

Symbol-string sensitivity and children's reading

Kristen Pammer, Ruth Lavis, Peter Hansen, and Piers L. Cornelissen*

Department of Psychology, University of Newcastle, Newcastle-Upon-Tyne, UK

Accepted 22 January 2004

Abstract

In this study of primary school children, a novel 'symbol-string' task is used to assess sensitivity to the position of briefly presented non-alphabetic but letter-like symbols. The results demonstrate that sensitivity in the symbol-string task explains a unique proportion of the variability in children's contextual reading accuracy. Moreover, developmental dyslexic readers show reduced sensitivity in this task, compared to chronological age controls. The results suggest that limitations set by visuo-spatial processes and/or attentional iconic memory resources may constrain children's reading accuracy.

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Keywords: Word recognition; Dyslexia; *Letter position*; Reading; Magnocellular; *Natural variability*

1. Introduction

Recently, Pelli, Farell and Moore (2003) showed that the efficiency of visual word recognition (i.e., the ratio of an ideal observer's word identification threshold to that of a human observer) is inversely proportional to word length. This means that, for a page of text, contrast energy (i.e., the product of squared contrast and 'ink' area) in the image must be divided equally amongst the letters, so that every letter is as visible as every other letter. The alternative possibility, which Pelli et al. refuted, was that contrast energy be shared equally at the word level regardless of word-length. This would mean that individual letters within a word become less visible as words get longer. Based on their psychophysical data, Pelli et al. used ideal observer models to show that human performance in visual word recognition never exceeds that attainable by strictly letter- or feature-based models. This therefore confirms the long held view that abstract letter identity, independent of font type and case, represents the basic perceptual unit of visual word recognition (Besner & McCann, 1987; Grainger & Jacobs, 1996). In short, the first bottle-neck for processing printed words is at the letter level.

However, as with many aspects of object recognition in general, there is a great deal of uncertainty about how letter representations are extracted from input to the visual system. It is commonly assumed that letters are identified by analysing suborthographic features (e.g., lines, angles, and curves). Several studies have indicated that letter features play a role in letter recognition and that similar features occurring in different locations interact with each other, where the degree of interaction depends on the spatial distance between the features (Bjork & Murray, 1977; Chastain, 1977; Krumhansl & Thomas, 1976; Strangert & Brännström, 1975). Consistent with this view, recent theoretical models of visual word recognition have shown how a level of feature extraction can be included prior to the level at which letters are represented (e.g. Whitney, 2001). Nevertheless, the psychophysical and neurobiological mechanisms underpinning feature extraction remain to be elucidated.

From a developmental perspective, recent research has highlighted the need for better understanding of the relationship between visual processing and the extraction of orthographic information from print. A number of studies have shown relationships between low-level dynamic visual sensitivities and reading skills in school age children. For example, Talcott et al. (2000) found that sensitivity to coherent motion is correlated with orthographic skills, and Sperling, Zhong-lin, Manis, and

* Corresponding author. Fax: +44-191-222-5622.

E-mail address: p.l.cornelissen@ncl.ac.uk (P.L. Cornelissen).

Seidenberg (2003) have shown that sensitivity to a phantom contour illusion is correlated with children's orthographic choice accuracy as well as their exception word reading. In our own work, we have established correlations between performance in single word reading tasks and coherent motion sensitivity in children, between lexical decision and coherent motion sensitivity in adults and between performance in Peressotti and Grainger's (1995) priming task and coherent motion sensitivity in adults (Cornelissen et al., 1998a; Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998b). In these studies, the reading and lexical decision tasks were designed to emphasise the need for subjects to extract information about letter position accurately. For example, in the children's reading task, we found that poor motion detectors were more likely to make orthographically inconsistent nonsense errors; misreading "PERSON" as "PRESON," "GARDEN" as "GRANDEN." In the lexical decision task, we showed that the probability of adults perceiving briefly presented anagrams like "OECAN" as a word, was directly related to their motion sensitivity. Effects like these would be expected if 'poor' motion detectors were less efficient at extracting letter position compared to 'good' motion detectors (Cornelissen & Hansen, 1998).

In the current study, we pursue the question: is there a relationship between natural variation in pre-orthographic visual processing and children's reading accuracy? Specifically, we used a novel 'symbol-string' task to assess children's sensitivity to the position of briefly presented non-alphabetic but letter-like symbols. We ask whether sensitivity in this task can account for individual variability in contextual reading. We have already demonstrated that sensitivity in the same symbols-string task predicts sensitivity to lexical decision for normal reading adults, independently of factors such as intelligence, speed of processing abilities, eye-movement fixation stability, and allocation of attentional resources (Pammer, Lavis, Hansen, & Cornelissen, 2004). However, while the relationship between sensitivity to the symbols task, and lexical decision is robust, the question whether natural variability in the symbols task is related to individual differences in contextual reading skills in children remains untested. In the current study we investigate this link.

2. Experiment 1

We measured reading accuracy with the Neale Analysis of Reading Ability (Neale, 1997) (NARA) in an unselected sample of primary school children. We then estimated the proportion of variance in NARA scores that is explained by symbol-string task sensitivity, while statistically controlling for effects attributable to age, IQ, short-term memory, and phonological skills.

2.1. Method

2.1.1. Participants

Forty two children were recruited from schools in the local Tyneside UK area, none of whom had participated in any other research with us. All the participants were reported to be native British-English speakers and had normal or corrected-to-normal visual acuity. Any subject whose score was ± 3 standard deviations from the sample mean on any task was excluded from the sample (see e.g., Cutting & Denckla, 2001). Four individuals were excluded by these criteria, leaving a total of 38 subjects.

All our methods conformed to the tenets of the Declaration of Helsinki and also had local ethics committee approval.

