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Temporal processing in poor adult readers

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Abstract

The aim of this study was to investigate the relationships between two different temporal processing tasks and word identification performance in skilled, dyslexic and poor adult readers. In Experiment 1 spatial and temporal sequencing tasks were conducted. It was found that adult dyslexics were significantly less accurate than skilled readers across all conditions in the temporal sequencing task, and when higher numbers of stimuli were presented in the spatial task. Experiment 2 replicated Experiment 1 in the temporal sequencing task and also found that poor readers had significantly higher motion coherence thresholds than those found in the skilled reader group. Ten percent of the variance in coherence thresholds was accounted for by performance on the temporal sequencing task. Multiple regression analyses determined that performance on the two temporal tasks could explain seventy percent of the variance in word identification scores, with the temporal sequencing task making the larger independent contribution. Experiment 3 replicated the findings of Experiment 2, while taking into account IQ, verbal memory and processing speed. Three things were concluded. First, the temporal tasks measure different aspects of temporal processing. The contribution to performance of higher-level perceptual and attentional components of the temporal sequencing task accounts for the relatively weak correlation found between the two measures. While sensory sensitivity to motion is measured at MT, the involvement of this area and PPC in higher-level perceptual and attentional processes is suggested by the findings of this study. Second, the association between temporal sequencing and reading skills may provide a stronger link between neural processing and poor reading skills than basic sensory processing measures alone, suggesting that a sensory magnocellular (M) system deficit cannot fully explain the relationship found between reading and visual neural processing. Third, problems with rapid sequential processing are predicted to be a generalised problem in poor adult readers, whether they are formally classified as dyslexic, or are poor performers on measures of word identification. Temporal processing may follow a distribution similar to that found for word identification skills.

Keywords: Temporal processing; Rapid sequencing; Motion coherence; Attention; Dyslexia

1. Introduction

It has been estimated that between 5 and 17.5% of the English speaking population experience significant problems with the acquisition of reading skills (Rutter & Yule, 1975; Shaywitz, Escobar, Shaywitz, Fletcher, & Makugh, 1992). Shaywitz et al. (1992) argue that this group forms the lower tail of the normal distribution. While there is considerable evidence of a core difficulty in phonological processing (Snowling, 2000), the evidence of a deficit in temporal processing in either or both the auditory (Farmer & Klein, 1995; Hari & Kiesila, 1996; Witton et al., 1998) and visual domains (Habib, 2000; Hari & Renvall, 2001; Talcott et al., 1998) is less consistent. Some of the more consistent evidence of a temporal processing deficit in the visual domain has found differences between dyslexic and non-impaired reader groups on measures of supra-threshold sensory processing (Talcott et al., 1998) and on tasks that measure processing of rapidly presented stimulus sequences (Hari & Renvall, 2001; Laasonen, Service, & Virsu, 2001; Laasonen, Tomma-Halmer, Lahti-Nuuttila Service, & Virsu, 2000). These effects have been found in both children and adults. Relationships have also been found in the normal population between measures of temporal processing and word identification (Au & Lovegrove, 2001; Conlon, Mellor, & Wright, 2001; Talcott et al., 2000b). These findings demonstrate that the association between visual temporal processing and word identification skills may be an individual difference, with poor word identifiers less efficient temporal processors, regardless of whether a formal classification of dyslexia is warranted. In this study, Experiment 1 will use participants with a specific childhood classification of dyslexia with Experiments 2 and 3 using poor word identification skills as a basis for reader group classification.

The second focus of the studies reported is the nature of the deficits found in the visual temporal processing system. A deficit in rapid sequential processing has been

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linked to a temporal processing deficit (Habib, 2000; Hari & Renvall, 2001; Stein & Walsh, 1997) in both the auditory (Tallal, 1980) and visual domains (Eden, Stein, Wood, & Wood, 1995; Hansen, Stein, Orde, Winter, & Talcott, 2001; Laasonen et al., 2000; Williams & LeCluyse, 1990). These effects may occur as a result of a direct sensory impairment (Slaghuis & Ryan, 1999; Stein, 2001; Talcott, Hansen, Assoku, & Stein, 2000a), attention deficits (Facoetti & Massimo, 2001; Steinman, Steinman, & Lehmkuhle, 1997) or in the perceptual requirements of the temporal tasks used (Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Hill & Raymond, 2002; Laasonen et al., 2001). Differences in the contribution of these variables to performance may account for some of the inconsistent findings found in the literature.

In the visual system, physiological evidence has shown that the larger M-cells project from the magnocellular (M) layers of the lateral geniculate nucleus (LGN) through V1 to some extrastriate areas including MT and MT+, with the posterior parietal cortex (PPC) as the endpoint (Merigan & Maunsell, 1993). The early description that an M deficit in dyslexia originated in the M layers of the LGN and occurred as a result of a neural abnormality (Livingstone, Rosen, Drislane, & Galaburda, 1991) has not been consistently supported. Some studies of contrast threshold have shown a temporal processing deficit among dyslexics (e.g. Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001; Felmingham & Jakobson, 1995; Martin & Lovegrove, 1988) with some showing no between group differences (e.g. Skottun, 2000; Stuart, McAnally, & Castles, 2001; Williams, Stuart, Castles, & McAnally, 2003). More consistent evidence of this deficit has been found at MT. Examples of stimuli that have produced between group differences on psychophysical tasks include motion coherence (Everatt, Bradshaw, & Hibbard, 1999; Raymond & Sorensen, 1998; Talcott et al., 1998) flicker fusion (Talcott et al., 1998), speed discrimination (Demb, Boynton, Best, & Heeger, 1998; Demb, Boynton, & Heeger, 1998) and motion transparency (Hill & Raymond, 2002). Investigation using functional MRI has found differences in activation between dyslexic and control groups at MT and MT+ on a speed discrimination task. In addition, a strong correlation has been found between individual differences in MT+ activity and reading rate (Demb, Boynton, Best, & Heeger, 1998; Demb, Boynton, & Heeger, 1998). Using the same technology Eden et al. (1996) found less activation at MT in a dyslexic than a control group on a motion coherence task. When a task that selectively activates the form processing system was used, no between group differences were found. These data demonstrate a relationship between temporal processing at MT and MT+ and reading.

In studies of motion coherence, where the dyslexic group requires a greater percentage of coherently moving dots to correctly identify the direction of stimulus motion, a number of parameters have been manipulated to determine the stimulus characteristics that explain between group differences. Talcott et al. (1998) have demonstrated that regardless of stimulus duration or dot size, a group of adult dyslexics has poorer motion coherence thresholds than a control group. With manipulation of dot density, performance of the dyslexic group improved as dot density increased with the highest dot density (12.2 dots/degree^2) producing no between group differences. Poorer summation of signal dots as well as poor temporal integration was used to explain these data. In a recent study that also used a high dot density, no between group differences were found (Hill & Raymond, 2002). Raymond and Sorensen (1998) manipulated the number of frames and frame duration, finding no between group differences with presentation of two-frames at short or long frame durations. Between group differences were found with presentation of four or seven-frames. Poorer temporal integration of visual signals has been used to explain poorer performance of the dyslexic group (Raymond & Sorensen, 1998; Talcott et al., 2000a).

