
■ Visual encoding mechanisms and their relationship to text presentation preference

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This study was designed to investigate the importance of spatial encoding in reading, with particular emphasis on visuo-spatial encoding mechanisms. Thirty one school children participated in the first study in which they were measured on their ability to solve a centrally presented spatial encoding task, as well as their sensitivity to the frequency doubling illusion across the retina. We found that both spatial frequency doubling sensitivity and performance in the spatial encoding task were correlated with reading, however these tasks were unrelated to each other. Furthermore, frequency doubling sensitivity was correlated with contextual reading, but not single-word reading, while the central spatial encoding task was correlated with both reading tasks. These findings may have functional implications for text presentation preference. Accordingly, in Experiment 2 we demonstrated that children with poor FDT sensitivity read more accurately when words were presented singularly rather than in a whole-text format. In conclusion, we suggest that contextual reading may depend upon two separate and functionally distinct visual encoding mechanisms—one central, important for the spatial discrimination of letters within words, and the other, a spotlighting mechanism important for spatial localization within a body of text. While both mechanisms may constrain reading efficiency, neither mechanism enforces an absolute limit on reading ability. Copyright © 2004 John Wiley & Sons, Ltd.

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MECHANISMS OF VISUAL ENCODING AND THE RELATION TO TEXT PRESENTATION PREFERENCE

In every cohort of young school children, there will be a small proportion who, despite being intelligent, socially well adjusted, and with no neurological impairments, will nevertheless find it inordinately difficult to learn to read. While a failure to learn to read may be the result of a number of different factors, the single most frequent characteristic is a difficulty in phonological processing, in which the child finds it difficult, sometimes impossible, to recognize, identify, and manipulate the phonological representations of letters and words (e.g. Bradley & Bryant, 1983; Brady & Shankweiler, 1991; Snowling, 1980, 2000). While phonological problems are the most salient characteristic of developmental dyslexia (DD), many of these children also demonstrate a concomitant range of subtle visual deficits. The interpretation of the assortment of visual processing difficulties identified in DD has resulted in at least two schools of thought: The first of these stems from research that has demonstrated that many dyslexic readers' visual processing skills are different from their peers: they are less sensitive than controls to dynamic visual stimuli, especially those of low contrast, low luminance, low spatial frequencies, and high temporal frequencies (Lovegrove *et al.*, 1982; Lovegrove, Martin, & Slaghuis, 1986; Livingstone, Rosen, Drislane, & Galaburda, 1991; Mason, Cornelissen, Fowler, & Stein, 1993; Cornelissen, Richardson, Mason, & Stein, 1995) and they show reduced sensitivity to the coherent motion in random dot kinematograms (Cornelissen *et al.*, 1995; Hansen, Stein, Orde, Winter, & Talcott, 2001; Pammer & Wheatley, 2001). In addition, performance differences between dyslexics and controls have been found for tasks that measure temporal and spatial properties of visual attention (Bouma & Legein, 1977; Brannan & Williams, 1987; Steinman, Steinman, & Garzia, 1998; Facoetti & Molteni, 2001). With some exceptions (Gross-Glenn *et al.*, 1995; Walther-Müller, 1995; Hayduk, Bruck, & Cavanagh, 1996; see: Stein, Talcott & Walsh, 2000; Skottun, 2000 for critical reviews), these results have been replicated in a number of psychophysical studies, and have been corroborated to some extent both electrophysiologically and with functional MRI (Livingstone *et al.*, 1991; Lehmkuhle *et al.*, 1993; Eden *et al.*, 1996; Demb, Boynton, & Heeger, 1997). The differences demonstrated by dyslexic readers on these tasks compared to normal readers may be indicative of impairment in the integration of, and/or sensitivity to visual information derived from M-cells in the retina—information which dominates input to the dorsal visual stream (Merigan & Maunsell, 1993). Indeed, in a study of five post-mortem dyslexic brains, Livingstone *et al.* (1991) identified anatomical abnormalities in the size, number and organization of cells only in the dorsal layers of the LGN which receive exclusively from M-cells. The ventral layers of the LGN, which receive exclusively from P-cells, were intact. Vidyasagar (1999) has integrated these findings to suggest that in perceptually demanding tasks, the dorsal system acts like a preattentive attentional spotlight. In this capacity, the dorsal system defines where objects are located in space and provides this information to the ventral stream within a feedback mechanism which then processes the more detailed features of the localized space. In reading then, the dorsal system is necessary to provide a quick, global spatial analysis of the text, defining the relative locations of details within text, which can then be fed back to the ventral system for a more

sophisticated analysis of form and detail. Moreover, it is possible that reading may be the only situation in the visual world in which this analysis must be done in a carefully dictated sequential fashion. This is compared to natural viewing in which it has been suggested that samples of the visual scene are selected randomly by the dorsal system, without reference to previously selected locations (Horowitz & Wolfe, 1998), although refer (Peterson, Kramer, Wang, Irwin, & McCarley, 2001). Neurologically then, part of the skill in learning to read may be not just having adequate spatial feedback from the dorsal stream to the ventral stream, but teaching the dorsal pathway to perform this feat in a methodical and sequential way, following the line of text. Indeed, it has been demonstrated that reading difficulty may be correlated with slow visual search performance which similarly requires adequate spatial spotlighting of the target scene (Vidyasagar & Pammer, 1999; Buchholtz, Pammer, & Vidyasagar, 2002).