Participants' cognitive and literacy skills were assessed at the time of testing. The cognitive measures comprised the Matrices, Verbal Similarities, and Digit Span subtests from the British Abilities Scales II (BAS-II) (Elliot, Smith, & McCulloch, 1996). Reading accuracy was assessed by the NARA. The NARA is a test of reading ability that requires the child to read progressively more difficult passages, until the child fails to attain an accuracy criterion. The child is then given three separate scores for: reading accuracy, speed, and comprehension. These can be used to generate a composite reading score. Phonological skills were assessed by a phoneme deletion task (i.e., "say BLOOT without the /t/," McDougall, Hulme, Ellis, & Monk, 1994) and rapid automatized naming (RAN) for digits from the Phonological Awareness Battery (Frederickson, Frith, & Reason, 1997). Details of the results from the psychometric testing are shown in Table 1.

2.1.2. Stimuli

The symbols task was intended to measure the accuracy with which participants could discriminate the position of briefly presented non-alphabetic but letter-like symbols. The task was controlled by a Windows PC which drove an Iiyama Vision Master Pro 17 inch CRT monitor. Stimuli were generated and responses (key-press) recorded by bespoke software that locked the timing of all events to the vertical screen refresh.

The stimulus set for this task comprised 26 symbols constructed from only vertical or horizontal lines, refer Fig. 1. The symbols were designed to contain a similar number of line elements to actual letters, and comparable spatial frequency and contrast characteristics, whilst being sufficiently unfamiliar as to minimise any top-down influence from word and/or letter representations. White symbol-strings (mean luminance 52.5 cd/m²) appeared briefly on a dark grey background (mean luminance 2.3 cd/m²), giving a Michelson contrast $[(L_{\max} - L_{\min}) / (L_{\max} + L_{\min})]$ of .9. At the constant viewing distance of 60 cm used in both experiments, the

Table 1
Subject characteristics for Experiments 1 and 2

	Experiment 1	Experiment 2		T test comparison
	N = 38 Mean (SD)	Dyslexic N = 13 Mean (SD)	Control N = 13 Mean (SD)	
Chronological age (years:months)	10:7 (0:6)	10:6 (0:5)	10:7 (0:7)	n.s.
Similarities BASII (t score)	57.0 (8.7)	59.5 (4.7)	57.6 (9.6)	n.s.
Matrices BASII (t score)	56.8 (6.6)	58.0 (4.7)	54.1 (7.1)	n.s.
Digit span BASII (t score)	46.5 (7.0)	42.1 (6.1)	49.6 (6.6)	p < .005
Neale Analysis of Reading Ability (standard accuracy score)	102.0 (11.7)	80.9 (9.3)	113.8 (13.0)	p < .0001
Phoneme deletion (raw score)	14.1 (3.5)	8.6 (1.8)	15.9 (1.9)	p < .0001
Rapid automatized naming for digits (standard score)	106.6 (12.9)	95.7 (11.7)	111.3 (14.4)	p < .005
Symbol-string task (d')	.97 (.45)	.70 (.46)	1.17 (.33)	p < .005

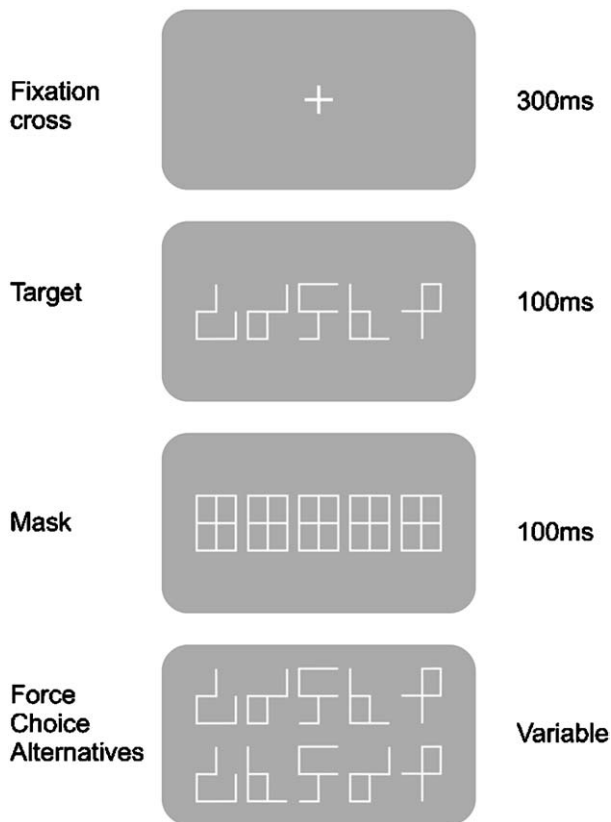


Fig. 1. Schematic to illustrate the stimulus sequence for the symbols task in Experiment 1. Note, the relationship between the grey “screen area” and the stimulus elements is not to scale, but serves only to demonstrate the spatial relationship between successive stimulus components and the middle of the display. This example shows a 2nd and 4th symbol position swap. See text for details.

symbol-string itself subtended 2.5° horizontally. Each symbol subtended a horizontal × vertical visual angle of .4° × .6°.

2.1.3. Procedure

The children viewed the computer monitor binocularly, and were tested individually in a small room lit by a single fluorescent ceiling light. After the task was ex-

plained, each child carried out a sequence of 15 practice trials to learn the symbol-string task with visual feedback provided. This was followed by a total of 216 trials divided into three separate blocks without feedback. As illustrated in Fig. 1, each trial consisted of: a fixation cross lasting 300 ms immediately followed by a target string (100 ms) that was masked for 100 ms. Two symbol-strings were subsequently displayed one above the other in a 2AFC (spatial) paradigm. 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 correct choice appeared at random in either the upper or lower position, with equal probability. The ‘incorrect’ choices were generated as follows: 1/3 contained 2nd and 3rd symbol position swaps, 1/3 contained 3rd and 4th symbol position swaps, and 1/3 contained 2nd and 4th symbol position swaps. These stimulus conditions were randomised across the three blocks of trials. Children responded by verbal report which was recorded by the experimenter using a key-press.

2.2. Results

Percentage correct and incorrect responses for each of the three blocks of the symbols task were collated and converted to d-prime (d') scores (Gescheider, 1997). d' scores allow a bias free estimate of task sensitivity to be calculated. Initial analyses were conducted to transform explanatory variables into standardised scores (Z-scores) and eliminate outliers.