In studies of motion coherence some overlap in performance between dyslexic and control groups has been found. Some data have led to predictions that efficiency of temporal processing may exist along a continuum, with increasing sensory sensitivity co-existing with word identification skills (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Talcott et al., 2000a; Witton et al., 1998). Using an unselected sample of 10-year olds, Cornelissen and Hansen (1998) demonstrated that children with increasingly poor motion coherence thresholds make a greater number of orthographic letter errors. Talcott et al. (1998) have found a high correlation between non-word reading, motion coherence thresholds and flicker fusion thresholds in a sample of adult developmental dyslexics and controls. A measure of orthographic processing was not obtained in the study. Using discriminant function analysis, 72.2% of the dyslexic group were successfully discriminated from controls using the two measures of visual processing. When a sample of 32, 10-year olds were used, Talcott et al. (2000b) found significant correlations between motion coherence thresholds and orthographic processing, phonological processing and segmentation skills. In a more recent study with a larger sample of school children, these relationships, while still found, were substantially smaller (Talcott et al., 2002). In a sample of dyslexic and control adults Demb, Boynton, Best, and Heeger (1998) found a high correlation ($r = -0.84$) between reading rate and speed discrimination thresholds. Together these findings demonstrate a link between different aspects of skilled reading and sensory processing of motion signals.

One recent study (Ben-Yehudah et al., 2001) has combined the presentation of sensory stimuli at a threshold level with different forms of two alternative forced choice (2AFC) techniques. In this method two panels are presented, either spatially or temporally, with the target stimulus presented in one panel only. The participant is required to determine in which of the two panels the stimulus is presented. In the spatial condition, two panels are presented simultaneously and in the temporal task the two panels are separated by an ISI of up to 1 s. Significant between reader group differences in the temporal contrast sensitivity function (CSF) were only found when the temporal presentation format was used. Ben-Yehudah et al. (2001) concluded that a temporal sequencing component contributes to or enhances the visual temporal processing deficit because of a need to briefly store information concerning the temporal signals presented (Bisley & Pasternak, 2000). This finding may reconcile some negative results found previously (e.g. Skottun, 2000) with measurements of temporal contrast sensitivity.

A number of researchers have predicted that impaired processing of stimuli presented in rapid succession can account for less accurate processing of temporal information among poor readers (Farmer & Klein, 1995; Habib, 2000; Hari & Renvall, 2001; Stein & Walsh, 1997; Tallal, 1980). The interstimulus interval (ISI), which is the time between presentations of individual stimuli, stimulus duration and the type of stimulus used have all been manipulated in these studies. In the auditory domain initial reports found poor readers were selectively impaired on tasks with presentation of a short but not long ISIs between stimulus presentations (Reed, 1989; Tallal, 1980). Using similar stimulus configurations other researchers have found reduced accuracy in poor reader groups relative to control groups on rapid sequencing tasks regardless of ISIs used (Waber et al., 2001). Changes in the perceptual load of the task may provide a viable explanation of different outcomes (Amitay et al., 2002; Laasonen et al., 2001; Waber et al., 2001; Walker, Shinn, Cranford, Givens, & Holbert, 2002). Negative results have also been found, with Nittroeur (1999) failing to find any auditory temporal processing difficulties among dyslexic children with severe phonological deficits.

The impact of rapid sequencing has also been found in the visual domain. Slaghuis and Lovegrove (1985) found that a group of reading disabled children required a significantly longer ISI than a control group to reliably perceive a gap between presentation of two low spatial frequency stimulus patterns. Recently, this result has been replicated using groups of average and above average adult readers. On average the above average reader group required an ISI of 153.15 ms with average readers requiring on average 183 ms to reliably detect the gap (Au & Lovegrove, 2001). Using a version of this task where skilled and dyslexic readers were required to determine if the percept of flicker was perceived between two stimulus presentations, Chiappe, Stringer, Siegel and Stanovich (2002) reported that overall the dyslexic group were less accurate than a control group, regardless of the ISI used.

Attentional blink tasks require participants to identify two or more stimuli, generally different letters, presented among an array of rapidly presented stimuli. The attentional blink is the length of time required between presentation of the initial stimulus and target stimulus for accurate identification of both stimuli. One study using groups of dyslexic and control adults has found that the dyslexic group requires on average 160 ms longer than the control group to accurately perform the task (Hari, Valta, & Uutela, 1999). When using groups of adults with and without dyslexia Laasonen et al. (2001) failed to find significant between group differences on measures of visual temporal order judgement and temporal acuity. They argued that increasing the perceptual load of the temporal tasks used would result in poorer performance among poor readers due to increases in the signal to noise ratio produced with increasing stimulus presentations. This finding would suggest sequencing tasks of greater complexity should produce more robust between group differences.

Eden et al. (1995) demonstrated that reading disabled children are significantly less accurate than controls when counting sequences of rapidly presented stimuli separated by ISIs of between 200 and 400 ms. The correlation between reading skill and performance on this task was 0.40. A corresponding spatial task where the stimuli were presented simultaneously for 500 ms failed to find significant between group differences, although a trend was found for poor readers to perform less accurately with presentation of a larger number of stimuli. There were a number of controls incorporated into Eden et al.'s (1995) study. First, the ISIs between presentations of the temporal stimuli controlled for the minimum gap in visible persistence required for skilled readers to differentiate between presentations of two separate stimuli. Second, ISIs were randomised to avoid rhythmic counting of stimuli, so that any differences found could be attributed to poorer visual task performance. Third, inclusion of the spatial condition controlled for attention and memory as there is considerable evidence demonstrating that short-term memory is impaired in poor readers (e.g. Snowling, 2000). These studies of sequential processing demonstrate that those with poor reading skills have a slower rate of visual processing when stimuli are presented rapidly, particularly when perceptual load is high.

Experiment 1 aimed to replicate Eden et al.'s (1995) findings using groups of skilled and dyslexic adult readers. The dyslexic group consisted of adults with a childhood history of dyslexia. In addition, due to recent findings that a temporal processing deficit is found in readers with poor orthographic and phonological skills (Borsting et al., 1996; Slaghuis & Ryan, 1999) only those readers with poor phonological and orthographic skills were included. This experiment will determine if difficulties with rapid temporal sequencing extend to the adult population.

2. Experiment 1

2.1. Method

2.1.1. Participants

There were 24 volunteers, 12 of these were registered as dyslexic with the disability office at either Griffith University or the University of Queensland. The control group was recruited from the student population at Griffith University. All participants were screened for reading level using the Boder Test of Reading and Spelling Ability (Boder &

Table 1
Scores on the final word identification list of the Boder, non-word and exception word lists (Experiment 1)

	Skilled readers		Poor readers		P
	Mean	95% confidence interval	Mean	95% confidence interval	
Boder	14.92	13.24–16.6	2.33	0.18–4.49	<0.0005
Non-words	10.17	9.64–10.7	5.5	3.98–7.02	<0.0005
Exception words	8.25	7.00–9.5	3.83	2.33–5.34	<0.0005
Grade level	All post-high school		Grade 8 ($n = 1$) Grade 9 ($n = 5$) Grade 10 ($n = 6$)		

Reading grade levels for participants are included at the bottom of the table.

Jarrico, 1982) and were required to identify 11 non-words and 11 exception words that were matched for word length. There were 12 participants in the skilled reader group (11 females and 1 male) with an average age was 27.67 years (S.D. = 11.19 years). Participants in this group identified words at the post-high school level on the Boder word identification test and obtained scores of 85% or better on both the non-word and exception word reading tasks. In addition they achieved scores of 90% or better on the spelling component of the Boder. There were 12 participants in the dyslexic group (nine female and three male). The higher number of females in this group occurred as a result of the higher response rate from this group. Average age was 24.75 years (S.D. = 8.49 years). All achieved word identification skills that placed them at the high school level or lower on the word identification component of the Boder and achieved scores of less than 40% on both exception word and non-word lists. In addition less than 5 out of 10 words were spelt phonetically correctly or as good phonetic equivalents on the spelling component for unknown words of the Boder. Group characteristics are shown in Table 1. The Pearson correlation of performance on the non-word and exception word tests was 0.56.

