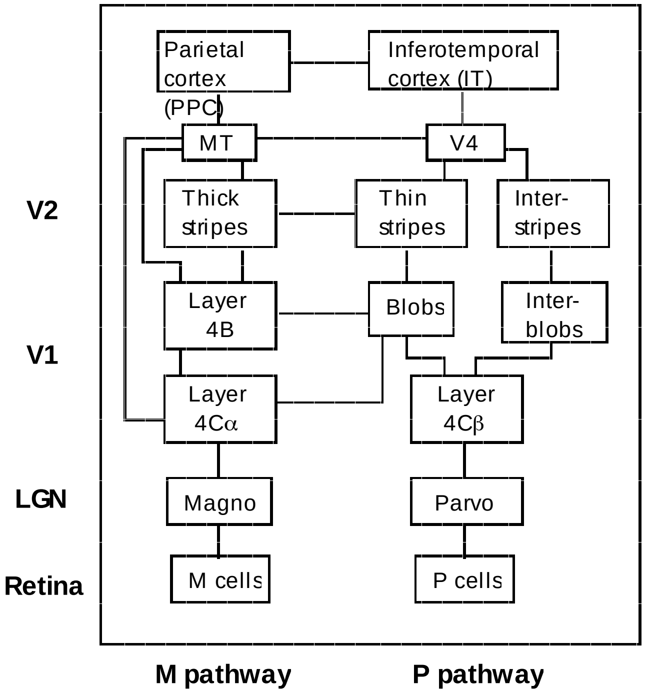

Figure 1: Parallel pathways in the primate visual system. The visual system is shown in schematic form from the retinal ganglion cells (bottom) to the higher levels of the cerebral cortex (top). The components of the magnocellular pathway have been grouped to the left; those of the parvocellular pathway have been grouped to the right. Lines show established connections between the illustrated components. As in other summaries of visual pathways, many cortical areas and connections have been omitted. Abbreviations: Magno, magnocellular layers of the LGN; MT, middle temporal area; Parvo, parvocellular layers of the LGN. (Adapted from Milner & Goodale, 1995).

Beyond the LGN, the parietal pathway, which carries largely M channel information, is highly sensitive to visual information related to space, such as movement, depth and positional changes, which are important for determining where an object is located. The temporal pathway, by comparison, carries largely P channel information which is sensitive to visual information dealing with colour, form and texture, and so is important in seeing stationary objects in detail, that is, in determining what is seen (Merigan & Maunsell, 1993; Logothetis & Sheinberg, 1996; Schiller, Logothetis & Charles, 1990a, 1990b; Ungerleider & Mishkin, 1982; Zeki, 1983). Visual detection using appropriate stimuli can thus be biased towards either the magnocellular or parvocellular pathways, allowing deficiencies to be observed.

Reading requires fine grained pattern vision, and object discrimination for which the parvocellular system would be expected to be specialised. It also requires fast and accurate processing of transient visual stimuli, for which the magnocellular pathway may be necessary. Thus one might expect to find deficits in either or both of the visual pathways of dyslexic individuals.

Research in the last 15 years has shown that both children and adults with reading disabilities perform differently from controls on a variety of visual tasks (Badcock & Lovegrove, 1981; Borsting, Ridder, Dubeck, Kelley, Matsui & Motoyama, 1996; Eden, VanMeter, Rumsey, Maisong, Woods and Zeffiro, 1996), and also demonstrate physiological and anatomical abnormalities (Livingstone, Rosen, Drislane and Galaburda, 1991) that are consistent with a deficit in only the magnocellular pathway of the visual system.

Evidence for a magnocellular pathway deficit in Dyslexia

In a neuroanatomical study, Livingstone and colleagues (1991) conducted post-mortem examinations of 5 dyslexic brains and reported a pathology of the magnocellular layers of the LGN. These layers showed disorganisation, and contained fewer cells which were more than 27% smaller and more variable in size and shape than matched controls. In contrast, no group differences were found in cell sizes of the parvocellular layers of the LGN.

Additional evidence suggesting a magnocellular-specific deficit comes from psychophysical contrast detection studies which use grating pattern stimuli manipulated in contrast and spatio-temporal frequency to preferentially activate either the M or the P pathways. In these studies dyslexics have consistently demonstrated reduced sensitivity for stimuli optimal for the M pathway, that is, having low spatial frequencies and low contrasts (Borsting et al, 1996; Chase & Jenner, 1993; Cornelissen, Richardson, Mason, Fowler & Stein, 1995; Martin & Lovegrove, 1987; Mason, Cornelissen, Fowler & Stein, 1993; Talcott, Hansen, Willis-Owen, McKinnell, Richardson & Stein, 1998). Visual persistence, that is, the temporal separation necessary to distinguish two visual stimuli represented in rapid succession, has been reported to be as much as 100 msec longer for dyslexics compared to normal readers (Lovegrove, 1993). Other psychophysical studies have reported that backward masking (Breitmeyer & Williams, 1990) and temporal judgments are also atypical in dyslexics (Chase & Jenner, 1993), reflecting a possible deficit of the magnocellular pathway. Two reviews (Breitmeyer, 1993; Lovegrove, 1993) of the large number of publications in this field support the validity of these findings. However, it is important to note that there are some studies which have failed to demonstrate psychophysical deficits (Gross-Glenn, Skottun, Glenn, Kusch, Lingua, Dunbar, Jallad, Lubs, Levin, Rabin, Parke & Duara, 1995; Lovegrove, 1993; Skottun, 1997).

Another line of evidence for the involvement of the magnocellular pathway in visual deficits exhibited by dyslexics can be found in lesion studies using macaque monkeys. The macaque's brain is thought to be sufficiently closely related to the human brain to justify applying anatomical and electrophysiological data from that species to human vision. These M-pathway lesioned monkeys have been shown to be impaired in psychophysical tests (Merigan & Maunsell, 1990) similar to those in which dyslexics perform poorly.