We found positive, statistically significant (p < .0005) Pearson correlations (.6 < r < .75) between the d' scores for each of the three blocks of the symbols task. This suggests a good degree of reliability in this task.

Positive associations between NARA scores and symbols and phoneme deletion tasks, respectively, are illustrated by the scatter-plots in Fig. 2. Multiple regression was used to estimate the variance in NARA reading accuracy that is explained by symbols task

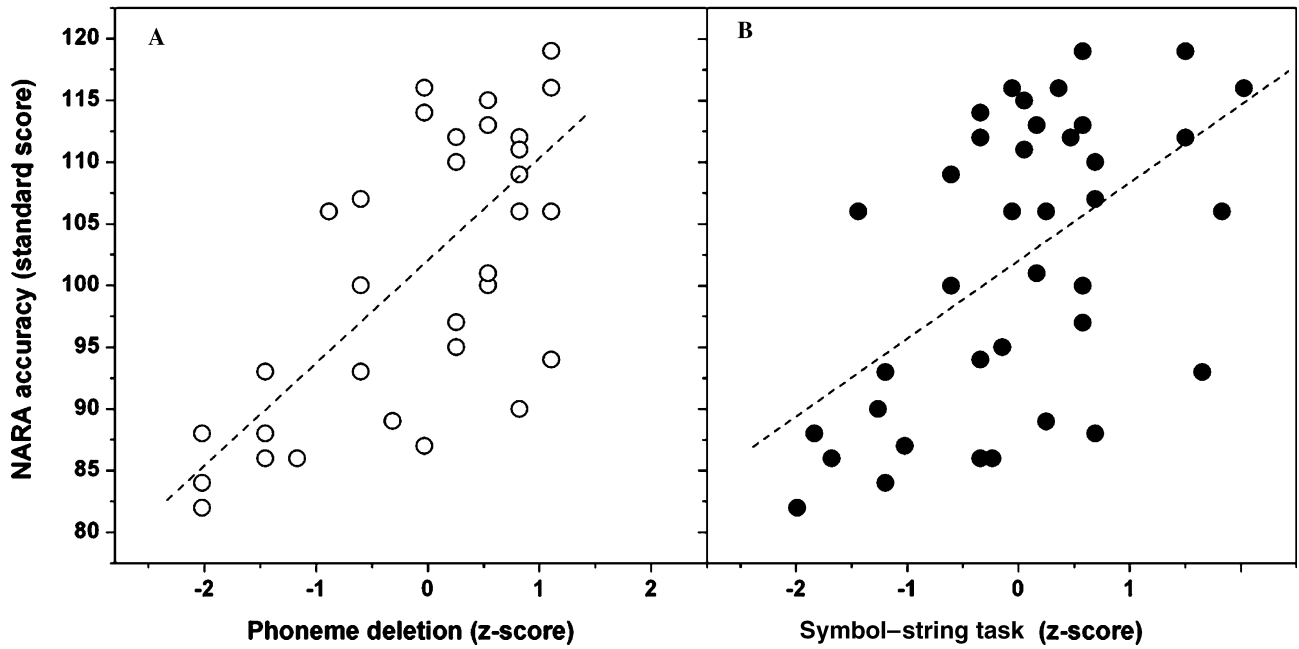


Fig. 2. Scatter plots showing the relationship between: NARA scores and (A) phoneme deletion (open circles) and (B) symbols (filled circles), respectively, in Experiment 1. Both phoneme deletion and symbols scores have been converted to Z-scores for centering in the multiple regression analysis. The dotted lines in each case represent simple linear regression curves between dependent and explanatory variables.

sensitivity, while statistically accounting for effects of IQ, age, phonological skills, and digit-span. The best-fit model accounted for 68% of the total variance in children’s reading accuracy and is: $y = 5.9x_1 - 3.8x_2 + 5.6x_3 + 102.0$, where: y = NARA accuracy, x_1 = Z-score for phoneme deletion ($p < .0001$), x_2 = Z-score for age ($p < .01$), and x_3 = Z-score for symbols task ($p < .0005$). This model minimises Mallows’ C_p statistic, maximises R^2 , and only contains explanatory variables significant at $p < .05$. Fifty-eight percent of the total variance was explained by the combination of symbols task and phoneme deletion alone, presumably because of the small variability in age of our sample population.

However, interpretation of this result is not straightforward, because, as Table 2 shows, there are a number of significant correlations between explanatory variables: e.g., between phoneme deletion and symbols,

between symbols and digit span, between symbols and age, and between age and phoneme deletion and RAN. This implies that the explanatory variables share common pools of variance.

Of primary concern is the correlation between symbols and phoneme deletion since they are two of the explanatory variables left in the best fit multiple regression model. The question here is; what cognitive/visual demands might these two tasks share? To address this, we ran a series of correlations between NARA, symbols and phoneme deletion while separately partialling out effects attributable to digit span, similarities, matrices, age or RAN. Table 3 shows that the correlations between NARA and symbols and between NARA and phoneme deletion always remained significant. However, only when the effects of digit span were partialled out, was the relationship between symbols and

Table 2
Pearson correlation matrix between dependent and independent variables in Experiment 1

	NARA	Age	Similarities	Matrices	Digit span	Symbols	Phoneme deletion
Age	-.14						
Similarities	.29	-.097					
Matrices	.48*	-.20	.33*				
Digit span	.45*	.012	-.015	.22			
Symbols	.54**	.42*	.18	.25	.58**		
Phoneme deletion	.71***	-.036	.06	.38*	.31	.40*	
RAN	.35*	-.076	.015	.23	.15	.16	.45**

* $p < .05$.
 ** $p < .005$.
 *** $p < .0005$.