All participants had English as a first language, normal or corrected to normal visual acuity and were studying at least at first year University level at the time of testing. An overall measure of verbal and non-verbal ability was not obtained in this study for two reasons. First, as all participants were studying at University level, it was felt they would achieve at least average levels of general ability. Second, Laasonen et al. (2001) found IQ measurement did not affect temporal processing differences between dyslexic and control adults, who had a similar educational profile to those used here. This study had Griffith University Ethics Committee clearance, which adheres to the guidelines of the National Health and Medical Research Council (NH&MRC) of Australia. All participants gave informed consent prior to participation.

2.1.2. Stimuli

A Power Macintosh computer with a super VGA monitor was used to generate stimulus presentations and collect participant responses. Director version 6.5 was used to create the spatial and temporal sequencing programs. For both conditions background luminance of the screen was 16.5 cd/m^2 to maximally stimulate the M system. The luminance of the stimulus square used for presentation was 1 cd/m^2, producing a dark square on a grey background. In both spatial and temporal conditions, each square subtended 0.57° of visual angle at a viewing distance of 30 cm.

For the temporal sequencing task, stimuli were flashed sequentially in the same location at the centre of the screen for 40 ms each. Presentation of each stimulus was followed by subsequent stimuli separated with variable ISIs ranging from 200 to 400 ms. This variable separation was used to ensure that participants could not count the number of stimuli in rhythmic order. On any one trial of the temporal condition a total of five to nine stimuli was sequentially presented. The total stimulus duration on a single trial varied on the basis of the number of stimuli presented and the variable ISI. In the spatial task, a number of stimuli ranging from five to nine were presented simultaneously for 500 ms on the computer screen in an area subtending 30.5° of visual angle vertically and 38° horizontally.

In both conditions there were 18 practice trials followed by three blocks of experimental trials, during which 12 trials per condition were randomly presented. Responses were made on the computer keyboard using keys labelled from 1 to 12.

2.1.3. Procedure

Testing took place in two sessions. In the first, word identification tasks were performed and in the second, the spatial and temporal tasks were conducted. Half the participants did the spatial task first and half the temporal task. Instructions and practice trials for each task were presented prior to the test trials in any one condition. Testing was conducted in a darkened room with a luminance of 5 cd/m^2. At the beginning of each trial a black fixation cross was presented in the centre of the computer screen, to be replaced by the first stimulus in the temporal task or the stimulus array in the spatial task. After a response was made a new trial automatically appeared. After each block of trials participants had a rest break of up to 5 min. The viewing distance was controlled by means of a chin rest and viewing was

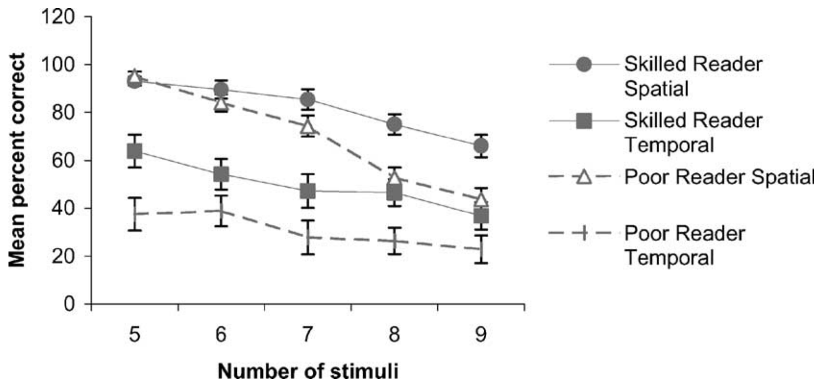

Fig. 1. Spatial and temporal counting task for mean percent accuracy scores, Experiment 1. Standard error bars represent ±1 standard errors.

binocular. Mean response accuracy was obtained for each condition.

2.2. Results

All assumptions of the mixed factorial analysis of variance were met. There was a significant main effects were found for the number of stimuli presented, $F(4, 88) = 32.73$, $P < 0.0005$. As the number of stimuli presented increased performance deteriorated overall. There was a significant main effect for condition, spatial or temporal, $F(1, 22) = 87.65$, $P < 0.0005$. Performance was less accurate in the temporal condition than the spatial condition. There was a significant main effect of reader group, $F(1, 22) = 15.80$, $P = 0.001$ and a significant three-way interaction between the condition, spatial or temporal, number of stimuli presented and reader group, $F(4, 88) = 3.47$, $P = 0.011$. The between group effect size, η^2 accounted for 41.8% of the variance in sequential counting scores. The effect size, η^2 for the three way interaction was 19.8%. The interaction is illustrated in Fig. 1. Regardless of the number of stimuli presented the dyslexic group performed less accurately on the temporal task. When the spatial task was considered no differences were found between the skilled and dyslexic groups when five to seven stimuli were presented, but for the nine and nine stimulus conditions the dyslexic group performed significantly less accurately than the skilled reader group.

2.3. Discussion

These data replicate those previously found by Eden et al. (1995), extending the findings of a deficit in temporal sequencing to dyslexic adults. In the spatial task performance in the dyslexic group deteriorated when a larger number of stimuli are presented simultaneously. This may occur because of poorer memory, which has previously been demonstrated among dyslexics (Talcott et al., 1998), poorer localisation of spatial information or restricted performance in the periphery of the visual field. The visual angle subtended by the array at a viewing distance of 30 cm was large. Experiment 2 will reduce the visual angle of the array to determine if the visual field size can explain the result.

When the temporal sequencing task is considered, performance of the dyslexic group was significantly less accurate across all conditions than that of the skilled reader group. These findings support Hari and Renvall's (2001) hypothesis of poor performance among dyslexic groups on rapid sequential processing tasks and are consistent with previous findings (Hari et al., 1999). The results cannot be explained by poorer concentration as no differences were found between groups in most corresponding conditions of the spatial task. The relationship between performance on this temporal sequencing task and a measure of motion perception, motion coherence, will be investigated in the following experiments using additional samples of adults classified as skilled and poor readers.

3. Experiment 2

The aim of this study was to determine the relationship between two different temporal tasks, a motion coherence task and the temporal sequencing task. The relationship of both to word identification skills was also investigated. On the basis of previous findings both measures should be related to reading skills, but may measure different components of temporal processing, due to the different nature of the tasks. In addition while, some poor readers in this study had a childhood history of dyslexia, other readers were included on the basis of poor word identification skills.

3.1. Method

3.1.1. Participants

Participants were adult readers from the Griffith University student population. There were 22 in the poor reader group and 21 in the skilled reader group. Average age of the poor reader group was 26 years (S.D. = 10.08 years) with the skilled reader group 25.89 years (S.D. = 8.33 years). There were 4 males and 17 females in the poor reader

Table 2
Performance of the skilled and poor reader groups on the WRAT-3, non-word and exception word tests (Experiment 2)

	Skilled readers		Poor readers		*P*
	Mean	95% confidence interval	Mean	95% confidence interval	
WRAT (standard)	111.32	109.24–113.46	87.38	82.71–92.06	<0.0005
Non-words	23.63	23.03–24.24	14.76	13.36–16.16	<0.0005
Exception words	20.68	19.92–21.44	10.19	9.55–11.5	<0.0005

group, with 12 males and 10 females in the skilled reader group. (The larger population from which this sample was drawn was predominantly female, explaining the disproportionate number of females in the poor reader group.) All poor readers had a standardised score of less than 95 on the word identification component of the Wide Range Achievement Test Revised (WRAT-3) (Wilkinson, 1993). (This test was used in preference to the Boder as a standardised reading score could be obtained for each participant, making direct comparison between readers performance in a regression analysis possible.) Standardised word identification scores ranged from 50 to 94. All poor readers were reading at a Grade 7 to high school level. In addition those in the poor reader group obtained scores on tests of 25 non-words and 25 exception words that were matched in word length at one standard deviation or more below the mean of a normative group. This resulted in scores of less than 18 out of 25 on the non-word test and scores of less than 15 out of 25 on the exception word test. Individuals in the skilled reader group had a standardised WRAT-3 score of 105 or greater, ranging from 105 to 121. All participants from this group performed in the post-high school range. Performances for the non-word and exception word tests for this group were above the average performance of a normative sample. The performance of the groups on these measures is presented in Table 2. Significant differences were found between groups on the different measures of word reading. In this study the poor reader group cannot be classified as dyslexic, but as individuals with poorer than expected reading skills for the level of education being undertaken.

