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Vision Research 44 (2004) 2521–2535

**Vision
Research**

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Children with dyslexia: evidence for visual attention deficits in perception of rapid sequences of objects

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Received 1 September 2003; received in revised form 27 April 2004

Abstract

The *attentional blink* (AB) refers to a decrease in accuracy that occurs when observers are required to identify, detect or classify the second of two rapidly-sequential targets. The AB is typically attributed to an inability to rapidly reallocate attentional resources from the first to the second target. Thus, it provides an ideal tool to investigate how visual attention is rapidly allocated to sequences of stimuli such as occurs when reading. In the present work, we compared the magnitude of the AB in children with developmental dyslexia to reading-matched and age-matched control groups. In Experiment 1, when two targets were presented in the same spatial location, the AB deficit was similar in the reading-matched and dyslexic groups, but greater in the dyslexic group than in age-matched controls. In Experiment 2, when targets were presented in different spatial locations, performance in the dyslexic group was worse than the age-matched controls and marginally worse than the reading-matched controls. Taken together, the results argue for developmental delays in the ability of children with dyslexia to allocate attention to rapidly-sequential stimuli, as well as some evidence for difficulties that are unique to this group.

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1. Introduction

The ability to read is one of the most important skills in modern society. Everything from choosing dishes on a restaurant menu to selecting a politician on an electoral ballot demands comprehension of written material. For some individuals, however, reading is greatly complicated by a disorder commonly referred to as *dyslexia*. In the present work, we focus on developmental dyslexia which occurs when “reading achievement, as measured by individually administered standardized tests of reading accuracy or comprehension, is substantially below

that expected given the person’s chronological age, measured intelligence, and age-appropriate education.” (DSM-IV; [American Psychiatric Association, 1994](#)). According to the DSM-IV, the level of reading impairment must also interfere with academic achievement or daily living, and must exceed symptoms that might be expected on the basis of any sensory deficits.

Numerous factors have been implicated in developmental dyslexia (although drawing causal links has been significantly more challenging). These factors have conventionally been separated into two broad categories ([Lassonen, Service, & Virsu, 2001](#)), which can occur either in isolation, or more commonly conjointly in those with dyslexia. One category consists of purely linguistic difficulties. Chief amongst these are deficits in phonological processing (see [Snowling, 2000](#) for a review). A second category consists of perceptual

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processing difficulties. Chief amongst these are deficits in temporal processing (see Farmer & Klein, 1995 for a review).

Temporal processing can be broadly defined to include any type of processing required when two or more stimuli are presented in sequence. Farmer and Klein (1995) elaborated on this definition by sub-dividing temporal processing into three components: determination of stimulus individuation; temporal order judgment; and, sequence discrimination. Experiments on adults and children with dyslexia have shown consistent deficits on all of these tasks across modalities (e.g. auditory: Bryden, 1972; McCroskey & Kidder, 1980; Tallal, 1980; tactile: Lassonen et al., 2001; Lassonen, Tomma-Halme, Lahti-Nuuttila, Service, & Virsu, 2000; Tallal, Miller, & Fitch, 1993; Tallal, Stark, & Mellits, 1985; and vision: Demb, Boynton, & Heeger, 1997; Di Lollo, Hansen, & McIntyre, 1983; Eden, VanMeter, Rumsey, & Zeffiro, 1996; Felmingham & Jakobson, 1995; Galaburda, 1993a, 1993b; Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Lovegrove, Martin, & Slaghuis, 1986; Lovegrove, McNicol, Martin, Mackenzie, & Pepper, 1989; Martin & Lovegrove, 1987, 1988). This can be contrasted with a number of studies that have shown no deficits associated with detection, discrimination, or identification of a single auditory or visual stimulus (e.g. Klein, Berry, Briand, D'Entremont, & Farmer, 1990; Tallal, 1980; although see Greatrex & Drasdo, 1995; Lovegrove, Garzia, & Nicholson, 1990; Martin & Lovegrove, 1987 for deficits in "single stimulus" tasks such as flicker sensitivity).