There is also evidence for a specific magnocellular deficit provided by physiological studies, which have examined visual cortical evoked potential (VEP) recordings in response to flickering binocularly presented black and white checkerboard patterns, at low and high contrasts and at varying spatial and temporal frequencies. Dyslexics showed abnormal VEPs for stimuli with low spatial and high temporal frequencies, being reduced or delayed by as much as 50 msec after visual stimulation. This is indicative of a deficit being present at an early stage in the M-pathway (Kubova, Kuba, Peregrin & Novakova, 1996; Livingstone et al, 1991; Maddock, Richardson & Stein, 1993; May, Lovegrove, Martin & Nelson, 1991). Another report (Lehmkuhle, Garzia, Turner, Hash & Baro, 1993) compared steady background and uniform flicker, and concluded that the magnocellular pathway response is slower in dyslexic children. A recent study using functional magnetic resonance imaging (fMRI) has demonstrated the presence of a deficit at a later stage of the M pathway. When presented with moving stimuli, normal V5/MT (a cortical component of the M-pathway) functional activity was not produced in dyslexics. However, presentation of stationary patterns produced activations of V1, V2 and ventral extrastriate cortex (cortical components of the P-pathway) which were normal (Eden et al, 1996).

The evidence for an association between the pathology of dyslexia and a magnocellular deficit is compelling, but the question of how such a deficit could contribute to the reading disabilities exhibited by dyslexics remains unanswered.

The possible effects of a magnocellular deficit on Dyslexia

Parvocellular suppression

Reading involves rapid eye movements (saccades) from one fixation point, lasting up to several hundred milliseconds, to another. During each fixation the parvocellular system is likely to be necessary for performing fine grained pattern (high spatial frequencies) recognition and object discrimination within the foveal area of vision (6 - 8 letters that subtend approximately two degrees of visual angle).

Breitmeyer (1993), suggested that the role of the magnocellular pathway in reading was one of suppression during eye movements. Given that the M system is vigorously activated by eye movements, he proposed that parvocellular activity generated as a consequence of fixation became suppressed by the M system during the saccades between fixations. In effect, this would help in temporally segregating the information gathered at each fixation. Accordingly, a magnocellular deficit would then be expected to result in image blurring, as fixations became indistinct, as reported by dyslexics. However, Burr, Morrone and Ross (1994) examined suppression associated with saccades and found that it was only selective for the M system and did not target the parvocellular system. Vidyasagar (1999) has pointed out that this experiment effectively refutes Breitmeyer’s theory.

The M-pathway impairments found in dyslexics are generally mild and have often been demonstrated under conditions not found in normal reading such as, very low contrasts, low light levels and unusual motion conditions. Stein & Walsh (1997), suggest that the visual perceptual deficits associated with dyslexia may be attributed to higher level processing impairments, resulting from low level magnocellular deficits. That is, the effects of small impairments may become magnified as a result of magnocellular connections from the LGN to the posterior parietal cortex (PPC), thereby producing difficulties in reading.

It has been demonstrated that while both magnocellular and parvocellular processing occurs in the cortex (Schiller, 1996), the PPC shows properties which are M-like, such as sensitivity to direction of motion, and relative colour and form insensitivity (Motter & Mountcastle, 1981). The PPC may have an important role in reading since it has been shown to be important in normal eye movement control and visuo-spatial attention (Kandel, Schwartz & Jessell, 1995, pp. 396).

Eye movement control

The relationship between impaired control of eye movements (that is, poor binocular control) and a magnocellular deficit has been extensively investigated. Eye fixation in dyslexics has been shown to be unsteady when attempting to view small letters and their pursuit eye movements have been shown to be less smooth then normals (Eden, Stein, Wood & Wood, 1994; Griffen, Christenson, Wesson and Erickson, 1998; Stein, Riddell & Fowler, 1988). One might expect that this unstable vision would lead to visual confusion and thus reading errors. Indeed, many of these dyslexics complain about letters and words moving around, merging and crossing over (Cornelissen, Bradley, Fowler and Stein, 1991).

While this fundamental observation of poor eye movement control is generally agreed upon, there are two opposing views as to the causal relation between eye movements and dyslexia. Some researchers and therapists have argued that abnormal eye movements cause reading difficulties (Fowler, Riddell & Stein, 1990; Pavlidis, 1989; Rayner, 1989). Others argue that the more frequent eye fixations and regressions in dyslexic readers are caused by their language-based word-decoding problems. This latter view has been strongly supported by several studies of dyslexic and normal readers’ eye movements in both reading and non-reading tasks (Aman & Singh, 1983; Olson, Conners & Rack, 1991; Stanovich, 1986). In fact, it seems unlikely, given the frequent co-existence of Ôvisual’ problems with language and sequencing deficits, that defective eye movements would be the sole cause of dyslexia. It may well be that there exists a central neurological defect which causes both dyslexia and erratic eye movements.

Visuo-spatial attention

Reading is a learned skill and such skills learning does not occur without prior focusing of attention and appropriate motivation. It involves not simply identifying and focusing on stimuli, but identifying appropriate stimuli on which to focus and, in addition, sometimes integrating two or more stimuli. Controlled shifts of attention to different locations in space are necessary for the selective attention of a word or sentence.

The evidence for an involvement of the M pathway in visuo-spatial attentional processes is extensive. In particular, electrophysiological investigations in macaques have found significant attentional modulation in the activity of neurones in V4, PPC, MT as well as IT (Luck, Chelazzi, Hillyard & Desimone, 1997; Motter, 1993; Steinmetz & Constantinidis, 1995; Treue & Maunsell, 1996). In humans, lesions of the PPC commonly affect the ability to attend to contralateral objects (Stein & Walsh, 1997). Finally, positron emission tomography (PET) studies have indicated that regions of the superior parietal cortex are activated when people shift attention to different regions of the visual field (Corbetta, Schulman, Miezin & Petersen, 1995; Nobre, Sebestyen, Gitelma, Mesulam, Frackowiack & Frith, 1997).

Given the above findings, it is hardly surprising that dyslexics have shown impairment on a number of attention tasks such as perceptual grouping, spatial cuing and inhibition of stimuli which are not the focus of attention (Brannan & Williams, 1987; Ruddock, 1991; Valdois, Gerard, Vanault & Dugas, 1995). However, attention to a particular stimulus may arise from suppression of competing stimuli, or a selective shift in attention to the stimulus site. Recent evidence supports a role for the M-pathway in selective attention.

The M-pathway and selective attention

Visual discrimination tasks often require attention to be directed to a particular object presented simultaneously with several competing objects in the visual field. Electrophysiological studies, using macaques and involving such a task, have shown significant attentional modulation, selectively influencing neuronal responses in the attended visual field location in the primary visual cortex (Motter, 1993; Vidyasagar, 1998). Suppression of these responses was reported when attention was directed elsewhere in the visual field. This effect was pronounced when there were a large number of competing items.