A second line of interpretation regarding the contribution of visual processing deficits to reading difficulty centres on the involvement of relative position encoding to reading. It is well known that word recognition is dependent upon our sensitivity to the relative locations of letters within a word string. For example, Mason (1980) demonstrated that poor readers were less sensitive to recognizing the serial position of letters and cued letters in strings compared to good readers. Humphreys, Evett, and Quinlan (1990) demonstrated that the facilitatory effect of an orthographic prime was enhanced when the prime and target shared both orthographic and relative position information. This finding was replicated by Peressotti and Grainger (1995) using non-alphabetic characters, and then again by Peressotti and Grainger (1999) demonstrating that priming effects disappeared when the common letters were not in the same relative position. Cornelissen, in an attempt to assess the relationship between reading and dynamic visual processing, showed that the likelihood of children making letter-errors (e.g. misreading GARDEN as GRANDEEN) was predicted by their coherent motion thresholds (Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998a), and that motion detection sensitivity predicted performance in a lexical decision task that emphasized the requirement for accurate letter-position encoding (Cornelissen *et al.*, 1998b). These findings are consistent with the view that natural variation in relative position encoding does predict natural variability in reading, but the inference is indirect. Therefore, we have recently tested this idea directly, demonstrating that sensitivity to the relative position of items in a word-like symbol string predicts a reader's ability to recognize words (Pammer, Lavis, Hansen, & Cornelissen, 2003; Pammer, Lavis, Hansen, Cooper, & Cornelissen, 2002).

Few studies have attempted to unite these two research positions, and there is little justification to assume that their relative impacts on reading and reading difficulty are mutually exclusive. The issue is whether or not these two processes are supported by independent mechanisms, or are two manifestations of the same underlying architecture. The aim of the current study is to assess the potential relationships between these two research positions, and their potential to explain inter-subject variability in different reading tasks. In this study then, we will investigate the relationship between dorsal-stream mediated dynamic visual processing, sensitivity to relative position encoding, and reading tasks. Should we find significant correlations between these tasks, then we provide reasonable evidence to suggest that sensitivity to dynamic visual encoding, and

relative position encoding share a common neural architecture that is intrinsic to reading. This question is not only of theoretical significance, but also has practical implications in the context of developmental dyslexia, such that it may be possible that one or both mechanisms provide a constitutional basis for a reading difficulty.

EXPERIMENT 1

Experiment 1 is an attempt to define an association between a dynamic visual processing task, a spatial visual encoding task designed to simulate letter position encoding, and the actual reading situation. The frequency doubling percept (FDT) is a visual illusion argued to be mediated exclusively by a subset of neurones in the dorsal system (e.g. Maddess & Henry, 1992), and has been demonstrated to differentiate between good and poor readers (Pammer & Wheatley, 2001). The presentation of the FD illusion using *Frequency Doubling Technology* allows an analysis of dynamic visual processing in 17 retinal locations across the periphery and fovea using exactly the same task, under exactly the same test conditions. A symbols recognition task (Pammer *et al.*, 2002a, b) will be used to assess relative position encoding.

METHOD

Participants

Thirty three children participated in the experiment; all the children were recruited from a primary school in the Tyneside, UK area. Characteristics of the participating children are presented in Table 1. The data for two participants were removed from the analysis; one child had a very poor reading score, and another demonstrated a very high false positive score (> 3.5 S.D. from the mean for each eye). This indicates that the child had a strong tendency to respond that a stimulus was present, when it was in fact absent.

Materials and Procedure

All visual stimuli were presented by a PII 400 MHz PC, running a 32 Mb Matrox Millennium G400 graphics card which drove an Iiyama Vision Master Pro 17 in monitor. Stimuli were generated and participant responses (key-press or mouse button press) recorded by bespoke software which locked the timing of all events to vertical screen refresh. Subjects sat in a windowless room illuminated by a single tungsten light bulb, seated ~ 0.5 m in front of the computer monitor.