In addition to substantial work linking phonological and temporal processing deficits to dyslexia, recent studies have provided suggestive evidence for a link between attentional deficits and dyslexia. This evidence comes primarily from tasks that have involved spatial attention. For example, Casco and Prunetti (1996) found that in a visual-search task, poor readers took longer than skilled readers to find complex, multi-featured targets amongst confusable distractors. Brannan and Williams (1987) and Facchetti, Paganoni, Turatto, Marzola, and Mascetti (2000) found that participants with dyslexia demonstrated reduced sensitivity to exogenous cues. Whereas a control group responded faster to targets that were preceded by an 80%-valid cue at the target's location, participants with dyslexia were no faster when the target appeared at the cued location than when it appeared at an uncued location. These results suggested that the cues did not attract attentional resources as efficiently in the group with dyslexia as in the control group.

Of interest in the present work is whether the attentional deficits found when participants with dyslexia are required to allocate attention across space are mirrored by deficits when they are required to allocate attention over time. Such a deficit might be expected

on two grounds. First, it would seem that reading requires both spatial and temporal shifts of attention between stimuli. This assumption is broadly consistent with studies that have shown strong correlations between visual attention shifts and reading performance (Asbjornsen & Bryden, 1998). Second, previous studies have shown evidence for both attention deficits and temporal processing deficits associated with dyslexia. Thus, it seems entirely plausible that participants with dyslexia would show deficits in their ability to allocate attention to sequential stimuli. Indeed, such deficits would be strongly consistent with the hypothesized link between attention and temporal processing suggested by Farmer and Klein (1995).

Investigations of the deployment of attention over time in normal readers have typically employed a paradigm in which observers are asked to identify two targets embedded in a series of distractors. These studies, using college undergraduates (e.g. Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992; Visser, Bischof, & Di Lollo, in press), have shown that while the first target (T1) is identified with a high level of accuracy, second-target (T2) accuracy is impaired to a degree that is directly dependent on the stimulus-onset asynchrony (SOA) between the targets. At relatively brief SOAs (e.g. 200 ms), T2 accuracy is maximally impaired; however, as the SOA increases, second-target accuracy improves as well. This variation in second-target accuracy as a function of inter-target interval has been termed the *attentional blink* (AB).

Theoretical accounts of the AB have focused on the role of visual attention in producing the deficit. The importance of attention is suggested by two findings. First, the AB is eliminated if T1 is omitted or observers are instructed to ignore it (e.g. Raymond et al., 1992; Seiffert & Di Lollo, 1997). This suggests that deficits in second-target processing arise directly from the requirement to process the first target. Second, omitting distractors does not eliminate the AB (Ward, Duncan, & Shapiro, 1997; Zuvic, Visser, & Di Lollo, 2000). This finding, combined with the fact that T2 is unimpaired when T1 is omitted or ignored, indicates that interference between targets and distractors is not necessary for the AB to occur.

According to various models of the AB (e.g. Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1995), all of which are broadly similar (Shapiro, Arnell, & Raymond, 1997), the requirement to attend to the first target prevents allocation of attentional resources to the second target for a period of several hundred milliseconds. As a result of this delay, if the second target is presented soon after the first, it cannot be processed immediately, and thus is vulnerable to decay or overwriting by subsequent stimuli. As inter-target interval increases, processing of the first target is more likely to be complete by the time the second target is presented. As a result, T2 is

able to gain immediate access to attentional resources on a larger proportion of trials, with a consequent improvement in T2 accuracy.

With respect to attention deficits in dyslexia, the AB paradigm provides an ideal tool for examining attentional allocation for a number of reasons. First, as noted above, there is abundant evidence that performance depends primarily on attentional availability rather than factors such as phonological processing or visual masking that have been implicated in dyslexia. Second, the basic paradigm can be easily modified to avoid confounding the results with linguistic-specific factors by using non-letter stimuli. Finally, the AB paradigm has already been used successfully with a variety of populations such as schizophrenics (Cheung, Chen, Ronald, Woo, & Yee, 2002), brain-damaged patients (Rizzo, Akutso, & Dawson, 2001) and the elderly (Lahar, Isaak, & McArthur, 2001). This flexibility implies that the paradigm can also be used successfully to examine attentional allocation in children.

To our knowledge, only one study has examined attentional deficits in dyslexia using the AB. Hari, Valta, and Uutela (1999) evaluated a population of adults with dyslexia who evidenced a history of reading disorders, and who were significantly slower than a control group of normal readers at reading and word recognition. In their experiments, participants were presented with a rapid-serial-visual presentation (RSVP) stream of black-letter distractors at a central fixation location. Embedded within this RSVP stream were two targets. The first target (T1) was a white letter. The second target (T2) was a black 'X' that was presented on two-thirds of trials. Participants were required to report the identity of the first target, and press a key if the second target had been presented in the stream.