All participants had normal or corrected to normal visual acuity and English as a first language. Prior to participation all participants gave informed consent. This study had Griffith University Ethics Committee clearance, which adheres to the guidelines of the NH&MRC of Australia.

3.1.2. Stimuli

3.1.2.1. Spatial and temporal tasks. These were similar to those used in Experiment 1, apart from the viewing distance, which was increased to 57 cm, and the number of stimuli presented in any one condition. An additional stimulus condition where four stimuli were presented sequentially or spatially was added to determine accuracy in a perceptually less difficult task. The visual angle of stimulus squares presented in both the temporal and spatial conditions was reduced to 0.30°. For the spatial condition the visual angle of the array was reduced to 16° of visual angle vertically and 20° of visual angle horizontally. The stimulus presentations consisted of four to nine stimuli in any one condition. In the temporal condition a variable ISI of between 200 and 400 ms was presented between each stimulus presentation. This was to prevent rhythmic counting of stimuli. There were 18 practice trials followed by 12 trials per condition presented randomly in three blocks of experimental trials.

3.1.2.2. Motion coherence task. The stimuli were generated on an IBM PC compatible computer with a 15 in. colour monitor with a screen refresh rate of 65 Hz. Motion coherence stimuli were based on the methodology of Raymond and Sorensen (1998). The stimulus consisted of a 7 cm^2 patch in the centre of the screen that subtended 8° of visual angle horizontally and vertically at a viewing distance of 50 cm. The stimulus patch was composed of 100 white single pixel dots, each with a luminance of 25 cd/m^2. Background luminance was 0.1 cd/m^2. A fixation cross was presented prior to presentation of the stimulus on each trial. A velocity of 10.4°/s either to the left or right displaced signal dots after 32 ms, whereas noise dots were randomly repositioned within the square after 32 ms. Random repositioning of the dots within the frame ensured that tracking an individual dot would not lead to an accurate perception of direction of motion. Frame duration was 32 ms with seven-frames presented on a single trial. This resulted in a total stimulus duration on a single trial of 224 ms. Coherency of the dots started at 70%. The percentage coherence was defined as the percentage of signal dots required when judging correctly the direction of motion. A PEST staircase method (up 3 dB, down 1 dB) was used. There were five blocks of trials, each terminating after 10 response reversals for left and right directions of motion. A trimmed mean of the reversals was calculated, rejecting the 5% of lowest and highest percentage values.

3.1.3. Procedure

Psychometric testing of reading skills was conducted prior to any psychophysical testing. Participants fulfilling group classification criteria were tested over two sessions with half the participants undertaking the counting tasks first and half undertaking the motion coherence task first. Following an explanation of each of the tasks, testing began after presentation of a series of practice trials. Both tasks took place in a darkened room ($5\,cd/m^2$) and viewing was binocular. The viewing distance was controlled by means of a chin rest.

In the sequencing tasks responses were made using keys marked 1–12 on the computer keyboard. The percentage of correct responses was obtained for each stimulus condition for both the spatial and temporal tasks.

For the motion coherence task participants selected either a left or right arrow key on the keyboard to respond to the direction of motion. Each block of trials resulted in two estimates of threshold, one for leftward and one for rightward motion. These were combined to produce an overall coherence threshold.

3.2. Results and discussion

3.2.1. Spatial and temporal tasks

Performance of the skilled and poor reader groups on the spatial component of this task revealed some ceiling effects in performance, particularly for the skilled reader group. Inspection of Fig. 2 shows little differences in performance between groups with presentation of four to seven stimuli. There was no ceiling effect for performance with presentation of eight or nine stimuli. A mixed factorial analysis of variance was conducted on this component of the data. All assumptions of analysis were obeyed. No significant between groups effect was obtained, $F(1, 41) = 1.81$, $P > 0.05$.

A mixed factorial analysis of variance was conducted on performance on the temporal sequencing component of the task. Apart from some violation of the assumption of sphericity for the number of stimuli presented all assumptions of the analysis were obeyed. To account for violation of the sphericity assumption those univariate effects that were also significant at the multivariate level only were interpreted. In addition the Huynh–Feldt correction was applied to the degrees of freedom. There was a significant main effect for participant group, $F(1, 41) = 83.03$, $P < 0.0005$ showing that regardless of the number of stimuli sequentially presented the poor reader group performed less accurately than the skilled reader group. The between group effect size, η^2 accounted for 66.9% of the variance in sequential counting scores (see Fig. 2). There was also a significant main effect for the number of stimuli presented, $F(3, 143) = 28.17$, $P < 0.0005$. As the number of sequentially presented stimuli increased response accuracy was reduced in both reader groups.

These results replicate the findings of Experiment 1 for the temporal sequencing task. In the spatial task no between groups differences were found. As reported some ceiling effects were also found. Inspection of the percentage correct responses in each condition for the spatial task, shows that on average poor readers performed with greater accuracy when higher numbers of stimuli were presented in the spatial condition than those found in Experiment 1. This is explained by the reduction in visual angle used for the spatial display in this experiment.

3.2.2. Motion coherence task

All tests obeyed the assumptions of the analyses. An independent groups t test revealed that there was a significant difference between skilled and poor reader groups on the coherent motion task, $T(40) = 3.00$, $P = 0.008$. Motion coherence thresholds for the poor reader group were significantly higher than that for the skilled reader group. The between group effect size, η^2 accounted for 15.1% of the variance. This result is illustrated in Fig. 3. Individual left, $T(40) = 2.78$, $P = 0.006$ and right, $T(40) = 2.95$, $P < 0.006$ thresholds also produced significant between group differences. These results replicate earlier between group findings in dyslexic children (e.g. Raymond & Sorensen, 1998) and adults (Talcott et al., 1998) showing that poor readers are less sensitive than skilled readers on this sensory processing task.

3.2.3. Relationships among measures

A percentage correct score was obtained for overall performance on spatial and temporal sequencing tasks for each participant. Pearson correlation coefficients (presented in

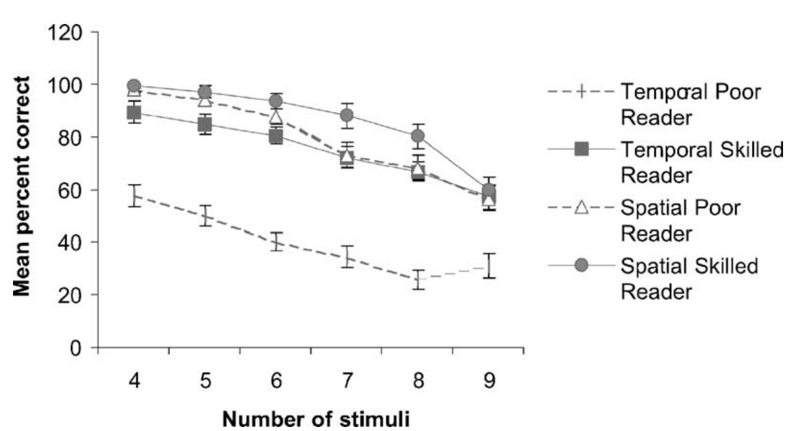

Fig. 2. Spatial and temporal counting for mean percent accuracy scores, Experiment 2. Standard errors bars represent ±1 standard errors for individual conditions.