Evidence from functional magnetic resonance imaging (fMRI) in humans (Brefczynski & DeYoe, 1999; Kastner, DeWeerd, Desimone & Ungerleider, 1998; Martinez, Anllo-Ventro, Sereno, Frank, Buxton, Dubowitz, Wong, Hinrichs, Heinze, and Hillyard, 1999) have also supported early selection in attention. When multiple stimuli were presented simultaneously in the visual field, in the absence of directed attention, their cortical representations within the object recognition pathway indicated suppressive interaction. Spatially directed attention reduced these interactions. Based on these findings, and those of previous electrophysiological studies already mentioned, Vidyasagar (1999) proposed that the feedback associated with selective attention may be mediated by a mechanism dominated by magnocellular inputs, arising in the PPC to focus attention. According to this model, selective attention may occur through the exploitation of the dichotomy of the visual pathways by the visual system.

Since the M-pathway is responsible for fast transmission and spatial coding, it is ideal as a feedback mechanism to an earlier stage of processing. Specifically, through facilitating selective shifts in attention to regions of interest before further processing by the slower P-pathway, particularly when there are several competing objects in close proximity. In most situations requiring a search of the visual field this process of directing attention would be expected to be random so as not to tax the visual system while maintaining visual sensitivity. This strategy would reduce the need to remember already visited locations and maintain visual sensitivity to changes that could occur in the visual field. A recent experiment (Horowitz & Wolfe, 1998) in which it was demonstrated that memory of inspected locations did not occur in visual search has supported this notion. However learning to read may be a special case where training of the attentional spotlight mechanism to move sequentially and systematically over the words in a line may be necessary (Vidyasagar, 1999). Therefore, it would be expected that deficits in this mechanism would become obvious during reading tasks, but could also be shown in other activities requiring visual search.

Visual Search and attentional processes

In a typical visual search experiment, observers are presented with a display containing a number of items. They are required to indicate, as rapidly as possible while avoiding errors, whether a prespecified stimulus, called the target, is present or not, among an array of other stimuli, called distractors, whose number is variable. Experimenters measure the reaction time to make a response and also note the accuracy of that response. Changes in accuracy and reaction time (RT) as a function of set size constitute the preferred measure of search performance.

The search paradigm is valuable because performance on these tasks vary in a systematic way with the nature of the search stimuli. When the target differs from distractors by a unique feature (e.g. red target, green distractor), it has been repeatedly demonstrated that the time required by normal individuals to detect the presence of a target is independent of the number of stimuli that are presented (Nakayama & Silverman, 1986; Treisman & Gelade, 1980). According to Treisman and her colleagues, these observations indicate that detection of a feature target is performed by a spatially parallel process which preattentively processes visually distinctive features and does not involve the selection of individual stimuli by visuo-spatial attention.

Conversely, to distinguish conjunction targets from distractors, combinations of features constituting the items need to be considered. For example, in a typical conjunction search if the target is a red horizontal bar, one set of distractors consists of red vertical bars and another of green horizontal bars. In this way the target cannot be distinguished from the distractors by a single unique feature, since it shares colour with some and orientation with others. Results of normal participants in such a conjunction task have shown linearly increasing RTs with an increasing number of stimuli displayed The rate of such a visual search is usually reported at about 20 - 30 msec per item (Horowitz & Wolfe, 1998; Pashler, 1987; Treisman & Gelade, 1980; Treisman & Sato, 1990). This result is considered as indicative of a search requiring sequential examination of each item. To correctly perceive a conjunction of features, visuo-spatial attention needs to be focused at the particular location of the stimulus. However, it has been reported that visual search for some conjunctions of features can be performed with RTs which are more consistent with a parallel search (Arguin & Cavanagh, 1990; Sagi, 1988; Treisman & Sato, 1990; for review see Wolfe, 1998). However, these findings are consistent with the model of attention proposed by Vidyasagar (1999). As he points out, if one of the features constituting the conjunction could be processed by the magnocellular pathway, such as movement, then target identification would not require serial search since the locations of interest to this pathway would become highlighted. This would allow the other unique feature to be identified by the parvocellular pathway in parallel. The selective attention functioning of the magnocellular pathway would be required when both features of the target required processing primarily by the parvocellular system, resulting in serial searches.

Two recent studies have supported the role of the magnocellular pathway in conjunction searches. Friedman-Hill, Robertson and Treisman (1995) examined the ability of a patient with bilateral lesions of the parietal cortex to correctly perceive features and conjunctions. They found this patient to be greatly deficient on the conjunction task and concluded that spatial information associated with the magnocellular pathway is necessary for the combining of features. Ashbridge, Walsh and Cowey (1997) applied transcranial magnetic stimulation (TMS) over the parietal visual cortex of participants as they performed parallel and conjunction searches. They found that only RTs for conjunction searches were detrimentally affected by stimulation given 100 msec after the onset of the visual display. This finding is consistent with the hypothesis that parietal areas generate a signal that projects back to extrastriate visual areas to enhance the processing of features in a restricted visual field.

According to Vidyasagar’s model (Vidyasagar, 1999) the following factors would determine the time taken for visual search: the extent to which the defining features of the target may be processed by the magnocellular pathway, with more processing leading to faster searches; the amount of crowding of items in the visual field, with more crowding requiring feedback by the attentional spotlight to an earlier level of processing (for example V1) thereby increasing the time of the search; the number of distractors present when conjunction of features requires parvocellular identification, with more distractors requiring increased use of the magnocellular attentional spotlight function and thus increase search time. In this way pure magnocellular deficits would be responsible for poorer performance of P-pathway mediated functions in situations where there are many competing stimuli, with differing defining features requiring attentional selection, such as in reading. One might therefore expect that if the attentional spotlight is compromised in dyslexia, then deficits would be evident when an appropriate visual search paradigm is used.

Visual Search and Dyslexics

There have only been a few studies which have examined visual search in dyslexia (Casco & Prunetti, 1996; Curley & Ginard, 1990; Ruddock, 1991; Vidyasagar & Pammer, 1999). In Curley and Ginard's study, participants were required to match, as quickly as possible, a centrally located design to an identical image among a checkerboard array. The results of their study showed dyslexics to be slower than normal readers, but did not address the question of differing search types or array sizes. In his study, Ruddock examined the performance in visual search of acquired dyslexics (those who had had brain trauma) and showed that this was stimulus dependent. Search involving a single feature such as orientation involved parallel processing, the same as for normal readers. However, complex stimuli which could be processed in parallel by normal readers tended to be processed serially by the dyslexics. This study did not, however, address the question of serial search when a conjunction of features is involved.