Table 3
Partial correlation analysis for Experiment 1

Correlation between NARA and symbols	Correlation between NARA and phoneme deletion	Correlation between symbols and phoneme deletion	Partial variables
.54**	.71***	.40*	None
.40*	.67***	.28 n.s.	Digit span
.52**	.73***	.39*	Similarities
.47**	.65***	.34*	Matrices
.67***	.71***	.45**	Age
.53***	.66***	.37*	RAN
.46**	.62***	.28 n.s.	Digit span, similarities, matrices, age, and RAN

The first, second, and third columns show the correlation coefficients between NARA and symbols, NARA and phoneme deletion, symbols and phoneme deletion, respectively. The fourth column states the variable(s) whose effects were partialled out.

* $p < .05$.

** $p < .005$.

*** $p < .0005$.

Table 4
Results of the hierarchical regression analysis

Model	Added variables	Total R^2 (%)	ΔR^2 (%)	F ratio	p value
(1) $I + AGE + SIM + MAT$		25		3.57	<.05
(2) $I + AGE + SIM + MAT + PHON + RAN$	+PHON & RAN	59	34	13.7	<.0001
(3) $I + AGE + SIM + MAT + PHON + RAN + DS$	+DS	65	6	4.9	<.05
(4) $I + AGE + SIM + MAT + PHON + RAN + DS + SYM$	+SYM	70	5	4.9	<.05

The first F ratio is a test of the hypothesis that the initial model has no predictive value. The second, third and fourth F ratios test whether the addition of new variables adds any predictive ability to the preceding model. NB: I , intercept; SIM, BAS similarities; MAT, BAS matrices; PHON, phoneme deletion; RAN, rapid automatized naming for digits; DS, BAS digit span; and SYM, symbols task.

phoneme deletion rendered non-significant. This suggests that the common pool of variance that is related to both phoneme deletion and symbols and which is also associated with reading accuracy is most likely acting through a common demand on short-term or working memory.

In Experiment 1 we sought correlational evidence for a visual component to children's reading—in this case related to symbol string position sensitivity. Accordingly, the partial correlation analysis showed that once digit span measures were taken into account, symbols and phoneme deletion were rendered statistically independent of each other while both remained significantly correlated with NARA scores. Nevertheless, it is still logically plausible that the symbols task is acting as a proxy cognitive/phonological task, for example, rather than a direct test of pre-orthographic visual sensitivity. If this alternative were true—that symbols is more of a cognitive/phonological task than a visual task—then so much of its variance should be bound up with the other explanatory variables, that there should be nothing left to explain when entered as the last step in a hierarchical regression. In contrast, if symbols is more of a visual than a cognitive/phonological task, despite sharing variance with other explanatory variables, it should nevertheless explain a unique component in NARA scores when entered as the last step in a hierarchical regression. The results of such an analysis are shown in

Table 4. Symbols remained statistically significant when entered last into the model and this is consistent with a purely visual component to children's reading.

3. Experiment 2

A widely accepted explanation for developmental dyslexics' reading difficulties is based in phonological deficit theory: fuzzy or under-specified phonological representations prevent the development of a fast, efficient mechanism for mapping letter/letter-clusters onto sound/sound-clusters during reading (Bradley & Bryant, 1983; Brady & Shankweiler, 1991; Stanovich, 1988). Consequently people with dyslexia are extremely slow and inaccurate readers. However, research has also shown that many dyslexics' 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 (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Livingstone, Rosen, Drislane, & Galaburda, 1991; Lovegrove et al., 1982; Lovegrove, Martin, & Slaghuis, 1986; Martin & Lovegrove, 1987; Mason, Cornelissen, Fowler, & Stein, 1993) 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). With some exceptions (Gross-Glenn et al., 1995; Hayduk, Bruck, & Cavanagh, 1996; Walther-Müller, 1995; also see Skottun, 2000; for review), these results have been replicated in a number of psychophysical studies, and have been corroborated to some extent both electrophysiologically and with functional MRI (Demb, Boynton, & Heeger, 1997; Eden et al., 1996; Lehmkuhle, Garzia, Turner, Hash, & Baro, 1993). The fact that laboratory experiments have shown visual processing correlates of developmental dyslexia therefore raises an important question: can reading difficulties be caused by visual system impairment as well as deficient phonological skills, or are the demonstrated visual problems merely an epiphenomenon?

Neurobiological models that might explain the deficient visual processing skills associated with dyslexia have previously been proposed: for example, it has been suggested that developmental dyslexia is associated with an underlying magnocellular system and/or temporal processing deficit (for critical reviews see Habib, 2000; Stein, Talcott, & Walsh, 2000). While these two theories are consistent with much of the experimental data, both remain controversial (Skottun, 2000; Snowling, 2000). Ultimately, they may be better at accounting for the co-occurrence of impairments across peripheral sensory domains (e.g., vision and audition, Talcott et al., 2000), than explaining in any detail how impaired visual processing affects reading per se (but see Chase, Ashourzadeh, Kelly, Monfette, & Kinsey, 2003 for a plausible account). Certainly, it has proven very difficult for either theory to predict patterns of reading impairment satisfactorily—perhaps in part because too many of the language-related links between vision, audition, and reading are still relatively unknown or poorly specified.

Alternatively, cognitive models of visual word recognition suggest that the early analysis of print provides information about the identity and position of each letter in a string (Grainger & Dijkstra, 1995; Whitney, 2001). Given this, it is not unreasonable to suggest that subtle visual impairment in reading impaired individuals may cause a subjective perceptual uncertainty about letter position when they read. In this way, sensitivity to position may provide a link between visual processing difficulties and reading impairment. In order to test this prediction, the symbols task was used to compare position sensitivity in poor readers and normal reading controls of the same average age, verbal, and non-verbal IQ.

3.1. Method

3.1.1. Participants

Thirteen poor readers and 13 normal readers participated in this experiment. All participants were recruited from schools in the local Tyneside area, and none of the children had participated in any of our other experi-

ments. The same psychometric assessment battery used in Experiment 1 was used to assess this subject group, the results of which are in Table 1. Clinical or educational psychologists had previously diagnosed each of the poor readers as reading disabled on the basis of significant discrepancies between their measured literacy skills and those predicted on the basis of their cognitive skills. We confirmed that our poor readers all had a standard score of ≤ 85 on a NARA composite score (where the composite score was made up of no two scores over 85).