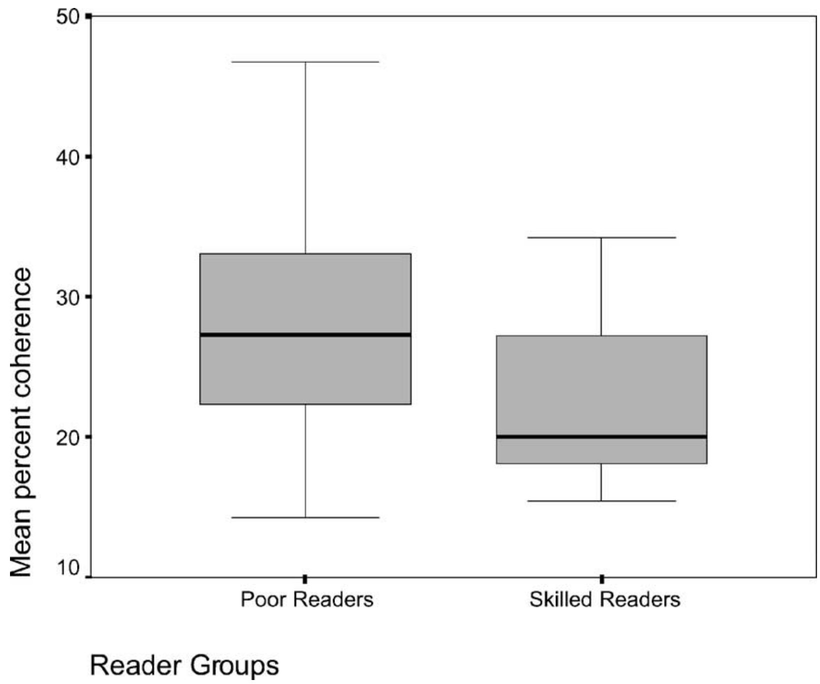

Fig. 3. Box-and-whisker display for coherence thresholds for skilled and poor reader groups from Experiment 2.

Table 3) describe the linear relationships found between these measures. Significant weak negative linear relationships were found between motion coherence threshold and performance on the temporal and spatial sequencing tasks, with a weak positive linear relationship found between the two sequencing tasks. When performance on the spatial sequencing task was partialled out of the relationship between the temporal sequencing and motion coherence tasks the correlation dropped slightly, $r = -0.25$, $P = 0.042$. These findings suggest two things. First, different functional relationships exist between different measures of temporal processing. The rapid sequencing task, a measure of rapid processing and the motion coherence task, a measure of motion sensitivity predominantly measure different components of temporal processing. Second, there may be a number of cognitive components, for example perceptual load or allocation of spatial attention that contribute to performance on these higher-level visual tasks, in addition to the way different forms of temporal information are processed. This supports recent findings of the impact of perceptual components on performance (Amitay et al., 2002; Ben-Yehudah et al., 2001).

Table 3
Bivariate correlations between word identification scores, motion coherence thresholds and temporal sequencing scores ($n = 42$, Experiment 2)

	Temporal sequencing	Motion coherence	Spatial counting
WRAT score	0.778	−0.512	0.40
Temporal sequencing		−0.322	0.35
Motion coherence			−0.42

All are significant beyond the 0.05 level.

The relationship between word identification skill (WRAT-3) and the temporal and spatial processing tasks was investigated using multiple regression analysis. Apart from two participants with unusually high scores on Cook's distance, there were no violations of the assumptions of the multiple regression analysis. One participant, a poor reader with an unusually high score on the motion coherence task was removed from the analysis. In the multiple regression analysis using word identification score as the dependent variable, 68.9% of the variance was explained using the temporal sequencing score totals and motion coherence thresholds, $F(2, 38) = 42.16$, $P < 0.0005$. Temporal sequencing score $T(37) = 6.89$, $P < 0.0005$ and motion coherence threshold, $T(37) = -3.83$, $P = 0.003$ made significant independent contributions to the outcome. There was no significant independent contribution of the spatial sequencing task. The squared semi-partial correlation showed that 42.6% of the variance in word identification score was accounted for by performance on the temporal sequencing task and 8.47% of the variance in word identification score was accounted for independently by the motion coherence thresholds. The remaining 17.83% of the variance accounted for was shared between variables.

A discriminant function analysis was conducted to determine how well the two temporal processing measures discriminated between skilled and poor reader groups. There were 88.5% of poor readers and 90% of skilled readers correctly classified using the temporal sequencing task and motion coherence thresholds for classification purposes. Temporal sequencing score was the most important contributor to this separation (standardised coefficient = 0.932), with motion coherence threshold less important (standardised coefficient = −0.270).

While it is tempting to argue from these data that rapid sequential processing is the strongest indicator of the relationship between word identification skills and temporal processing, verbal memory, rapid processing and generalised verbal skills may contribute. To determine the impact of these variables a further experiment was conducted. A measure of general ability was obtained using verbal and nonverbal tests from the Wechsler Scales of Adult Intelligence (WAIS-3) (Wechsler, 1998). Measures of verbal memory and processing speed (the digit span from the Wechsler Scales) and spatial memory, the spatial span task from the Wechsler Memory Scales (WMSs) (Wechsler, 1997) were obtained.

4. Experiment 3

4.1. Method

4.1.1. Participants

This study used adult readers from the Griffith University pool of staff and students. No participant took part in either Experiment 1 or 2. There were 17 participants in the poor reader group and 19 participants in the skilled reader group. Average age of the poor reader group was 24.61 years (S.D. = 9.33 years) with the skilled reader group 23.95 years (S.D. = 7.81 years). There were 6 males and 11 females in the poor reader group, with 8 males and 11 females in the skilled reader group. All poor readers had a standardised score of 94 or less on the word identification component of the WRAT-3 (Steinman et al., 1997) and scores on the non-word and exception word tests conducted in Experiment 2 of at least one standard deviation below the mean performance of a normative sample. Individuals in the skilled reader group had a standardised WRAT-3 score of 105 or greater. In addition, those in the skilled reader group obtained scores on tests of non-word and exception word reading at least one standard deviation or more above the mean of a normative sample. Significant differences were found between groups on all measures of word identification. An estimated general ability score using one verbal (vocabulary) and one performance (picture completion) test from the WAIS-3 (Wechsler, 1998) was obtained. No differences were found between groups on measures of general ability. These group characteristics are displayed in Table 4.

All participants had normal or corrected to normal visual acuity and English as a first language. Prior to participation all volunteers gave informed consent. This study had Griffith University Ethics Committee clearance, which adheres to the guidelines of the NH&MRC of Australia.

4.1.2. Stimuli

4.1.2.1. Temporal sequencing task. This was similar to that presented in Experiment 2. Additional conditions were added, with presentation of stimuli ranging from a single stimulus (a control condition to determine that the task count be undertaken successfully with a 40 ms stimulus presentation) up to presentation of nine stimuli in a sequence. Other stimulus parameters were the same as those presented in Experiment 2. There were 12 trials presented per stimulus condition and 18 practice trials.