Symbols Task

A symbol matching task was designed to measure the accuracy with which the children could discriminate the relative positions of local elements of a word-like stimulus that were not built up from letters. The symbol string consisted of five letter-like symbols. Therefore, following a 500 ms fixation point, a symbol-string

Table 1. Specifications for the children participating in the Experiments

Variable	Experiment 1			Experiment 2		
	Mean	SE	Range	Mean	SE	Range
Age	10.3	0.51	1.2	10.5	0.6	1.8
NARA rate (standard score)	96.6	2.03	50	101.2	1.99	52
NARA accuracy (standard score)	101.0	2	40	98.2	2.3	50
NARA comprehension (standard score)	92.63	1.5	36	88.6	1.58	54
BAS Digit Span	43.9	1.31	31	45.9	1	30
BAS Verbal Similarities	55.13	1.13	28	56.8	1.3	39
BAS Matrices	50.03	1.03	28	56.4	1	33
Rhyme (PhAB)	113.9	2.52	43	—	—	—
Phoneme Deletion	—	—	—	13.3	0.6	12
Rhyme Fluency (PhAB)	—	—	—	99.9	2.4	118
NST Digits (PhAB)	102.0	1.95	41	102.9	2.5	86
NST pictures (PhAB)	107.1	2.19	40	105.6	2.1	58
Non word reading	25.2	0.82	17	—	—	—
Irregular word reading	16.7	0.64	17	—	—	—
Regular word reading	28.1	0.52	14	—	—	—
FDT	35.27	0.69	15	31.3	0.39	13
FDT number false positives	0.28	0.1	4	0.25	0.06	3
FDT number false negatives	0	0	0	0	0	0
FDT number overt eye movements	1.84	0.25	3	2.17	0.17	6
Retinal deviation	—	—	—	-1	0.4	14

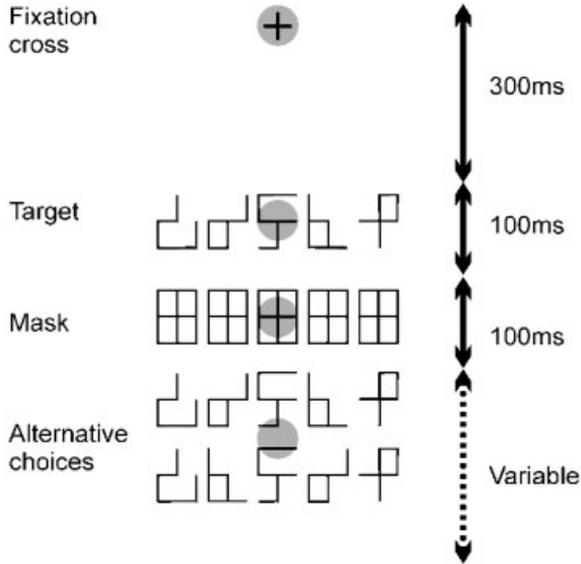


Figure 1. Schematic to illustrate the stimulus sequence for the symbols task. Note, the grey circle is included to demonstrate the spatial relationship between successive stimulus components and the middle of the display. It was not present during the actual task.

appeared for 100 ms on the screen, which was followed immediately by a mask for 100 ms. After the stimulus sequence two alternative symbol-strings were displayed one above the other, remaining visible until the participant responded by key press, which initiated the next trial. Participants were asked to pick which

of the two alternatives they had just been shown; one was the same string, and the other was a string with the same symbols, but arranged in a different order. The incorrect choices were arranged such that $\frac{1}{3}$ contained second and third symbol position swaps, $\frac{2}{3}$ contained third and fourth symbol position swaps and $\frac{1}{3}$ contained second and fourth symbol position swaps. The stimulus set for this task comprised 26 symbols constructed from only vertical or horizontal lines and they were designed to contain a similar number of line elements to actual letters. Figure 1 is a graphical representation of the symbols task.

There were four blocks of 64 trials. In addition to the rest period between blocks, the children were allowed to take a break when necessary. All symbol strings appeared as white letters (mean luminance 52.5 cd/m^2) on a dark grey background (mean luminance 2.3 cd/m^2), Michelson contrast was 0.9. The five-symbol stimuli string subtended 2.5° VA horizontally, and each component symbol subtended 0.4° by 0.6° VA.

Frequency Doubling

Stimuli were presented on an FDT machine (Humphrey Instruments FDT Visual Field Instrument). Each stimulus trial was presented to one of 17 regions throughout the central 20° radius of the visual field. Each target area was a 10° diameter square, except the central area, which was a 5° diameter circle, within which was a small black fixation square that remained on throughout the entire testing session. Each stimulus was a 0.25 c/deg sinusoidal grating, modulated at a 25 Hz counterphase flicker. Stimulus duration was 720 ms consisting of 160 ms ramped onset and offset. The inter-stimulus interval was variable up to 500 ms to avoid anticipatory responses. The contrast of the frequency doubling stimulus at each location was manipulated according to a modified binary search (MOBS) threshold strategy (Tyrrell & Owens, 1988). Staircase completion consists of at least four staircase reversals as well as upper and lower staircase boundaries within $0.3 \log_{10}$ units of each other. The MOBS threshold was calculated to be the mean of the last upper and lower presentations satisfying the staircase completion criteria. The range of possible threshold level values is between 0 dB ($\sim 100\%$) maximum contrast (lowest sensitivity) and 56 dB ($\sim 0\%$) minimum contrast (highest sensitivity). The mean background illumination was 100 cd/m^2 , self-calibrated at the beginning of each testing sequence. In general terms then, each subject saw on each trial a grey field in which they saw a small, square contrast grating of varying contrast, briefly flashed in one of 17 locations.