3.1.2. Stimuli and procedure

The experiment was conducted according to the procedure described in Experiment 1, and used the same stimuli and hardware.

3.2. Results

The initial treatment of the data was the same as for Experiment 1. Group performance on the symbols task is shown in Fig. 3. A two-sided Wilcoxon–Mann–Whitney comparison showed that poor readers (mean = .7, *SE* .12) had significantly reduced symbols sensitivity compared to controls (mean = 1.17, *SE* .09), ($Z = 2.57$, $p = .01$). The correlation matrix in Table 5, between the variables is consistent with Experiment 1, with the exception of the fact that the matrices task now no longer demonstrates a significant correlation with the NARA, phoneme deletion, and similarities task.

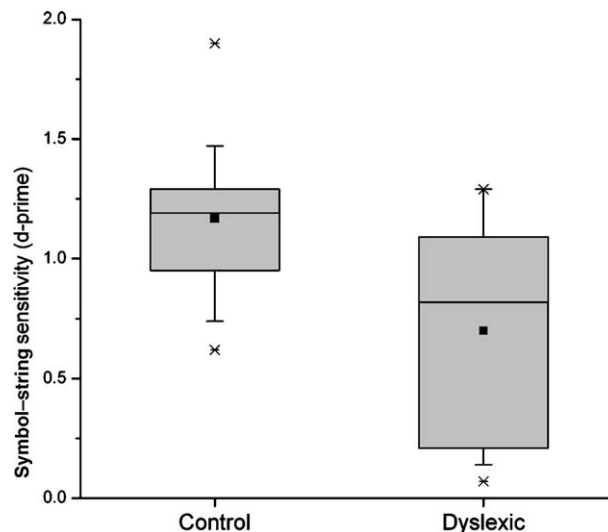


Fig. 3. Box plots showing the groups' performance on the symbol-string task in Experiment 2. Horizontal lines within boxes represent the group medians. Box edges define the first and third quartiles, whisker edges define the 10th and 90th percentiles. The solid square in each case represents the group mean. The * represents 1st and 99th percentiles.

Table 5
Pearson correlation matrix between dependent and independent variables in Experiment 2

	NARA	Age	Similarities	Matrices	Digit span	Symbols	Phoneme deletion
Age	-.03						
Similarities	.05	-.068					
Matrices	.32	-.20	.11				
Digit span	.55**	-.31	-.10	.23			
Symbols	.50**	.18	.43*	.28	.59**		
Phoneme deletion	.89***	.072	.10	.46*	.47*	.52**	
RAN	.64**	-.11	-.15	.27	.13	.026	.61**

* $p < .05$.

** $p < .005$.

*** $p < .0005$.

3.3. Discussion

We investigated the relationship between individual performance in the symbols task and contextual reading. In Experiment 1, we found that better performance on the symbols task is associated with more accurate reading in primary school children. In Experiment 2 we found that developmental dyslexics perform worse than age-match controls on the same symbol-string task. Together, these results suggest that reduced sensitivity to the symbols task, and therefore some aspect of pre-orthographic processing, may represent a hitherto unrecognised visual component in children's reading difficulties. However, an important question remains: what does the symbols task measure?

4. Position sensitivity

Since the information that differentiates the two alternatives in the symbols task is symbol position, it is plausible that the task is measuring some aspect of position encoding. To understand the potential relevance of this to visual word recognition, it is important to distinguish between two possibilities: absolute versus relative position encoding schemes. For words, absolute position encoding means that there exist separate representations of each letter in each position in a string, i.e., there are separate units representing "A" in the first position, "A" in the second position, etc. Therefore, for a given input, an optimal match can only occur for the same letter in the same position. Relative-position encoding means that the order of letters is encoded, without specification of their absolute positions, although anchoring of the initial and final letters is often assumed. Evidence for relative-position coding for visually presented words has been obtained from priming studies (Humphreys, Evett, & Quinlan, 1990; Peressotti & Grainger, 1999). Accordingly, the string "GRDN" can prime the target "GARDEN" just as much as "GRD-N." However, "GDRN" does not prime "GARDEN." Thus, when letter order is preserved, even when

absolute position is not, there is priming, but when order is not preserved there is no priming.

The symbols we used were unfamiliar to the children who took part in the study, so they were very unlikely to have had access to abstract representations of these stimuli. Since relative-position encoding schemes require abstract representations of ordered sequences, it is unlikely that the symbols task was measuring relative position sensitivity. It is much more likely that, if the symbols task is a measure of position sensitivity at all, then it is a measure of absolute-position sensitivity. When detecting that ABCD differs from ACBD (where A,B,C,D are any symbols), it is sufficient to notice an absolute-position mismatch (i.e., positions 2 and 3 are different).

One interesting question is whether there is any evidence to suggest that the representation of the symbol string in memory is in the form of symbol-position pairs (e.g., AB, BC, CD, etc., where A,B,C,D are any symbols), as opposed to a purely spatial pattern where no differentiation exists between individual symbols and their positions? If symbol strings were encoded as undifferentiated patterns, then there should be no differences in sensitivity to the three kinds of position swap (i.e., between positions 2/3, 3/4, and 2/4). However this was not the case; mean d' scores for these three conditions were: .79 (SD .13), .78 (SD .12), and .67 (SD .09), respectively, suggesting that the non-adjacent, position 2/4 swaps were harder to detect than the two kinds of adjacent position swaps. Moreover, the pattern of Pearson correlations between the three conditions was: .55 ($p < .0005$), .32 ($p > .05$), and .16 ($p > .1$) for position swaps 2/3 versus 3/4, 2/3 versus 2/4, and 3/4 versus 2/4, respectively. Thus, children's performance was more similar when the two adjacent position swaps are compared, than it was for either of the comparisons between adjacent and non-adjacent swaps. In short, it matters where the position swaps occur. This suggests one of two possibilities: children's viewing strategies could have resulted in these within task difference. For example, they may have preferred to focus their attention towards one or other end of the symbol-string rather than the middle. Alternatively, the spatial coding system for

symbols may indeed operate on a scale smaller than the complete 5-element string and some kind of symbol pair scheme is one plausible candidate.