In an attempt to determine the basis for the lower performance of disabled readers on search tasks with complex stimuli, Casco and Prunetti (1996) assessed the type of strategies used by normal and dyslexic readers on classical visual search tasks. They also examined the performance of these two groups when stimuli were letters or complex geometrical shapes defined by groups of features. They found no differences in reaction times between the two groups in search for simple features (colour or orientation) and conjunction of features (colour and orientation, or shape and orientation), and concluded that the strategies used by dyslexics were not impaired.

However, poor readers were shown to experience difficulties compared to normal readers with stimuli like letters and geometrical shapes which required the integration of features by a single pathway of the visual system.

Vidyasagar and Pammer (1999), also examined the performance of dyslexics and normal readers on a classical visual search task, looking for a unique conjunction of two features (form and colour) among a number of distractors. In comparison to Casco and Prunetti’s result, they found a significant difference between the reaction times of good and poor readers when the number of distractors increased. This suggested to them that visual search mechanisms in the poor readers were compromised when the visual scene was cluttered. While encouraging, these results are by no means conclusive as there are other possible explanations for their occurrence.

The Alternative explanations

Since Vidyasagar and Pammer presented the same search task across 2 blocks at a time, there may have some priming effect occurring, which differentially affected the two reading groups. That is, some small beneficial residue of a previous trial of the same colour and form may have accumulated, resulting in subsequent trials of the same colour and form being slightly faster for good readers rather than for dyslexics. Priming has been shown to occur in parallel searches where trials of a single feature are presented in several blocks (Nakayama & Joseph, 1998).

Another explanation may be that participants in Casco and Prunetti’s study completed fewer trials than those in Vidyasagar and Pammer’s. Thus, the assessment of the dyslexic group in the latter study may have been confounded by performance factors, such as fatigue, boredom and distractibility, eye movement control or even perhaps in the timing of motor responses.

Still further, the reaction time measures, as used in the aforementioned studies, could contain components related to a number of factors, for example, voluntary attention, motor responses, decision processes and stimulus driven attention. Thus, deficiencies in any, or all of these factors in dyslexics would result in the observed poorer latencies compared to normals.

The use of isoluminant displays also poses a problem. Firstly, it cannot be assumed that isoluminance results in removing only magnocellular form analysis, since it has been demonstrated that all parvocellular neuronal activity is somewhat reduced under these conditions. Also, only some magnocellular neurons are completely silent for any particular isoluminant stimulus, while the rest remain active (for review see Kaplan et al., 1990). Thus, the observed deficits in performance by the dyslexics may relate to parvocellular functioning, and not the hypothesized magnocellular spotlight function. Additionally, it is very difficult to ensure isoluminance for each participant, due to individual differences, so magnocellular processing may have occurred to varying degrees between the two reading groups.

Finally, it may be that the combined effects of the previously mentioned factors produce the different reaction time responses observed in dyslexics.

The purpose of the preceding discussion was to illustrate the problem of inferring properties of central mechanisms when peripheral mechanisms could also operate. Therefore, it is clearly advantageous to preclude such factors when addressing the role of putative central processes in feature and conjunction searches.

In this study, a visual search paradigm was developed to overcome these confounding factors, allowing the attentional spotlighting function to be examined and compared in dyslexic and normal readers. The hypothesis that the attentional spotlighting function of the magnocellular (M) pathway is compromised in dyslexia was tested.

The visual search paradigm for this study

Poor and age matched normal readers were tested on their abilities to perform a feature search task in which a single feature (orientation) required detection, both before and after the completion of a conjunction search (size and orientation). This allowed performance factors to be examined. To overcome any priming effects, two different targets were randomly presented from trial to trial. In order to determine whether poor readers and normal readers would perform similarly when the attentional demands of the visual search task was low, their performances on two feature search tasks (orientation or size) were compared.

Since reaction time measures could be associated with various factors, an alternative visual search paradigm was employed in this study. Each stimulus set was presented for a total time dependent on the number of items, such that time per item was 30 msec (that is, at normal visual search rates as previously discussed). These short display times should result in stimulus driven attentional processes, that is, a need for an attentional spotlight when the target is present. Participants responses were verbal, either “Yes” for target present, or “No” for target absent, and these were recorded by the experimenter. The accuracy of these responses was assessed. Available studies of visual search accuracy of normal readers, when the time of displays was held constant, have shown modest effects of increasing the number of items in the stimulus set (set size) for simple stimuli (Bergen & Julesz, 1983; Poirson & Wandell, 1990). These effects are modelled as being directly related to the qualitative limits of processing, such as attentional phenomena (Palmer, Ames & Lindsey, 1993). Thus, by allowing search to occur at a normal rate, any set size effects on accuracy should relate directly to deficits in attentional mechanisms.

The effects of eye movements and peripheral vision were kept to a minimum by presenting stimuli foveally (approximately 3.2¡ by 2.2¡ visual angle), and having a maximum of 11 items presented in any stimulus set, thus ensuring that the maximum time of presentation was 330 msec.

Predictions

It was predicted that no differences in performance between poor and normal readers would be found for the searches involving a single feature (orientation or size), and that performance by the two groups would not decline between feature search blocks. However, when the search involves selective shifts in attention, as in a conjunction search (size and orientation), then poor readers would be expected to do worse with an increasing number of items in the visual field.

Method

PART I

Pilot trials

Four normal readers, as determined by class teachers, in grade 5 at a local government school in Canberra were selected as participants in the pilot trials of the procedure. Results of these trials allowed any ambiguities in the procedure to be detected and removed, ensuring that in the experiment clear instructions could be given. They also indicated that the procedure could be completed by children without resulting in ceiling (too easy) or floor (too hard) effects.

Participants

Thirty-eight primary school children selected from two local government schools in Canberra initially participated in this study. These children were selected on the basis of teacher recommendation, such that there were equal numbers of poor readers and normal readers, matched as closely as possible in terms of gender and age.

The sample of normal readers (control group) demonstrating average reading ability and cognitive development (IQ), consisted of 5 females and 7 males with an average age of 10 years 10 months, and a range from 10 years 2 months to 11 years 10 months.