For each testing sequence, each child was seated comfortably with their face against the eyepiece. The right eye was tested first, followed by the left eye. The child was given a description of the display, and instructed to press the response button each time they saw a pattern against the homogeneous background. Each child engaged in the practice session, which consisted of the frequency doubling display occurring randomly in all possible locations. It was emphasized to the child they must continue to look at the fixation point throughout the entire testing sequence. The testing sequence for each eye took approximately 4 min. The child was instructed that they may pause the display at any time by maintaining a constant pressure on the response button, and they were given a longer break between testing the right and left eye.

Cognitive Tests

It is well documented that individual differences in intelligence can account for inter-subject variability in psychophysical performance (Hirsh & Watson, 1996). For these reasons, all participants were tested on two rapid automatized naming tasks: the Naming Speed Test (NST)—pictures and digits, from the Phonological Abilities Battery (PhAB) (Frederickson, Frith, & Reason, 1997), as well as the Rhyme Test from the same test battery. In addition, from the British Abilities Scales II (BAS), (Elliott, Smith, & McCulloch, 1996) each child was given the following subtests: Digit Span, Matrices, and Verbal Similarities as measures of general cognitive processing. Contextual reading abilities were assessed using the NARA reading test (Neale, 1997), as well as a non-word reading test (Castles & Coltheart, 1993) as an index of single word reading. The rhyme and non-word reading tests were further used as measures of phonological ability.

RESULTS

The results of the symbols task were recorded as the number of times the participant selected the correct response. Percentage scores were then used to calculate d' for the symbols task. In the frequency doubling task, thresholds for detecting the illusion for 17 retinal locations were determined for each eye. These 17 thresholds were collapsed to represent a single mean threshold score for the FDT for each eye, which was then averaged to form a single average FDT score (Pammer & Wheatley, 2001). In addition to the retinal thresholds, the FDT machine records false positives (situations in which the child incorrectly responds to a blank delay in the stimulus sequence), false negatives (when the child fails to respond to a stimulus presentation at maximum contrast), eye movements from fixation, as well as a retinal deviation score—a measure of the degree of variability across the retina. The results from these reliability measures are in Table 1.

The initial correlational analysis is presented in Table 2 and this includes 95% confidence intervals for all correlation coefficients where $p < 0.05$. The cognitive aptitude scores (digits, similarities and matrices) are overall not correlated with the reading measures, indicating that reading ability in this sample is not related to general cognitive performance. All reading scores and phonological tasks (NARA, nonword reading and rhyme) are correlated, as is to be expected. Moreover, as predicted, the symbols task correlates well with the reading tasks. However, surprisingly, the FDT scores are completely unrelated to the symbols scores, and are only related to the NARA reading scores, but not the single-item non-word reading scores.

CONCLUSION

There is good evidence from the literature to support the importance of dynamic visual encoding (as measured here by the FDT score), as well as relative position encoding (measured here by sensitivity to the symbols task), to reading. As such, we anticipated that in a single study measuring both these factors, they would be

Table 2. Correlation matrix between all variables in Experiment 1 (95% confidence intervals for significant correlations)

	NARA	FDT	Symbols	Digit span	Similarities	Matrices	NST pictures	NST digits	Rhyme	Non-words
NARA	—									
FDT	0.41* (0.07–0.6)	—								
Symbols	0.53** (0.2–0.8)	0.13	—							
Digit span	0.27	0.3	0.27	—						
Similarities	0.13	0.08	0.01	0.23	—					
Matrices	0.29	0.15	0.3	0.18	0.45* (0.1–0.7)	—				
NST pictures	0.46** (0.1–0.7)	0.15	0.14	0.15	0.27	0.23	—			
NST digits	0.63** (0.4–0.8)	0.22	0.35	0.09	0.03	–0.06	0.48** (0.2–0.7)	—		
Rhyme	0.42* (0.8–0.7)	0.13	0.28	0.18	0.09	0.11	0.29	0.24	—	
Non words	0.41* (0.7–0.7)	0.15	0.42	–0.008	0.04	0.19	–0.06	–0.06	0.39* (0.04–0.6)	—

* $p < 0.05$.** $p < 0.01$.

highly correlated, both with each other, and with reading, perhaps suggesting a common neural mechanism. However, we found that while both the FDT and symbols tasks were related to reading, they were in fact unrelated to each other, suggesting that they may in fact represent *independent* early visual mechanisms both of which are intrinsic to reading.