Both the control and dyslexic groups showed pronounced ABs, with second target detection maximally impaired at a T1–T2 SOA of 200 ms, and steady improvement as SOA increased. This suggested that readers with and without dyslexia processed sequential targets in a broadly similar manner. Importantly, however, the group with dyslexia showed a significantly longer AB, with T2 performance asymptoting at an SOA of approximately 700 ms, compared to the control group whose performance asymptoted at an SOA of approximately 540 ms. Hari et al. (1999) interpreted this difference as indicating that “dyslexic adults have a significantly prolonged attentional dwell time: identification of a visual object occupies their attentional capacity . . . longer than it does in normally reading control[s]. . . ” (p. 203).

The findings of Hari et al. (1999) provide suggestive evidence that observers with dyslexia are impaired in their ability to allocate attention to rapidly-sequential targets. However, before a strong conclusion can be made, a number of important issues remain to be ad-

ressed. First, it is uncertain whether perceptual interference from the distractor stream may have contributed to the larger AB deficit found in the dyslexic group. Although previous studies have shown that distractors need not be present for the AB to occur in college undergraduates (e.g. Raymond et al., 1992), it is uncertain whether this is also true of dyslexics. Thus, to check on the role of distractors, it is necessary to run a control condition in which only a single target has to be identified from amongst the RSVP distractors. Under these conditions, if interference does occur between targets and distractors, it should be revealed by deficits in single-target identification.

Second, because Hari et al. (1999) did not report levels of T1 identification accuracy, it is not known whether requirements to attend to two consecutive targets impaired only T2 accuracy or whether both targets were affected. This has important implications for the nature of the mechanisms underlying processing deficits in dyslexia. Third, because the stimuli used by Hari et al. (1999) were letters, it is possible that at least part of the reported deficits were due to language-specific factors in the group with dyslexia. Thus, to isolate more global attentional problems in the processing of sequential stimuli, it is necessary to use non-linguistic stimuli.

A final issue, which is central to the present work, is whether the AB deficit found in adults with dyslexia would also be found in children with dyslexia. Although conventional wisdom might suggest that deficits apparent in an older population of dyslexics should be even greater in a younger population, it is equally plausible that the increased dwell time found by Hari et al. (1999) reflects the influence of compensatory strategies that were developed by participants with dyslexia in order to improve their reading performance. Thus, the presence of an increased AB deficit in children with dyslexia must be assessed empirically.

These issues were addressed in Experiment 1 by comparing the duration and magnitude of the AB across a group of children with developmental dyslexia and two separate control groups. One control group consisted of “age-matched” participants who had the same mean age as the group with dyslexia, but were more proficient readers. The second control group consisted of “reading-matched” participants who had the same reading level as the group with dyslexia, but were younger. Comparisons between these groups were designed to yield some insight into whether performance deficits in the group with dyslexia were mediated by developmental factors or reading level. To examine the contribution of distractor interference to target identification, we included a single-target control condition. To eliminate the contribution of linguistic-specific factors, that might arise from using letter targets, we used targets that consisted of one of five different geometric shapes. Additionally, participants were not required to name the

shapes but instead to simply match them to an identical drawing on a response button. This ameliorated demands on mechanisms responsible for object and word identification. Finally, we measured both T1 and T2 identification on trials in which two targets had to be identified. This allowed us to determine whether identification of one or both targets was impaired when two targets were to be identified.

2. Experiment 1

2.1. Participants

Thirty-six right-handed children took part in the study. The children were split evenly into three groups: a group with dyslexia (six girls, six boys), an age-matched control group (eight girls, four boys) and a younger reading-matched control group (seven girls, five boys). Children in the dyslexic and age-matched control groups ranged in age from 10 to 15 years. These children had received detailed psychometric, neurological, and ophthalmologic examinations as part of an earlier study on motion processing in dyslexia (see Edwards et al., in press for details). Children in the reading-matched control group ranged in age from 7 to 10 years. These children had been participants in a large study on the development of temporal processing ability and were selected to fall within the same reading range as the children in the dyslexic group. Informed, written consent was obtained from each child and the child's parent(s) before testing commenced.