Poor readers (dyslexic group) were classified based on a reading lag of 2 or more years, with cognitive development (IQ) within the normal range, and no contributing social, cognitive or somatic disturbances, as determined through consultation with specialist teachers. This resulted in a sample consisting of 7 females and 7 males, with an average age of 11 years, and a range from 10 years 3 months to 12 years.

These 26 participants all showed normal stereoscopic vision as determined using a Wheatstone stereoscope with classical stereo half-images, and had normal or corrected to normal visual acuity.

Eight children did not fit into either group, five being below normal in cognitive development, and three having a reading lag between 1.5 and 2 years, and were excluded from analysis. The results of a further four children were eliminated from analysis, three due to impaired vision and one because of parental reporting of ADHD.

The results for some children were removed from the data set for reasons specified at the appropriate section in the results.

Materials and Design

Reading ability was assessed for each child using the Accuracy subtest of the Neale Analysis of Reading Ability - Revised (NARA-R: Neale, 1988), either from direct testing, or by school testing within the previous 12 months. This subtest measures how accurately a child identifies words in seven increasingly difficult reading passages when read aloud. Accuracy raw scores are calculated by summing the raw scores of all the passages that were read prior to the passage in which the reader made the maximum number of allowed errors (20). These scores are then converted to reading age. Reading lag is determined by subtracting the reading age from the chronological age of the reader. General cognitive performance (IQ) was determined using Ravens Standard Progressive Matrices for children not previously assessed on this measure. Scores above the 25th percentile ranking (as determined in the Ravens Guide) were taken as indicative of normal ability. Children previously tested by the schools using the WISC-R were considered of normal ability when their verbal and performance scores were both greater than 85.

Displays were generated using a 386-IBM-PC on a standard computer monitor, with a refresh rate of 17.8 msec. Stimuli consisted of small (1.5 x 3 mm) and large (3 x 6 mm) rectangles which were organised into 5 blocks of trials. Each block of trials consisted of 48 trials, giving 240 trials in total.

In all blocks the targets consisted of small horizontal rectangles on 50% of the trials and small vertical rectangles on the other 50% of trials. In the first and last blocks, distractor items differed from the target in orientation only. This constituted the feature search conditions of the experimental procedure.

In the middle three blocks the distractors consisted of small rectangles of different orientation to the target, and large rectangles of the same orientation as the target. This constituted the conjunction search condition of the procedure, since distractors only differed on one feature of the target - size or orientation.

At the completion of each block an encouraging message was presented on the computer screen as follows:-

****
"Take a break, you are doing very well"
****

This was included as a means of maintaining the participant's confidence. The experiment finished on a positive note with the following message:-

****
"Congratulations, that is the end of the experiment!"
****

The stimulus array consisted of a set of items arranged within a constant stimulus area (approximately 3.2¡ by 2.2¡ visual angle), centrally positioned on the computer screen, with items being white against a black background. Within this area the number of items (set size) varied across 3 levels (5, 7, 11) and were positioned at randomly chosen locations on an invisible grid consisting of 24 locations in a 4 X 6 array. The target could be positioned randomly at any location within the grid and appeared in the stimulus array randomly on 50% of the trials. When it was not present a small rectangle of opposite orientation was substituted to maintain the number of items at each level.

A single trial consisted of the target being presented for 1000 msec followed, after a delay of 500 msec, by the stimulus array. The time of this delay minimised the likelihood of retinal visual persistence of the target being a contributing factor to responses. Each stimulus array remained on the screen such that the time per item remained constant at 30 msec/item. These short stimulus display times also reduced the effects of eye movements. After a delay of 100 msec a mask, consisting of a random line pattern, was presented for 75 msec. By using a mask to visually integrate with the stimulus, processing could be terminated. The design of a single trial is illustrated in Figure 2a, for feature searches and Figure 2b, for conjunction searches.

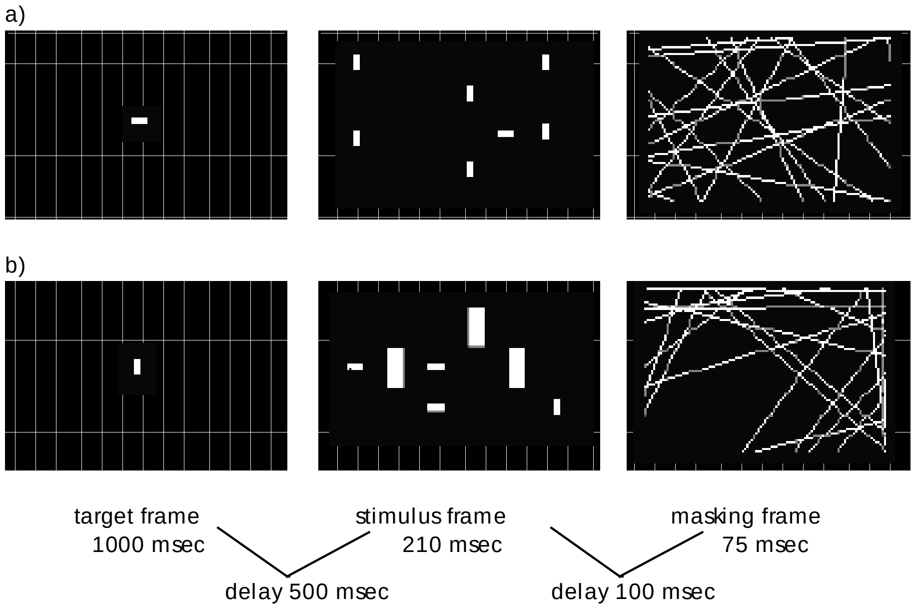

Figure 2: Examples of a single target present (among seven items) trial in a) a feature and b) a conjunction search from the experiment. Target frames were followed by a stimulus frame (presented at 30 msec/item) which were followed by a * masking frame (to scale).

Procedure

In both the experimental and diagnostic procedures, participants were tested individually in a separate room. The experimental procedure was completed first with participants seated 80 cm from the computer monitor and the windows in the room were covered to control for natural light variations. All participants completed the experimental procedure before being tested individually regarding their reading ability and general academic performance.

Prior to testing, participants were given a brief description of what to expect in terms of stimuli and procedures. The total testing time for the experimental procedure was approximately 1/2 hour and participants were informed that they could take a break at any time. At the end of each block, participants were given a 3 minute break regardless of whether any other breaks had been taken within the block.