Moreover, while the FDT score was correlated with the NARA reading test, which is a test of contextual reading, it was not however, correlated with the single word reading condition.

On the face of it, it could be argued that the symbols task is simply a proxy measure of other factors, such as attention, vigilance, processing speed, shape encoding, or fixation stability. We have however demonstrated elsewhere (Pammer *et al.*, 2002, 2003) that word recognition appears to be dependent upon sensitivity to the symbol task *independently* of such factors. Similarly, the significance of the position swaps may be of interest. This has also been addressed by us in the aforementioned papers. In general, previous evidence indicates that there is little evidence to suggest a reliance on any particular position swap (the subject attending only at the second and third positions for example) which might suggest a reliance on a particular strategy.

The implication from the current results is that there may be two visual encoding mechanisms important in reading: a central spatial encoding mechanism demonstrated both here and elsewhere (Pammer *et al.*, 2002, 2003) to predict reading ability, and a second mechanism—dynamic encoding, mediated by the dorsal processing stream, which has also been demonstrated to predict reading, but is statistically unrelated to the symbols task.

Vidyasagar (1999) and Vidyasagar and Pammer (1999) have suggested that good reading is dependent upon a pre-attentive visual navigation system that guides the visual system systematically across the page. The result then in the current study that FDT sensitivity is correlated with contextual reading, but not single word reading raises the intriguing possibility that sensitivity to the FD illusion may dictate a preference for the way text is presented, with individuals who are less sensitive to the FD illusion preferring text that is presented one-word at a time instead of the conventional whole-text format. Indirectly, this idea is supported by Hill and Lovegrove (1993) who demonstrated that dyslexic children read more fluently when there is less text to navigate, and Pammer and Wheatley (2001) demonstrated that dyslexic readers are less sensitive to the FD illusion than good readers. The functional consequence of the above prediction is that children with impaired peripheral visual processing are likely to find it easier to read text when the words are presented individually, where an impaired visual 'navigation' system would be of little consequence.

EXPERIMENT 2

If reading difficulty is compounded by an impairment in dorsal stream processing, then children with poor FDT sensitivity should find it more difficult to read when words are presented in normal text where there is a substantial amount of visual clutter to navigate. Moreover, since children with poor reading skills are also more likely to have poor FDT sensitivity (Pammer & Wheatley,

2001), we should also expect that they demonstrate better reading skills in the single word reading condition.

Participants: Forty four children were recruited from two primary schools in the Tyneside, UK area. These were different schools from Experiment 1. The schools had not participated in any previous relevant research. Characteristics of the children are presented in Table 1. The data for two of these children was not included in the analysis because they were performing below chance level on the symbols task.

Materials and Procedure

Text Presentation

The text presentation manipulation consisted of presenting each child with two reading-age appropriate texts, one of which was presented in a one-word at a time format, the other in a whole-text format.

Fifteen different texts were chosen from the NARA (Neale, 1997). These consisted of two level one passages, two passages from level two, two passages from level three, and three passages each from levels four, five, and six. Each child read two passages consistent with their reading level. They had not encountered either passage when previously tested on the NARA. One of the two passages was presented on the computer screen one word at a time; the other passage was presented in a whole-text format. The assigning of passages within a level to each of the presentation conditions was randomized.

Both text presentation conditions were presented on a Gateway Solo laptop computer running a ATI 8-MEG graphics card, and a screen resolution of 1280×1024 pixels, using *Presentation* software (<http://www.neurobehavioralsystems.com/index.shtml>). All text was written in Times Roman font with each character subtending a horizontal visual angle of approximately 0.3° . All text was white on a black background with a Michelson contrast of ~ 0.9 . In the one-word condition, each word appeared individually in the centre of the computer screen, with each subsequent word in the text sequence replacing the previous word. The rate of presentation was self paced, with the child initiating the presentation of each word by pressing the space bar. Each word remained on the screen until the space bar was pressed which initiated the appearance of the next word. In the whole text condition, the text passage appeared in its entirety on the computer screen. Because of the range of text difficulty, easier passages constituted approximately 50 words (level 2 text), compared to 140 words (level 6 text). Therefore, so that each condition in the whole text presentation had the same amount of text to navigate, all passage constituted 14 lines of text or pseudo-text. Pseudo-text was created by generating sequences of nonsense words which preserved the apparent visual qualities of real text. Examples of the two test conditions are in Figure 2.

Perceptual Tests

All children did the FDT and symbols tasks described in Experiment 1, ambient conditions and stimulus specifications were the same as described in Experiment 1.