4.1.2.2. Motion coherence task. This is the same motion coherence task as that used by Hansen et al. (2001). Two patches of 300 high luminance (130 cd/m^2) white dots were presented on a black background. One patch contained a variable percentage of target dots that moved coherently either to the left or right, with the second panel containing noise elements only. The direction of motion was reversed every 572 ms, with noise dots randomly changing direction in a Brownian manner with each screen refresh. Lifetime of a single dot was three animation frames (85 ms). Dots would disappear and then regenerate at a randomly selected stimulus location within the same stimulus patch. Motion coherence percent was corrected for this finite lifetime (Hansen et al., 2001).

Each patch subtended $10^\circ \times 14^\circ$ of visual angle and was separated by a dark stripe subtending 5° of visual angle, at a viewing distance of 57 cm. The stimulus program randomly selected the stimulus patch that contained the motion signal. Stimulus duration for each trial was 2.3 s, followed by a response based on which panel contained

Table 4
Performance of the skilled and poor reader groups on the WRAT-3, non-word and exception word tests, memory and tests of general ability (Experiment 3)

	Skilled readers		Poor readers		*P*
	Mean	95% confidence interval	Mean	95% confidence interval	
WRAT (standard)	109.69	109.24–113.46	89.18	82.71–92.06	<0.0005
Non-words/25	23.63	23.03–24.24	13.82	13.36–16.16	<0.0005
Exception words/25	20.68	19.92–21.44	11.94	9.55–11.5	<0.0005
Digit span (scale)	12.47	11.02–13.93	9.12	8.24–10.31	<0.05
Digits backward	8.63	7.41–9.86	5.76	4.95–6.12	<0.0005
Digits forward	12.00	10.83–13.17	9.88	8.81–11.08	<0.05
Spatial span forward	9.74	8.8–10.67	8.35	7.48–9.41	<0.05
General ability (IQ)	111.85	105.86–116.98	109.69	102.17–115.39	>0.05

the coherently moving stimuli. The psychophysical procedure used was an adaptive three up, one down staircase technique, which was based on the percentage of target dots (angular velocity = 7.0°/s) within a single animation frame of 28.6 ms. Catch trials at 66.7% coherence were presented randomly at least once every five trials. Two blocks of test trials were conducted. The smallest proportion of coherently moving stimuli needed to detect coherent motion was defined as the threshold. Mean coherency was the geometric average of 8 of the last 10 reversals for each block of trials. Beginning coherency was 66.7%.

4.1.3. Procedure

Each participant was tested individually over two sessions. In the first session all psychometric measures of word identification, general ability and memory and processing speed were obtained. In the second, the temporal sequencing and motion coherence tasks were conducted. Psychophysical testing took place in a darkened room with a mean luminance of 5 cd/m^2. Half the participants did the motion coherence task first and half the temporal sequencing task. Viewing distance was controlled by means of a chin rest and viewing was binocular.

4.2. Results and discussion

4.2.1. Memory and processing speed

Initial analysis of the different forms of memory and processing speed tasks revealed that the poor reader group performed less accurately on all components of the verbal digit span tasks. Significant differences were found in digits forward, a verbal task similar to that used in the temporal sequencing task, $T(34) = 2.66$, $P = 0.012$, digits backward, $T(34) = 4.24$, $P < 0.0005$, a measure of working memory, and scaled verbal memory scores, $T(34) = 3.96$, $P < 0.0005$. The poor reader group also performed significantly less accurately on the forward component of the spatial span task, $T(34) = 2.10$, $P = 0.041$. With the spatial span backwards task and the scaled scores, which combined both components of the task, no between group differences were found. Descriptive statistics for these measures are found in Table 4. These data confirm previous findings of poorer performance on tasks of memory and processing speed. To determine the impact of these different measures on performance on the temporal sequencing task, correlations were initially obtained between each measure and the individual stimulus conditions from the task. The verbal digits forward condition produced the strongest relationships with the temporal sequencing task. No significant relationships between the two measures were found using accuracy scores on the one to four stimuli conditions. When five and six stimuli were presented weak correlations were found, and when seven to nine stimuli were presented the correlation between performance on the two measures was stronger. These data are presented in Table 5.

Table 5
Correlations between number of stimuli presented in the temporal sequencing task and the digits forward memory task (Experiment 3)

No. of stimuli in sequence	Digits forward
1	0.130
2	0.117
3	0.289
4	0.219
5	0.382*
6	0.359*
7	0.544**
8	0.478**
9	0.556**

* Significant at 0.05 level.
** Significant at 0.01 level.

4.2.2. Temporal sequencing task

For the single stimulus control condition of the temporal sequencing task all participants obtained accuracy scores close to 100%. No between group differences were found. Due to the ceiling effect found on performance, this condition was not used in further analyses. The results demonstrate that when rapid sequencing is not required poor readers have no difficulty in target detection.

A mixed repeated measures analysis of covariance was conducted on the remaining data. General ability and the digits forward component of the digit span task were used as covariates with the number correct for each of the stimulus conditions between two and nine used as repeated measures. Reader group was the between groups factor. Evaluation of the assumptions of the analysis of covariance revealed violation of the assumption of homogeneity of regression between the different stimulus conditions and the digits forward task. To deal with this violation, two analyses were conducted. The first used conditions that presented between two and six stimuli. The second used the remaining three stimulus conditions. Using this technique all assumptions of the analyses were obeyed. In the analysis using the two to six stimulus conditions, there was a significant main effect for reader group, $F(1, 29) = 20.94$, $P < 0.0005$. There were no significant effects of the covariates general ability, $F(1, 32) = 0.365$, $P > 0.05$ or the digits forward task, $F(1, 32) = 0.841$, $P > 0.05$. No significant interactions were found. The between group effect size, η^2 accounted for 41.9% of the variance. In the second analysis a significant between groups effect was found, $F(1, 29) = 6.24$, $P = 0.02$. There was also a significant effect of the covariate digits forward, $F(1, 29) = 8.01$, $P = 0.008$. The between group effect size, η^2 accounted for 17.7% of the variance. These results are presented in Fig. 4. These data demonstrate that when groups do not differ on IQ and the effect of the short-term memory and processing speed is removed from the analysis the poor reader group still performs significantly less accurately than the skilled reader group across all stimulus presentations.

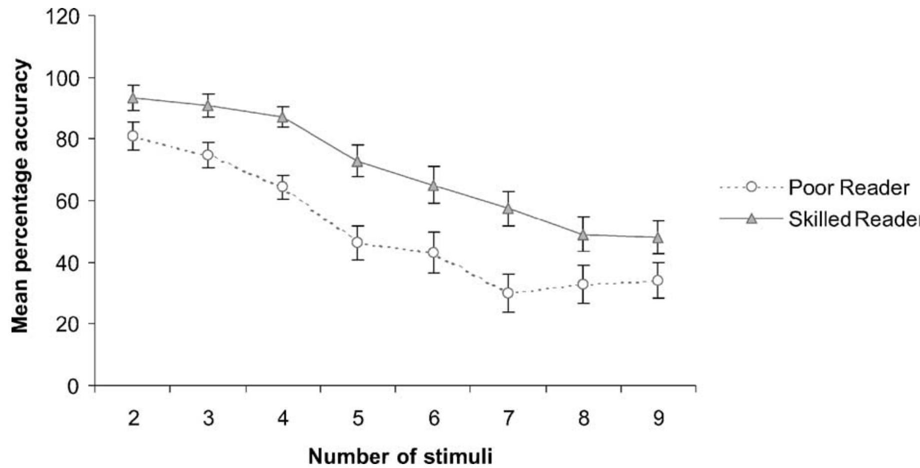

Fig. 4. Temporal sequencing task showing performance of skilled and poor reader groups, Experiment 3. Adjusted means for general ability and verbal memory and processing speed. Standard errors shown are the actual standard errors.