In the first and last blocks, each participant completed a simple feature search, looking for a small rectangle, of either horizontal or vertical orientation, in a background of small rectangles of different orientation. This was to firstly, allow participants to be familiarised with the task, secondly, to ensure that both groups could undertake such a task, and thirdly to determine if completion of the conjunction search blocks had any deleterious effects on the ability of either group to perform a simpler search task. The conjunction search was completed as three blocks between the two feature search blocks.

In all trials, participants were required to respond verbally with “yes” if the target was present or “no” if it was absent, and the experimenter entered their responses. The experimenter was positioned such that she was unable to see the computer monitor. A new trial did not begin until after the participant had responded.

All procedures conformed to the Declaration of Helsinki on human experimentation and were completed with the approval of the institutional Human Experimentation Ethics committee.

Results

Separate analyses were conducted for each visual search condition, on group averages of accuracy (percentage correct) scores using SPSS (Statistical Package for the Social Sciences). One participant’s results (poor reader) were not included in analyses as they had scores which fell more than 3 standard deviations outside the means for their group, in both search conditions, and was thus considered an outlier.

It should be noted at this point that, even though participants were asked to respond with a verbal “yes” or “no”, some, particularly the poor readers, answered with “don’t know”, and “probably not”. These responses were collectively recorded as “no” responses, and as a consequence target absent search data were not true accuracy measures so were analyzed separately from target present search data. Care should also be taken when interpreting such data.

Feature search

The results of three participants (two poor readers and one normal reader) were removed from analysis due to a misinterpretation of instructions. One participant's results from the poor reading group was removed from this analysis due to their falling more than 3 standard deviations outside the mean for that group, and therefore was considered an outlier. Eleven participants remained in each group for analysis. The means and standard errors of accuracy score for the feature search conditions are presented in Figure 3.

It appears from this figure, that there were little differences between the two groups, with normal readers performance being slightly better than that of the poor reader. Overall performance by both groups seems to be better in the target absent condition, after completion of the conjunction search task. It also appears that a ceiling level of accuracy responses may have been attained by the normal readers in this condition.

Analyses consisted of two separate 2 x 3 repeated measures analysis of variance (ANOVA), one for target present and one for target absent data. Each ANOVA had two within group factors; Time with 2 levels (before or after the conjunction search) and Set Size with 3 levels (5, 7, or 11 items in the stimulus array). The single between group factor was Condition of 2 levels (poor or normal readers).

*

Target present condition

There were no breaches in ANOVA assumptions for this condition.

There were no main effects for Condition (F(1,20) = 2.572, p > 0.10), Time (F(1,20) = 2.572, p > 0.10), or Set Size (F(2,19) = 2.068, p > 0.15). There were no significant two-way interactions between Time and Condition (F(1,20) = 0.333, p > 0.55), Set Size and Condition (F(2,19) = 2.251, p > 0.10) and Time and Set Size

($F(2,19) = 0.024$, $p > 0.95$). There was no significant three-way interaction between Time, Set Size and Condition ($F(2,19) = 0.484$, $p > 0.60$).

As predicted, these results indicate that for the feature search when the target was present there were no differences in performance between the two reading groups. There was no effect of increasing the number of distractors on accuracy scores and performance on this task did not decline between the feature search blocks.

<u>Target Absent</u>

Violations of the homogeneity of variance assumption were detected for all levels of Set Size, in the after conjunction search conditions using Levene’s test (5 items, $F(1,20) = 8.125$, $p = 0.01$; 7 items, $F(1,20) = 16.744$, $p < 0.01$; 11 items, $F(1,20) = 10.469$, $p < 0.01$). These violations were indicative of the greater variation in responses by the poor readers, possibly reflecting their greater uncertainty, in these conditions than the normal readers. Given this finding a more stringent significance level $a = 0.025$ was adopted. Also since the target absent scores were calculated on the basis of a number of different responses, they were not considered crucial to testing the hypothesis of this study.

There were main effects for Condition ($F(1,20) = 14.944$, $p < 0.01$) and Time ($F(1,20) = 6.735$, $p < 0.025$) but no main effect of Set Size ($F(2,19) = 3.866$, $p > 0.035$). There were no significant two-way interactions between Time and Condition ($F(1,20) = 0.677$, $p > 0.40$), Set Size and Condition ($F(2,19) = 1.420$, $p > 0.25$) and Time and Set Size ($F(2,19) = 1.359$, $p > 0.25$). There was no significant three-way interaction between Time, Set Size and Condition ($F(2,19) = 1.107$, $p > 0.35$).

These results indicate a general improvement in accuracy for the feature search task when the target was absent, between before completion ($M = 83.14\%$, s.d. $= 12.16$), and after completion ($M = 90{,}91\%$, s.d. $= 11.11$) of the conjunction search task. Also, the performance of the poor readers ($M = 81.06\%$, s.d. $= 8.25$) was generally lower than that of the normal readers ($M = 92.99\%$, s.d. $= 6.06$), perhaps indicating their general uncertainty in this task. There was no effect of increasing the number of distractors on accuracy scores. Again these results are consistent with predictions.

Conjunction Search

Since the three participants who had misinterpreted the first part of the feature search showed results for the second part consistent with their group membership, their results for the conjunction search were included in the analysis. The results of thirteen poor readers and twelve normal readers were analysed. The means and standard errors of accuracy score for the conjunction search condition are presented in Figure 4.

It appears from this figure that the poor readers performance was generally lower than that of the normal readers. It also appears that the number of distractors only affects the poor readers performance in the target present condition. An interesting observation is that the performance of the normal readers is lower for the target absent condition than the target present condition, while that of the poor readers is reversed. This may simply be a consequence of the scoring system for negative responses.

Analyses consisted of two separate repeated measures ANOVAs performed for target present and target absent data. Each analysis had a single within group factor; Set Size with 3 levels (5, 7, or 11 items in the stimulus array). The single between group factor was Condition of 2 levels (poor and normal readers).

*

Conjunction search data satisfied the assumptions of ANOVA.

Target present

There were main effects for Condition ($F(1,23) = 37.826$, $p < 0.001$) and Set Size ($F(2,22) = 8.350$, $p < 0.01$). There was a significant two-way interaction between Set Size and Condition ($F(2,22) = 3.791$, $p < 0.05$).