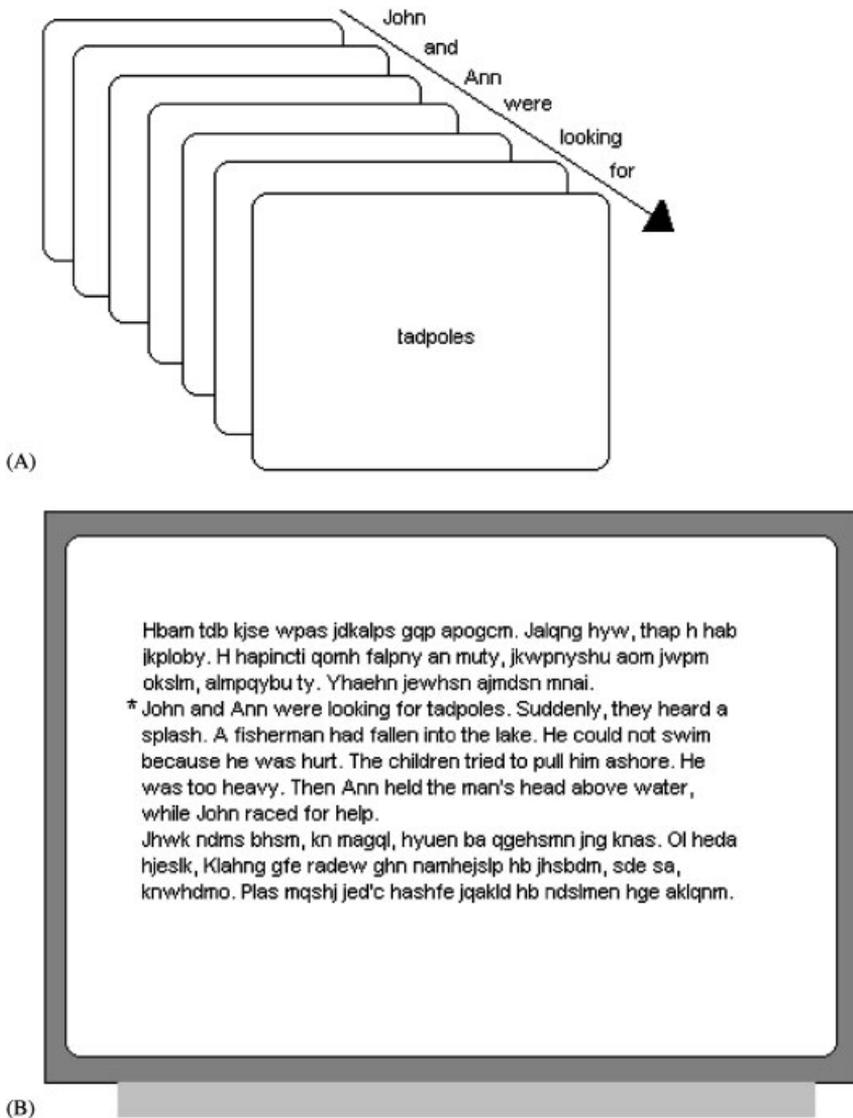


Figure 2. A representation of the text presentation manipulation in Experiment 2. One word at a time presentation (A), and the whole text condition (B).

Cognitive Tests

All the children were tested on the cognitive tests used in Experiment 1, except for the phonological assessment battery. After consultation (Snowling, 2002, pers comm.), we decided to substitute the Rhyme Task from the Phonological Assessment Battery, (Frederickson *et al.*, 1997), with a phoneme deletion task (McDougall, Hulme, Ellis, & Monk, 1994). The phoneme deletion task consists of the child articulating the remaining real word when part of the non-word has been removed e.g. what are you left with when you take the /b/ from BLOOT.

RESULTS

Percentage correct responses in the symbols task were converted to d' as in Experiment 1 and FDT scores were derived by averaging threshold measures over all 17 locations for both eyes. In the text reading condition, both reading accuracy (proportion of words in the text correct), and reading rate in words per minute (WPM) were recorded.

The data was analysed using the same method as in Experiment 1, and the correlation matrix is presented in Table 3. It demonstrates that the cognitive aptitude scores are not correlated with either of the visual measures, with the exception of symbols with digit span. The NARA scores were similarly not correlated with the cognitive measures. As with Experiment 1, both the FDT and symbols tasks are correlated with reading, but not correlated with each other.