4.2.3. Motion coherence task

All participants were 100% accurate on the catch trials used in this task so it could be concluded that vigilance could not explain any between group effects found. A square root transformation was conducted on the motion coherence scores to equalize the between group variance. A one way analysis of covariance using general ability as a covariate found that using this alternative measure of motion coherence the poor reader group had significantly higher coherence thresholds than the skilled reader group, $F(1, 32) = 12.68$, $P < 0.0015$. The effect size η^2 was 28.9%. These results are displayed in Fig. 5. One methodological difference between the motion coherence tasks used in Experiments 2 and 3 was the stimulus duration. The task conducted in this experiment using stimulus durations 2 s longer than that used in Experiment 2. This resulted in lower motion coherence thresholds for both skilled and poor reader groups. This may have occurred because the longer stimulus duration allowed for greater stimulation of the M system producing a greater overall advantage for the skilled reader group. The longer stimulus duration acted to enhance the effects of poor temporal integration in the poor reader group. Finding significant between group differences for the two different techniques provides additional evidence that it is sensitivity to motion not, methodological considerations that produce the differences in sensitivity found.

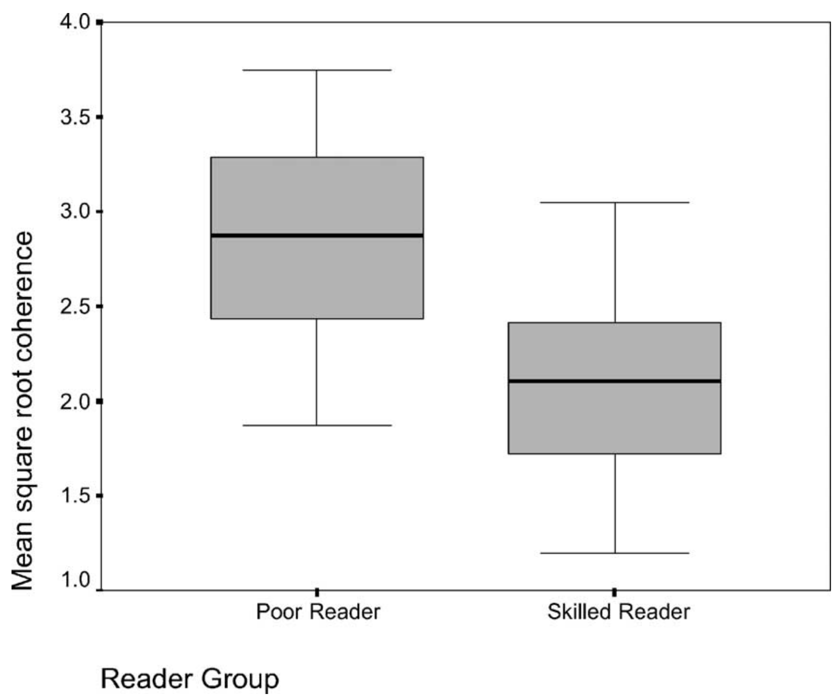

Fig. 5. Box-and-whisker display of motion coherence thresholds for skilled and poor reader groups, Experiment 3.

4.2.4. Relationships among measures

As found in Experiment 2, a weak negative linear relationship was obtained between motion coherence threshold and performance on the temporal sequencing task, $r(34) = -0.304$, $P = 0.076$. This relationship accounted for 9.24% of the variance. This finding confirms the result of Experiment 2 that the two tasks are predominantly measuring different things.

A hierarchical multiple regression analysis was conducted using word identification scores on the WRAT-3 as the dependent variable. At step 1, general ability and the measure of short-term memory and processing speed (digits forward) were entered to partial out the effect of performance on the temporal sequencing and motion coherence tasks at step 2. A total correct temporal sequencing score was obtained, by summing the number correct across the different stimulus conditions. Square root motion coherence thresholds were used as the measure for motion coherence. All assumptions of the multiple regression analysis were obeyed. Twenty-two percent of the variance in word identification score was accounted for using the combined effect of general ability and short-term memory and processing speed, $F(2, 30) = 4.43$, $P = 0.025$. The measure of short-term memory and processing speed made a significant independent contribution to the relationship, $T(30) = 2.61$, $P = 0.02$. A further 36.7% of the variance was accounted for at step 2, $F(2, 28) = 12.71$, $P < 0.0005$. Both the temporal sequencing, $T(28) = 3.65$, $P < 0.005$ and motion coherence tasks, $T(28) = -2.79$, $P = 0.009$ made significant independent contributions to word identification scores. The squared semi-partial correlation for the temporal sequencing task showed that 19.27% of the variance in word identification skill was independently accounted for with this measure. This is about half that found in Experiment 2. Motion coherence threshold independently accounted for 11.29% of the variance in word identification skill.

A discriminant function analysis was conducted to determine how well the two temporal processing measures discriminated between skilled and poor readers. There were 93.8% of poor readers and 89.5% of skilled readers correctly classified using the temporal sequencing task and motion coherence thresholds as independent variables. Inspection of the structure matrix reveals that both measures contributed significantly to this classification with the coefficient for temporal counting 0.794 and for motion coherence, −0.556. This finding reflects the greater contribution of the motion coherence task used in this study to the outcome than that found in Experiment 2. The stronger effect of the temporal sequencing task was repeated.

5. General discussion

The results of the experiments show that the two temporal processing measures distinguish between reader groups whether they had a childhood history of dyslexia or could be classified as poor readers, not specifically dyslexic. Weak relationships were found between the two measures of temporal processing, suggesting that they predominantly measure different aspects of temporal function. In the final two experiments performance on the temporal sequencing task was a stronger predictor of performance on the word identification task than performance on the motion coherence task. These data support earlier predictions of an association between rapid sequencing and poor reading skills (Eden et al., 1995; Hari & Renvall, 2001). Each of these findings will be discussed separately.

5.1. Visual temporal processing and poor reading skills

Early investigations of a temporal processing deficit in the visual domain found performance differences between dyslexic and control groups. The results of the experiments reported here demonstrates that poor temporal processing influences performance in readers with dyslexia and also those with poor word identification skills in both the phonological and orthographic domains. Participants in Experiment 1 had a childhood history of dyslexia, with those in the latter two studies having low scores on tests of word identification and phonological and orthographic processing. These data show that it is not a classification of dyslexia only that is implicated when considering poor temporal processing skills, but poor literacy skills generally. A number of studies that have used unselected reader samples supports this finding (Au & Lovegrove, 2001; Conlon et al., 2001; Talcott et al., 2000b, 2002). Borsting et al. (1996), and Slaghuis and Ryan (1999) have demonstrated in adults and children respectively that poor performance on measures of both orthographic and phonological processing produces significant difficulties in temporal processing for these groups. Efficiency of temporal processing skills may form a normal distribution with poorer performers corresponding to the lower tail in the same way that Shaywitz et al. (1992) predict occurs in the distribution of reading skills.