5. Iconic memory and visual attention

Individual differences in the symbols task might also reflect variation in the speed/accuracy of read-out from iconic memory into a more durable short-term store (cf. Coltheart, 1980). Interestingly, Gang and Siegel (2002) found recently that developmental dyslexics showed iconic memory impairments compared to age matched controls. This implies that deficits in iconic memory could well impinge on visual word recognition skills. In our experiments, the fact that we always used backward masking means that iconic memory would have been erased on each trial of the symbols tasks (cf. Averbach & Coriell, 1961). However, as shown by Gegenfurtner and Sperling (1993), prior to erasure, transfer of information from iconic memory to more durable storage is governed by a combination of the quality of the information stored (they use the term 'iconic legibility,' which depends on time and retinal location) and the allocation of attention. Indeed, in their computational model of this information transfer, Gegenfurtner and Sperling (1993) explicitly state that transfer rate from iconic memory is determined by the *product* of attentional allocation and iconic legibility. Therefore, not only could individual variability in iconic memory account for at least some of the variability in the symbols task, but the same could also be true for visual attention.

Visual attention serves to filter and prioritise the visual information available at any given moment. It is a critical determinant of what portions of the visual field and what features of objects our brains preferentially process. Research has directly linked attention to reading, and by implication, the symbol-string task (Casco, Tressoldi, & Dellantonio, 1998; McCarthy & Nobre, 1993). Reading may be conceived of as a sequential attention model: attention is allocated at the location at which one is fixating, then moved to the specific location toward which the eyes are about to move. Reaction-time word identification studies (Rayner, 1992) have provided empirical evidence for this model. A number of studies have reported that deficits in visual attention exist in people with reading disabilities (Bouma & Legein, 1977; Brannan & Williams, 1987; Facoetti & Molteni, 2001; Steinman, Steinman, & Garzia, 1998; Vidyasagar & Pammer, 1999; Williams, Brannan, & Lartigue, 1987). It is therefore plausible that individual differences in symbols task performance might simply be a reflection of natural variation in either the spatial or the temporal aspects of visual attention. While we were able to exclude this possibility with respect to performance in the symbols task and lexical decision in adults (Pammer et al., 2004),

further research is required to exclude this possibility in relation to the symbols task and children's reading.

6. Phonological awareness and short-term memory

A third possibility is that the symbols task is really a proxy measure of phonological awareness. While logically plausible, this suggestion has little face validity because the symbols task and the phoneme deletion task are very different both in mode of presentation, and their general stimulus properties; the symbols task constitutes the rapid visual presentation of previously unseen items, whereas the phoneme deletion task is presented auditorily, by the experimenter, slowly in comparison and requires conscious manipulation of speech sounds. Moreover, the correlation between symbols and phoneme deletion was relatively weak ($r = .4$), and the hierarchical regression showed that symbols predicted a unique proportion of the variance in children's reading. This suggests that the non-shared proportion of the variance in the symbols-string task is more likely to be related to a component of children's visual rather than phonological skills.

However, the correlation between phonological awareness and the symbols task still needs to be explained. A key observation is that once the effects of digit span were partialled out, symbols and phoneme deletion were rendered statistically independent of each other. This suggests that the relationship between the symbols and phoneme deletion tasks is mediated through a common requirement for short-term or working memory resources. One might expect that the phoneme deletion task makes demands on both the storage and processing components of working memory, because it requires a child to hold a word in mind (perhaps spell it out or visualise it), remove one sound, and work out what is left. Similarly, the symbols task is likely to draw on working memory resources, and may even require some degree of subvocal rehearsal between the presentation of the target and the point at which a child chooses between the alternative symbol-strings. It is known that complex working memory tests (like counting span and listening span) are correlated with phonological awareness tasks (like onset rime detection and phoneme deletion) and reading (Goswami & Bryant, 1990; Leather & Henry, 1994; but see Oakhill & Kyle, 2000). Therefore, if individual variation in our sample's digit span were largely attributable to individual variation in storage capacity, then this may account for the correlation we found between the symbols-string and phoneme deletion tasks. Once it was removed by the partial correlation procedure, the symbols and phoneme deletion scores were thereby rendered independent of each other.

Another possible explanation for the relationship between phoneme deletion and the symbols task is

dependence on speech rate. The number of items in a digit span task that can be recalled immediately is also related to the rate at which an individual can speak (Cowan, 1999; Cowan et al., 1998). This fact may in turn be related to either subvocal rehearsal (articulatory recoding) in working memory or speed of processing (Smyth & Scholey, 1996). In principle therefore, the link between symbols and phoneme deletion might have been mediated by individual variation in the articulation/processing speed components of the digit span task. For this to be true, we would also have expected to see a significant relationship between symbols and the rapid automatized naming task (RAN); performance on RAN tasks is known to depend to some extent on speed of articulation (Neuhaus, Foorman, Francis, & Carlson, 2001). But no such correlation was found. Moreover, the same lack of correlation between symbols and RAN makes it unlikely that the children who were good at the symbols-string task were merely good at developing and rapidly rehearsing new verbal labels for the novel symbols. Also, presentation of the symbols string was only 100 ms, which is likely to be too fast to apply a phonemic-based coding strategy. In summary, the relationship between reading and the symbols task cannot be easily explained in terms of individual variation in phonological skills and/or verbal short-term memory.

7. Conclusions

The results presented here, suggest a plausible link between individual variation in pre-orthographic visual processing skills and reading. The fact that we found reduced sensitivity to the symbols task in our dyslexic sample is also consistent with the idea that a visual impairment of some kind could affect (some) children's reading, although we are unable to make any assertions regarding causality. This would require longitudinal studies which are beyond the scope of the current paper. There is reasonable evidence to support the idea of reciprocal causation, such that learning to read promotes phonological awareness as well as vice versa (Perfetti, Beck, Bell, & Hughes, 1987). It is therefore possible that extensive practice at learning to read facilitates children's ability to rapidly encode any string-like stimulus presented visually.