These results indicate that the overall performance of the poor readers ($M = 61.43\%$, s.d. = 8.75) was generally lower than that of the normal readers ($M = 84.49\%$, s.d. = 8.45).

The effect of Set Size for each group was examined using repeated measures ANOVA. These revealed that there was a significant effect for the poor readers ($F(2,11) = 9.575$, $p < 0.005$), but not for the normal readers ($F(2,10) = 0.731$, $p > 0.50$). Follow-up within subject contrasts of Set Size were carried out for the poor readers and found to be significantly linear ($F(1,12) = 20.847$, $p = 0.001$) These results indicate that performance declines for poor readers when there are more items in the stimulus set as predicted.

Target Absent

There was a main effect for Condition ($F(1,23) = 6.215$, $p < 0.05$) but not for Set Size ($F(2,22) = 2.016$, $p > 0.15$). There was no significant two-way interaction between Set Size and Condition ($F(2,22) = 0.047$, $p > 0.95$).

These results indicate that the overall performance of the poor readers ($M = 72.01\%$, s.d. = 8.15) was generally lower than that of the normal readers ($M = 80.44\%$, s.d. = 7.25).

The results of this experiment indicate that the poor reading group perform significantly worse than normal readers on the conjunction search task, regardless of whether the target is present or absent. This performance declines further when the target is present among a larger number of distractors.

A further feature search (size) experiment was conducted to determine if these results might be explained by poor readers having difficulty in processing information with respect to size alone.

Method

PART II

Participants

The children who had completed the conjunction search tasks participated in this experiment. One child (normal reader) was not available, leaving thirteen poor readers and eleven normal readers as participants.

Materials and Design

Materials were the same as described in Part I. A feature search consisting of a single block of trials (N = 48) in which distractor items differed from the target in size only was performed by each participant. A single target present trial is illustrated in Figure 5.

*

Procedure

Participants were given a brief description of what to expect. They were seated 80 cm from the computer monitor and natural light conditions were controlled by covering the windows. The testing time for this block of trials was approximately 5 minutes.

Each feature search trial required the participant to verbally respond to the presence “Yes” or absence “No” of the target, a small rectangle, in a background of distractors, large rectangles of the same orientation. The experimenter was unable to see the computer monitor and entered the responses. A new trial did not begin until after the participant had responded.

Results

The means and standard errors of group accuracy scores for the feature search conditions are presented in Figure 6.

*

Figure 6 : Mean percentage correct for normal and poor reading groups on the feature search task (size), when the target was (A) present and (B) absent. No significant differences were found between the two groups. Vertical lines represent s.e.m.

It appears from this figure, that there was little difference between the two groups with accuracy responses being close to the maximum possible (100%), regardless of whether the target was present or absent.

Analyses consisted of two separate repeated measures ANOVAs, one for target present and one for target absent data. Each had a single within group factor; Set Size with 3 levels (5, 7, or 11 items in the stimulus array). The single between group factor was Condition of 2 levels (poor or normal readers). There were no breaches in ANOVA assumptions for either condition.

Target present condition

There were no main effects for Condition ($F(1,22) = 0.008$, $p > 0.90$) or Set Size ($F(2,21) = 1.607$, $p > 0.20$). There was no significant two-way interactions between Set Size and Condition ($F(2,21) = 0.392$, $p > 0.65$).

Target absent condition

There were no main effects for Condition ($F(1,22) = 0.177$, $p > 0.65$) or Set Size ($F(2,21) = 0.084$, $p > 0.90$). There was no significant two-way interactions between Set Size and Condition ($F(2,21) = 0.084$, $p > 0.90$).

As predicted, these results indicate that for feature searches there are no differences in performance between the two reading groups, and performance is independent of the number of distractors in the stimulus array.

Taken together, the results of this study are consistent with predictions. Poor readers are as competent as normal readers in detecting simple features such as orientation and size, but are worse at searches involving a conjunction of features.

Their performance declines further when the target is present and the number of distractors increases.

Discussion

In this study, two groups of children (poor readers and normal readers) were compared with respect to their ability to perform visual search tasks. Consistent with predictions, poor readers were found to be as competent as normal readers in detecting targets based on simple features (size or orientation), but were deficient when targets were defined by a conjunction of features (size and orientation). Furthermore, their performance on this conjunction search was shown to decline as the number of items in the visual field increased. These results indicate that the preattentive processes involved in a feature search of size or orientation are not deficient in poor readers, while those mechanisms involved in processing a conjunction of features is compromised. The visual search paradigm used in this study was designed such that the effect of set size could be directly related to the visuo-spatial attentional demands of the task. Therefore, since set size showed no effect on the performance of normal readers, it may be deduced that the functioning of their visuo-spatial attentional mechanisms was able to accommodate the increasing number of items in their visual field. However, the performance of poor readers demonstrated set size effects and thus deficiencies in their visuo-spatial attentional mechanisms.

Given that the magnocellular pathway has been attributed a spotlighting function in focusing spatial attention (Vidyasagar, 1998, 1999), and deficits of this pathway have been shown to exist in dyslexics (Breitmeyer, 1993; Lovegrove, 1993), the results of this study have supported the hypothesis that the attentional spotlighting function of the magnocellular pathway is compromised in dyslexia.

Comparison with previous visual search studies involving poor readers

Performance of the poor readers on the feature search tasks used in this study is consistent with previous findings (Casco & Prunetti, 1996; Curley & Ginard, 1990;

Ruddock, 1991; Vidyasagar & Pammer, 1999). However, unlike Vidyasagar and Pammer (1999), who found that differences between the two groups on conjunction search tasks only became significant when there was a large number of items in the visual field, this study revealed significant differences even when there were a few items in the stimulus array. It is possible that the lack of significance at relatively low set sizes, in Vidyasagar and Pammer's study, arose because the paradigm used may not have been demanding enough for the visual pathways and/or may have allowed some compensatory mechanism, such as priming, to operate to overcome some of the demands. In comparison, the paradigm used in this study required fast object discrimination within an area of foveal vision and therefore the demands could be likened to those found in reading.

It is unlikely that the set size effects found in this study are due to other factors such as eye movement, experimental demands or motor response times as these were controlled for through short stimulus display times and forced choice responses. Furthermore, there was no evident decline in performances in the feature search task, involving orientation, after the completion of the conjunction search, seemingly indicating that neither group was bored nor suffered fatigue related problems.