5.2. Relationship between temporal processing tasks

Regardless of the type of motion coherence task used the relationship between coherence threshold and accuracy of temporal sequencing was similar. Two of the possible explanations for the weak correlation found between performance on the two tasks are: (1) the two tasks measure different aspects of temporal processing with the first a measure of temporal integration of motion signals and the second a measure of temporal separation of stimulus events and (2) the temporal sequencing task while being a measure of efficiency of temporal separation also has additional attentional and perceptual components that may contribute to performance efficiency. Addition of this attentional component may make processing in the temporal sequencing task a two-stage process, with the first a stage sensory, and the second attentional. This attentional component may either be a function of the M system, or may be part of a higher-level attentional processing mechanism. In the temporal sequencing task attention is focused on a specific spatial location. In addition, with sudden onset of a stimulus automatic attention becomes dominant in the attended location with presentation of the specific stimulus accelerating visual processing in the region of stimulus presentation (Facoetti & Massimo, 2001). The M system has been implicated in directing this form of attention (Raymond, O'Donnell, & Tipper, 1998; Steinman et al., 1997). Supporting evidence includes findings that sensitivity to motion at MT and MT+ in single cell recordings can be influenced by the attentional state of the receptive field (Treue & Maunsell, 1996; Treue & Trujillo, 1999). Using functional MRI technology these findings have been extended to demonstrate an increased level of activation at MT/MT+ on the basis of a manipulation of attention to specific stimulus attributes (Buchel et al., 1998; O'Craven, Roden, Kwong, Triesman, & Savoy, 1997). In addition to increases in activity at MT with an attention manipulation, Buchel et al. (1998) found increased activity in the posterior parietal cortex, and suggested, that activity is increased in MT/MT+ with a top–down feedback loop from PPC. This feedback loop acts to modulate sensory performance. In this study attentional components were not manipulated in the two motion coherence tasks. While the specific neural location of processing for the temporal sequencing task is unknown, the importance of attentional components in similar tasks, for example, the attentional blink, is well documented (Hari et al., 1999). Hari and Renvall (2001) have argued that poor performance on rapid sequential processing tasks is a measure of 'sluggish attentional shifting', an effect predicted to occur in the PPC. These data support this prediction.

Supporting evidence of the impact of increasing perceptual load has also been obtained. Ben-Yehudah et al. (2001) found that performance on the temporal CSF only differed between a dyslexic and control group when a sequential component was introduced into the 2AFC task. They argued that components of higher order perceptual memory needed in a retain-and-compare paradigm could explain their results. Perceptual memory cannot explain the results obtained in this study as the task required only that stimuli be counted, not compared. Hill and Raymond (2002) using a motion transparency task that required identification of two directions of motion presented simultaneously, found that performance discriminated between dyslexic and control readers more consistently than a motion coherence task. Both findings suggest that increased perceptual load impacts performance when processing the temporal aspects of a stimulus. The sensory and behavioural components of the task may interact. Further research, which separates the role of low-level sensory processing and high-level perceptual events, is required to differentiate the contribution of sensory and higher order components. The sensory and higher order aspects of visual temporal processing may explain the differences found in the relationship between performance on the temporal tasks and word identification skills.

5.3. Temporal processing and word identification skills

Consistent with the results of previous research this study has shown that poor adult readers are also less sensitive than skilled readers on the motion coherence task (Raymond & Sorensen, 1998; Talcott et al., 2000a,b). In poor readers, summation is required over a larger number of receptive fields to determine the presence of stimulus motion. Talcott et al. (2000b) predict that this occurs as a result of poor ability to integrate sensory signals. The results from the spatial and temporal sequencing tasks also replicate those of Eden et al. (1995) who found poorer temporal sequencing accuracy in a sample of dyslexic children. Other temporal processing tasks, for example persistence measures, have also produced significant between group differences among less well defined reader groups (Au & Lovegrove, 2001). While both tasks used in this study made significant independent contributions to word identification skills, the temporal sequencing task accounted for a much larger proportion of the variance in Experiment 2. In Experiment 3 where general ability and memory were taken into account, the percentage of the variance accounted for was reduced but still greater than that found for the motion coherence task.

There are two aspects of the temporal sequencing task that may have produced difficulties for poor readers. These are the individuation of stimulus events (sensory component) and the sequential nature of the task. The temporal sequencing task required individuation of separate stimulus components. When a single stimulus was presented as a control condition in Experiment 3 no differences in performance were found between skilled and poor reader groups. Less accurate performance of the poor reader group even when two to six stimulus events were presented is based on the explanation that the ISIs used were not long enough to allow poor readers to distinguish between presentations of separate stimulus presentations. The ISIs used in this study were based on previous research on visible persistence where participants were required to detect the presence of a gap between presentation of two identical stimuli. The minimum ISI used was longer than those found previously for average readers to successfully detect the gap (Au & Lovegrove, 2001). Detection of the gap may be less perceptually demanding than performance on a task where attention is directed to the specific stimulus presentations. This sequencing task did not require identification of the stimulus but detection of individual stimulus presentations. Detection of individual stimulus components may require longer gaps between stimulus presentations for the poor reader group. Previous research where no between group differences were found in rapid sequential processing tasks used longer stimulus ISIs and stimulus durations than those presented in this study (Brydon, 1972). An alternative explanation of the less accurate performance of the poor reader group on the temporal sequencing task may be the stimulus duration used. Repeated presentations of a short duration stimulus may increase the signal to noise ratio in the visual system, resulting in poor detection of individual events (Laasonen et al., 2001). Some support for this explanation has been obtained in the auditory domain (Walker et al., 2002). Hari and Renvall (2001) have argued that difficulties with the rapid sequencing component of the task is the link between poor word reading and temporal processing. Further research is required to determine the exact nature of this link.

One of the criticisms of much research that has investigated sequential processing has been the influence of memory on task performance. For example, one of the methodologies used has been to present two sequences of visual stimuli, the task to determine if presentation of the two sequences is the same (Zurif & Carson, 1970). The task presented here did not require memory of the whole sequence but detection of individual components. The results of the comparable spatial task where the stimuli were presented simultaneously showed that poorer memory could not explain these data, particularly with presentation of the shorter stimulus sequences. In Experiment 3 the influence of a verbal memory and processing speed task where participants were required to repeat a series of digits was partialled out of the analysis. This measure was not related to performance on the sequential counting task, when up to four stimuli were presented in a single sequence. These data show performance was still significantly less accurate among poor readers when performance on this measure and that of general ability was removed from the analysis. This shows that memory cannot be used as an explanation.

The relationship between sequencing rapidly presented temporal information and word identification skills may be explained by the combination of a sensory processing deficit in the M system (Stein & Walsh, 1997), and difficulties with attentional shifting (Hari & Renvall, 2001). This attentional component may be M in origin or a higher-level component of processing that influences lower level sensory events in the M pathway. Overall this produces a slower rate of processing of temporal signals. The way that this subtle dysfunction is related to the reading process is less clear. In an above section, research showing that attention to specific stimulus attributes can modulate performance in the detection of the sensory components of the stimulus was presented. This modulating effect may occur as a result of the interaction between top–down (signals possibly emanating from the attentional processing areas of PPC) and bottom up (sensory) M processing. One of the consequences of poorer capacity to utilize the M components of attention could produce poorer temporal sequencing capacity in less skilled readers. A number of researchers have previously implicated these poor sequencing skills in phonological processing (Cestnick & Coltheart, 1999), orthographic processing (Cornelissen & Hansen, 1998) and letter identification (Hari et al., 1999) tasks.

6. Conclusion

This study has demonstrated that in poor adult readers there may be different aspects of temporal function related to reading skill. First, this study has replicated previous research showing the existence of a low-level sensory deficit in temporal processing. Second, the involvement of higher-level attentional components has been demonstrated. Whether these components are a function of M system processing or a higher-level perceptual effect, which influences lower level sensory processing is yet to be determined. The functional differences between tasks that measure different aspects of temporal processing and the effects of manipulations that selectively stimulate sensory function at basic and higher attentional and perceptual levels should be further investigated. A slower rate of processing may explain the relationship between reading and temporal processing. This may be most clearly demonstrated with higher-level perceptual processing tasks where the mechanisms of attention are involved.

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