In order to establish the relationship between the reading text manipulation and FDT, first of all the FDT scores were divided into participants who performed well on the FDT measure and those who performed less well. Poor performers were those participants who achieved an overall FDT score less than or equal to one-standard deviation below the sample mean ($N = 12$). Good FDT performers were those who performed equal to or higher than one-standard deviation above the sample mean ($N = 13$). We used the General Linear Models procedure (called PROC GLM) in SAS (SAS Institute Inc., North Carolina, US) to run a one-between groups (FDT; good and poor performers), one repeated measures (text presentation; one-word at a time and whole text) ANOVA of reading accuracy and speed. The analysis for reading accuracy showed a main effect of text presentation ($F(1, 23) = 13.11, p < 0.001$), and no effect of FDT. However, there was a significant interaction between FDT and text presentation ($F(1, 23) = 7.78, p < 0.05$), such that poor FDT performers made significantly more reading errors in the conventional whole-text condition compared to the one-word condition. Conversely, good FDT performers were largely insensitive to the differences between the two modes of text presentation, see Figure 3.

Reading speed was measured in words per minute (WPM). The ANOVA results revealed only a main effect of text presentation, such that single words were read more slowly than whole text by both good and poor FDT performers, see Figure 4. This result is not unexpected given the added time necessary to generate and perform a motor response (i.e. key-press) after each word.

Finally, in order to look specifically at how poor readers performed on the FDT task compared to good readers, a mean split of the FDT data over both the whole text and one-word reading conditions revealed that 50% of the subjects performing below average on the FDT task, were also poor readers, compared to children who's sensitivity to the FDT was above average, where only 17% were poor readers. (NB this is different from the previous analysis in which good and poor FDT-er's were specifically defined by <or> 1 S.D. from the mean. Moreover, as this was an analysis specifically about FDT sensitivity, the two subjects originally omitted from the analysis were included here). In other words, children who perform below average on the FDT constitute 50% poor readers (8 out of 16 children), whereas children who perform above average on the FDT, constitute only 17% poor readers (5 out of 28 children). This pattern was reflected in good readers ($N = 10$) demonstrating a significantly higher FDT sensitivity than poor readers ($N = 9$) $t(19) = -4.2, p < 0.0001$.

Table 3. Correlation matrix between all variables in Experiment 2 (95% confidence intervals for significant correlations)

	NARA	FDT	Symbols	Digit span	Similarities	Matrices	NST pictures	NST digits	Phoneme deletion
NARA	—								
FDT	0.43** (0.2-0.7)	—							
Symbols	0.52** (0.3-0.7)	0.28	—						
Digit span	0.44** (0.2-0.7)	0.25	0.56** (0.3-0.8)	—					
Similarities	0.2	-0.09	0.23	0.11	—				
Matrices	0.51** (0.3-0.7)	0.09	0.3	0.3	0.33* (0.03-0.6)	—			
NST pictures	0.2	0.64** (0.4-0.8)	0.21	0.15	0.01	0.07	—		
NST digits	0.48** (0.2-0.7)	0.39* (0.1-0.6)	0.23	0.23	0.15	0.17	0.62** (0.4-0.8)	—	
Phoneme deletion	0.79** (0.7-0.9)	0.4** (0.1-0.6)	0.43** (0.2-7)	0.32* (0.02-0.6)	0.1	0.42** (0.2-0.7)	0.31* (0.01-0.6)	0.56** (0.3-0.8)	—

* $p < 0.05$.
** $p < 0.01$.

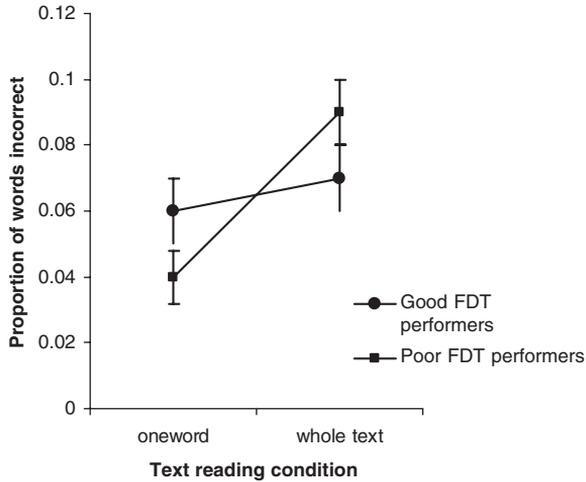


Figure 3. Proportion of words correct in the text reading task when reading one-word at a time or the whole text condition. This is by subjects who perform equal to or greater than 1 S.D. from the mean on the FDT task (good FDT-ers), and subjects who perform equal or less than 1 S.D. from the mean (poor FDT-ers). Error bars are standard error.