Implications of an attentional spotlight deficit

According to Vidyasagar (1999) reading requires an unnatural use of visual search mechanisms. Normally, visual search is a random process which does not keep track of previously inspected locations (Horowitz & Wolfe, 1998). However, when reading, the attentional spotlight needs to be trained to move Ôsequentially and systematically' over the words in a line. In this way, the letters could be attended to and integrated into words. Individuals who have a deficient magnocellular pathway may not be able to learn this skill effectively and therefore their reading will be poor. A recent study, by Steinman, Steinman and Garzia (1998), measured the spatiotemporal attentional response functions of both poor and normal readers using a Line Motion Illusion task. They found that poor readers showed specific abnormalities in the visual attentional mechanisms, supporting the view that these mechanisms may be affected by a deficient magnocellular pathway.

The finding that the attentional spotlight functioning of the magnocellular pathway is compromised in dyslexia may also account for the failure to consistently find evidence of a magnocellular deficit, since this deficit, if mild, would only become evident when the demands on this particular function are high, such as in the paradigm used in this study. Also the function of the magnocellular pathway to carry signals to higher processing centres may remain intact while the mechanism guiding the attentional spotlight, that is providing parietal feedback to the striate cortex, may be damaged. This would result in what appears to be normal magnocellular pathway functioning on many tasks not specifically directed towards examining attentional spotlight functions.

Implications for future research

The visual search paradigm used in this study is unique in its design which allows direct examination of attentional spotlight functioning of the magnocellular pathway through manipulations of set sizes in conjunction searches, thus providing a useful tool for future research.

Studies comparing Dyslexic subtypes

In this study the poor readers were treated as an homogeneous group, however, there are several lines of evidence which suggest the existence of distinct types of developmental dyslexia (for review see Castles & Coltheart, 1993), dependent on their ability to read irregular and non-words. Phonological dyslexics are defined as those who have deficiencies in reading non-words, Surface dyslexics are impaired in reading irregular words and Mixed dyslexics have difficulty with both non-words and irregular words. There have been several studies suggesting a deficit in magnocellular pathway functioning of phonological and mixed dyslexics only (Borsting et al., 1996; Spinelli, Angelelli, DeLuca, DiPace, Judica & Zoccolotti, 1997; Witton, Talcott, Hansen, Richardson, Griffiths, Rees, Stein & Green, 1998). However, deficits may simply be milder in surface dyslexics or be associated with the mechanism guiding the attentional spotlight as previously discussed. By examining the performance of each subtype of dyslexia on visual search tasks using the paradigm designed in this study, it may be possible to delineate the degree to which the attentional spotlight is compromised. Greater effects of increasing set size would represent greater deficiencies.

Studies investigating the persistence of an attentional spotlight function deficit

For the most part, previous studies which have supported a magnocellular pathway deficit in dyslexia have only included children between the ages of 8 and 14 years. The limited range of ages included in these studies raises the question of whether these deficits persist beyond childhood, or whether the results may be generalised to all ages. Previous research has revealed that word recognition deficits and other important markers of childhood dyslexia, such as poor knowledge of spelling-sound relationships and phonological awareness, persist from childhood into adulthood (Bruck, 1990, 1992; Felton, Naylor, & Woods, 1990). Given that these basic deficits of dyslexia remain, if visual deficits are major determinants of dyslexia, it might be expected that magnocellular pathway deficits might also persist into adulthood. However, there is limited research which directly addresses whether magnocellular pathway deficits exist in adults. In particular, Hayduk, Bruck and Cavanagh (1996) compared the performance of dyslexic adults (referring to adults with childhood diagnoses of dyslexia), dyslexic children and age matched normal readers on a computerised counterphase flicker contrast threshold task. This type of task has provided the clearest evidence of a magnocellular deficit in children with dyslexia. In contrast to previous findings, their results showed that dyslexics and normal readers did not differ in their performances, suggesting that a magnocellular pathway deficit is not a general characteristic of developmental dyslexia. As with the previous visual search studies involving dyslexics, this study did not address the confounding role of performance factors and attentional factors. By examining the performance of adult dyslexics on visual search tasks, using the paradigm designed in this study, it would be possible to determine whether the attentional spotlight functioning of the magnocellular pathway persists into adulthood, without the confounding effects of performance factors.

Studies comparing developmental and acquired Dyslexics

Acquired dyslexias refer to reading disorders which have been produced as a consequence of brain damage, generally to areas of the posterior parietal cortex (PPC). Attentional processes have also been linked to the PPC. Thus it seems reasonable to expect that acquired dyslexics would show deficits on tasks requiring visuo-spatial attention. In a case study reported by Friedman-Hill, and her colleagues, (1995), the feature binding capabilities of a neurological patient with bilateral parietal-occipital lesions was examined. This patient not only demonstrated poor performances with set size effects on target present conditions in feature conjunction searches (colour and shape) but also reported more illusory conjunctions (ICs) as the set size increased. While the results of the present study did not indicate the presence of more IC's by poor readers it is possible that this occurred but was hidden by the scoring system used. By recording the actual number of 'yes' responses to target absent conditions in this paradigm it may be possible to determine the degree to which the groups report ICs. This type of study might provide some insight into the location of the neuronal mechanisms which play a role in directing the spotlighting function of the magnocellular pathway.

Further studies

Conditions under which dyslexics may perform as well as normal readers could also be determined using this paradigm. Changing the time of stimulus presentation or reducing the number of items in a set might provide some insights into the capabilities of dyslexics.

It might be argued that the stimuli used in this paradigm, white presented against a black background, were not representative of reading since this typically involves the presentation of black letters against a white background, and consequently the findings may not relate to reading ability at all. By reversing the stimuli and background colours, this problem could be addressed.

Conclusion

The visual search paradigm used in this study has allowed the selective attention functioning of the magnocellular pathway to be compared between poor and normal readers by minimising a variety of non-attentional contributions to set size effects. Performance of poor readers was found to be significantly lower than normal readers on conjunction search tasks. Set size effects were consistent with the hypothesis that the magnocellular pathway mechanism which is compromised in dyslexia is that of selective attention. This deficit may be responsible for the reading difficulties observed in dyslexia. Given the limited number of studies which have attempted to examine the functional capabilities of attentional processes in dyslexics, generally, there is great scope for future research in this area.

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