In summary, we have shown that dyslexic readers are less sensitive than controls on the symbol-strings task, and that high sensitivity is associated with accurate reading in primary school children. Therefore, while the symbols task itself requires further elucidation, the present results strongly suggest that there are pre-orthographic visual factors, independent from phonological deficits, which may also contribute to some children's reading difficulties.

Acknowledgments

The authors thank Andy Thomson and Don Boogart for technical assistance during this study. This research was supported by grants to Dr. Cornelissen from the Wellcome Trust and the Royal Society.

References

- Averbach, E., & Coriell, E. (1961). Short-term memory in vision. *Bell System Technical Journal*, *40*, 309–328.
- Besner, D., & McCann, R. (1987). Word frequency and pattern distortion in visual word identification and production: An examination of four classes of models. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading*. Hillsdale, NJ: Erlbaum.
- Bjork, M. J., & Murray, J. T. (1977). On the nature of input channels in visual processing. *Psychological Review*, *84*, 472–484.
- Bouma, H., & Legein, C. (1977). Foveal and parafoveal recognition of letters and words by dyslexics and by average readers. *Neuropsychologia*, *15*, 69–79.
- Bradley, L., & Bryant, P. (1983). Categorizing sounds and learning to read—a casual connection. *Nature*, *301*, 419–421.
- Brady, S., & Shankweiler, D. (1991). *Phonological processes in literacy*. Hillsdale, NJ: Erlbaum.
- Brannan, J., & Williams, M. (1987). Allocation of visual attention in good and poor readers. *Perception & Psychophysics*, *41*, 23–28.
- Casco, C., Tressoldi, P., & Dellantonio, A. (1998). Visual selective attention and reading efficiency are related in children. *Cortex*, *34*, 531–546.
- Chase, C., Ashourzadeh, A., Kelly, C., Monfette, S., & Kinsey, K. (2003). Can the magnocellular pathway read? Evidence from studies of color. *Vision Research*, *43*, 1211–1222.
- Chastain, G. (1977). Feature analysis and the growth of a percept. *Journal of Experimental Psychology*, *3*, 291–298.
- Coltheart, M. (1980). Iconic memory and visible persistence. *Perception & Psychophysics*, *27*, 183–228.
- Cornelissen, P., & Hansen, P. (1998). Motion detection, letter position encoding, and single word reading. *Annals of Dyslexia*, *48*, 155–188.
- Cornelissen, P., Hansen, P., Gilchrist, I., Cormack, F., Essex, C., & Frankish, C. (1998a). Coherent motion detection and letter position encoding. *Vision Research*, *38*, 2181–2191.
- Cornelissen, P., Hansen, P., Hutton, J., Evangelinou, V., & Stein, J. (1998b). Magnocellular visual function and children's single word reading. *Vision Research*, *38*, 471–482.
- Cornelissen, P., Richardson, A., Mason, A., Fowler, S., & Stein, J. (1995). Contrast sensitivity and coherent motion detection measures at photopic luminance level in dyslexic readers and controls. *Vision Research*, *35*, 1483–1494.
- Cowan, N. (1999). The differential maturation of two processing rates related to digit span. *Journal of Experimental Child Psychology*, *72*, 193–209.
- Cowan, N., Wood, N., Wood, P., Keller, T., Nugent, L., & Keller, C. (1998). Two separate verbal processing rates contributing to short-term memory span. *Journal of Experimental Psychology—General*, *27*, 141–160.
- Cutting, L., & Denckla, M. B. (2001). The relationship of rapid serial naming and word reading in normally developing readers: An exploratory model. *Reading and Writing: An Interdisciplinary Journal*, *14*, 673–705.
- Demb, J., Boynton, G., & Heeger, D. (1997). Brain activity in visual cortex predicts individual differences in reading performance. *Proceedings of the National Academy of Sciences*, *94*, 13363–13366.