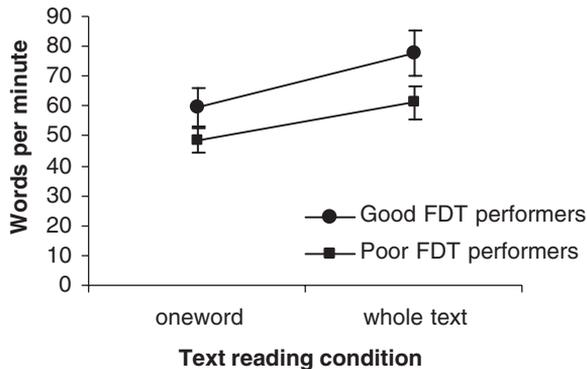


Figure 4. Reading speed in words per minute in the text reading task when reading one-word at a time or the whole text condition. This is by subjects who perform equal to or greater than 1 S.D. from the mean on the FDT task (good FDT-ers), and subjects who perform equal or less than 1 S.D. from the mean (poor FDT-ers). Error bars are standard error.

DISCUSSION

In the introduction, we pointed out two components within reading research that have, to date, been treated in isolation. First, we have the suggestion that dorsal-stream mediated visual functioning is intrinsic to the reading process. Second, that sensitivity to relative position encoding is an integral component of reading. As the literature demonstrates that both components are clearly important to reading, we anticipated a strong correlation between the key indexing tasks (FDT

and symbols, respectively). However, what we in fact found was that both mechanisms appear to contribute independently to the reading process.

One way to interpret the current findings is that they may reflect a functional division between two scales of spatial processing for reading—a fine scale mechanism important in identifying detailed spatial relationships in a central localized field, and coarse scale, peripheral mechanism mediated by dorsal activity and important in guidance.

The results from this study may therefore be summarized as follows:

- Both the symbols task (indexing letter position encoding) and the FDT task (indexing an M-cell biased dynamic visual process) are significantly correlated with reading ability.
- These two tasks are not correlated, therefore likely to be unrelated to each other, and possibly sub-served by different neural mechanisms.
- The symbols task is correlated with single word reading as well as contextual reading, but the FDT score is only correlated with contextual reading.
- Children with poor FDT sensitivity read better with less surrounding text.
- Children with good FDT sensitivity are less sensitive to text presentation.
- Half the children with FDT sensitivity that was below average were also poor readers.
- All the poor readers read better with less surrounding text.

These results suggest a functional division between the visual encoding mechanisms. One way to synthesize these results would be to suggest that a central mechanism defines the spatial arrangement of letters within words—important therefore in identifying both isolated words and words in text. Conversely, a broader scale spatial spotlighting mechanism may be necessary only in the natural reading situation which requires spatial localisation at the text level rather than just at the word level.

The results from Experiment 1 suggested that adequate functioning of one or the other of these mechanisms should have clear consequences for reading preference. An impaired peripheral spatial ‘navigational’ system is likely to provide most difficulty for the reader in situations in which there are substantial amounts of visual clutter. Indeed Experiment 2 demonstrated that children with poor FDT sensitivity are less accurate when reading conventionally displayed text compared to when text is presented one-word at a time. Of this category of readers, half of them were classified as poor readers. Moreover, all the poor readers without exception also read less accurately in the full text condition. This research therefore provides empirical evidence to suggest that the majority of dyslexic readers would benefit from reading strategies that include minimising the amount of text they are required to navigate when reading. It also suggests a physiological mechanism to explain such reading preferences.

What was further interesting about these results is that neither mechanism provides absolute limits on reading ability. While the results in themselves are compelling, we are clearly still only looking at one piece of the overall puzzle. The results demonstrate that eight out of the 16 children who are relatively less sensitive to the FD illusion were also poor readers. Conversely however, there were also eight out of the 16 children who were below average on the FD illusion, and were more accurate reading single-word text, but who did not have a

demonstrable reading difficulty. What added mechanisms or strategies are these children employing? Similarly, five children were clearly reading impaired, but had normal or above average FDT sensitivity. These children preferred the single-word reading condition, but it still begs the question why these children have good visual encoding skills, but still find it difficult to read. This suggests that while adequate functioning of both systems is the optimal situation for reading acquisition, it is by no means a necessary situation. Moreover, the causal relationship between spatial encoding and reading or dyslexia is still open to speculation. While it is imprudent to make firm conclusions based on a single, correlational study with only one example each of the experimental positions (FDT and the symbols task), this speculation nevertheless provides a plausible framework within which to study further the relationship between basic visual processes and reading failure. Moreover, this approach has the advantage that the link between visual processes, reading, and language processes are intuitively much clearer than is the case for other visual measures such as coherent motion or contrast sensitivity. It is possible that these mechanisms are limiting factors in reading because the poor reader is less sensitive to determining the relative spatial locations of letters within words, and or poor at pre-attentive visual navigation within a cluttered scene. However, equally possible, is that efficacy of both mechanisms emerges as a consequence of becoming a skilled reader, such that individuals who are accomplished at rapid visual word recognition and pre-attentive spatial guidance, have similarly developed the neural skills necessary to decode relative position information. This chicken-and-egg argument is an enduring theme in dyslexia research and will provide a foundation for subsequent research.

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