- Eden, G., VanMeter, J., Rumsey, J., Maisog, J., Woods, R., & Zeffiro, T. (1996). Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. *Nature*, *382*, 66–70.
- Elliot, C., Smith, P., & McCulloch, K. (1996). British abilities scales. 2nd ed.
- Facoetti, A., & Molteni, M. (2001). The gradient of visual attention in developmental dyslexia. *Neuropsychologia*, *39*, 352–357.
- Frederickson, N., Frith, U., & Reason, R. (1997). *Phonological assessment battery*. NFER-Nelson: Windsor.
- Gang, M., & Siegel, L. S. (2002). Sound-symbol learning in children with dyslexia. *Journal of Learning Disabilities*, *35*(2), 137–157.
- Gegenfurtner, K. R., & Sperling, G. (1993). Information transfer in iconic memory experiments. *Journal of Experimental Psychology: Human Perception and Performance*, *19*(4), 845–866.
- Gescheider, G. (1997). *Psychophysics, the fundamentals*. London, NJ: Erlbaum.
- Goswami, U., & Bryant, P. (1990). *Phonological skills and learning to read*. Hove: Erlbaum.
- Grainger, J., & Dijkstra, T. (1995). Visual word recognition. In A. Dijkstra & K. Smedt (Eds.), *Computational psycholinguistics: symbolic and subsymbolic models of language processing*. UK: Harvester Wheatsheaf.
- Grainger, J., & Jacobs, A. (1996). Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review*, *103*, 518–565.
- Gross-Glenn, K., Skottun, B., Glenn, W., Kushch, A., Lingua, R., Dunbar, M., et al. (1995). Contrast sensitivity in dyslexia. *Visual Neuroscience*, *12*, 153–163.
- Habib, M. (2000). The neurological basis of developmental dyslexia—An overview and working hypothesis. *Brain*, *123*, 2373–2399.
- Hayduk, S., Bruck, M., & Cavanagh, P. (1996). Low-level visual processing skills of adults and children with dyslexia. *Cognitive Neuropsychology*, *13*, 975–1015.
- Hansen, P., Stein, J., Orde, S., Winter, J., & Talcott, J. (2001). Are dyslexics' visual deficits limited to measures of dorsal stream function. *Neuroreport*, *12*, 1527–1531.
- Humphreys, G., Evett, L., & Quinlan, P. (1990). Orthographic processing in visual word identification. *Cognitive Psychology*, *22*, 517–561.
- Krumhansl, C. L., & Thomas, E. A. C. (1976). Extracting identity and location information from briefly presented letter arrays. *Perception & Psychophysics*, *20*, 243–258.
- Leather, C., & Henry, L. (1994). Working memory span and phonological awareness tasks as predictors of early reading ability. *Journal of Experimental Child Psychology*, *58*, 88–111.
- Lehmkühle, S., Garzia, R., Turner, L., Hash, T., & Baro, J. (1993). A defective visual pathway in children with reading-disability. *New England Journal of Medicine*, *328*(14), 989–996.
- Livingstone, M., Rosen, G., Drislane, F., & Galaburda, A. (1991). Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia. *Proceedings of the National Academy of Sciences (USA)*, *88*, 7943–7947.
- Lovegrove, W., Martin, F., Bowling, A., Blackwood, M., Badcock, D., & Paxton, S. (1982). Contrast sensitivity functions and specific reading disability. *Neuropsychologia*, *20*, 309–315.
- Lovegrove, W., Martin, F., & Slaghuis, W. (1986). A theoretical and experimental case for a visual deficit in reading disability. *Cognitive Neuropsychology*, *3*, 225–267.
- Martin, F., & Lovegrove, W. (1987). Flicker contrast sensitivity in normal and specifically disabled readers. *Perception*, *16*, 215–221.
- Mason, A., Cornelissen, P., Fowler, M., & Stein, J. (1993). Contrast sensitivity, ocular dominance and specific reading disability. *Clinical Vision Sciences*, *8*, 345–353.
- McCarthy, G., & Nobre, A. (1993). Modulation of semantic processing by spatial selective attention. *Electroencephalography and Clinical Neurophysiology*, *83*, 210–219.
- McDougall, S., Hulme, C., Ellis, A., & Monk, A. (1994). Learning to read: The role of short-term memory and phonological skills. *Journal of Experimental Child Psychology*, *58*, 112–133.
- Neale, M. (1997). *Neale analysis of reading ability*. NFER-Nelson: Windsor.
- Neuhaus, G., Foorman, B., Francis, D., & Carlson, C. (2001). Measures of information processing in Rapid Automatized Naming (RAN) and their relation to reading. *Journal of Experimental Child Psychology*, *78*, 359–373.
- Oakhill, J., & Kyle, F. (2000). The relation between phonological awareness and working memory. *Journal of Experimental Child Psychology*, *75*, 152–164.
- Pammer, K., Lavis, R., Hansen, P., & Cornelissen, P. (2004). Natural variability in position encoding predicts lexical decision. *Society for the Scientific Study of Reading* (under review).
- Pammer, K., & Wheatley, C. (2001). Isolating the M(y)-cell response in dyslexia using the spatial frequency doubling illusion. *Vision Research*, *41*, 2139–2147.
- Peressotti, F., & Grainger, J. (1995). Letter-position coding in random consonant arrays. *Perception & Psychophysics*, *57*, 875–890.
- Peressotti, F., & Grainger, J. (1999). The role of letter identity and letter position in orthographic priming. *Perception & Psychophysics*, *61*, 691–706.
- Perfetti, C., Beck, I., Bell, L., & Hughes, C. (1987). Phonemic knowledge and learning to read are reciprocal: A longitudinal study of first grade children [Special issue]. *Merrill-Palmer Quarterly*, *33*, 283–320.
- Rayner, K. (1992). *Eye movements and visual cognition: Scene perception and reading*. New York: Springer.
- Skottun, B. (2000). The magnocellular deficit theory of dyslexia: the evidence from contrast sensitivity. *Vision Research*, *40*, 111–127.
- Smyth, M., & Scholey, K. (1996). The relationship between articulation time and memory performance in verbal and visuospatial tasks. *British Journal of Psychology*, *87*, 179–191.
- Snowling, M. (2000). *Dyslexia*. Oxford: Blackwell Publishers.
- Sperling, A. J., Zhong-lin, L., Manis, F. R., & Seidenberg, M. S. (2003). Selective magnocellular deficits in dyslexia: A “phantom contour” study. *Neuropsychologia*, *41*, 1422–1429.
- Stanovich, K. (1988). Explaining the differences between the dyslexic and the garden-variety poor reader: the phonological core, variable-difference model. *Journal of Learning Disabilities*, *21*, 590–612.
- Stein, J., Talcott, J., & Walsh, V. (2000). Controversy about the visual magnocellular deficit in developmental dyslexics. *Trends in Cognitive Sciences*, *4*, 209–211.
- Steinman, S., Steinman, B., & Garzia, R. (1998). Vision and attention II: Is visual attention a mechanism through which a deficient magnocellular pathway might cause reading disability? *Optometry and Vision Science*, *75*, 674–681.
- Strangert, B., & Brännström, L. (1975). Spatial interaction effects in letter processing. *Perception & Psychophysics*, *17*, 268–272.
- Talcott, J., Witton, C., McLean, M., Hansen, P., Rees, A., Green, G., & Stein, J. (2000). Dynamic sensory sensitivity and children's word decoding skills. *Proceedings of the National Academy of Sciences of the United States of America*, *97*, 2952–2957.
- Vidyasagar, T. R., & Pammer, K. (1999). Impaired visual search in dyslexia relates to the role of the magnocellular pathway in attention. *Neuroreport*, *10*, 1283–1287.
- Walther-Müller, P. (1995). Is there a deficit of early vision in dyslexia? *Perception*, *24*, 919–936.
- Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review*, *8*, 221–243.
- Williams, M., Brannan, J., & Lartigue, D. (1987). Visual search in good and poor readers. *Clinical Vision Science*, *1*, 367–371.