Detailed information about age, IQ and reading ability is presented in Table 1. Children in the reading-matched control group were significantly younger than children in both the dyslexic group (Scheffe's F $p < 0.001$) and the age-matched control group (Scheffe's

F $p < 0.001$). There was no age difference between the latter two groups (Scheffe's F $p = 0.9445$). All children had at least average intelligence, with average defined as a composite scaled score equaling or exceeding a lower cutoff of 1 SD below the mean for scaled scores on the Weschler Intelligence Scale for Children-III (WISC-III; $M = 10$, $SD = 3$), i.e., a mean scaled score of 7 or higher. The composite score was derived from the *vocabulary* and *block design* subtests. The three groups did not differ on the subtest (vocabulary $F(2,33) = 1.553$, $p = 0.2267$; block design $F(2,33) = 0.075$, $p = 0.9281$) or composite scores ($F(2,33) = 0.657$, $p = 0.5252$).

To be included in the dyslexic group a child had to score at least 1 standard deviation (SD) below the level expected on two or more of the following reading subtests: the *recognition* subtest of the Peabody Individual Achievement Test-Revised (PIAT-R); the *word attack* subtest of the Woodcock-Johnson Tests of Achievement-Revised (WJ-R); and the *rate* measure of the Durrell Analysis of Reading Difficulty (Durrell). These subtests index three aspects of reading ability, namely word identification, phonological decoding and reading speed, respectively. The age-matched control children's scores were not more than 0.5 SD below the age-norm on all three reading subtests, which provided a clear separation in reading ability between the two groups. The mean scores of the dyslexic group were significantly lower than those of the age-matched control group on all three measures (recognition $t(22) = 12.411$, $p < 0.0001$; word attack $t(22) = 5.843$, $p < 0.0001$; rate $t(22) = 9.111$, $p < 0.0001$). Scores on these reading tasks were not available for the reading-matched control group.

Reading performance for the current study was based on the *word identification* subtest of the WJ-R that was administered to each participant following the attention

Table 1
Means (standard deviations) of the dyslexic and control groups

Measure	Dyslexic	Age-matched control	Reading-matched control
<i>Chronological age*</i>	12.7 (1.55)	12.9 (1.14)	9.5 (0.96)
<i>Intelligence (WISC-III)</i>			
Vocabulary (Verbal IQ)	9.9 (2.39)	11.7 (1.97)	11.5 (3.98)
Block design (Performance IQ)	10.9 (3.78)	11.3 (3.14)	11.4 (2.12)
Composite	10.4 (2.70)	11.5 (1.71)	11.5 (2.33)
<i>Reading</i>			
PIAT-R (recognition)*	76.6 (8.86)	118.9 (7.82)	
Durrell Rate (words/min)*	57.7 (31.4)	156.3 (20.5)	
WJ-R (attack)*	86.1 (11.8)	125.3 (20.1)	
WJ-R (identification)*	92.8 (10.9)	125.3 (9.22)	114.6 (9.27)
WJ-R grade score*	5.5 (1.88)	13.4 (2.98)	5.6 (1.00)

* Indicates a significant group effect, $p < 0.001$.

Note: Standard scores ($M = 100$, $SD = 15$) reported for the PIAT-R and WJ-R; raw scores reported for the Durrell.

tasks. The standard score for each child in the reading-matched control group was not more than 0.5 SD below the age-norm on this subtest. A significant group effect was observed for both the standard scores ($F(2,33)=34.083$, $p<0.0001$) and the reading grade scores ($F(2,33)=54.415$, $p<0.0001$). The mean standard score of the dyslexic group was significantly lower than that of the age-matched control group (Scheffe's F $p<0.0001$) and the reading-matched control group (Scheffe's F $p<0.0001$). The mean standard score of the age-matched control group was slightly higher than that of the reading-matched control group (Scheffe's F $p=0.0388$). The reading grade score of the age-matched control group was significantly higher than that of the dyslexic group (Scheffe's F $p<0.0001$) and the reading-matched control group (Scheffe's F $p<0.0001$). There was no difference in reading grade score between the dyslexic group and the reading-matched control group (Scheffe's F $p=0.9821$).

2.2. Apparatus and stimuli

All stimuli were displayed on a Tektronix 608 oscilloscope equipped with fast P15 phosphor. The viewing distance, set by a headrest, was 57 cm. All stimuli subtended approximately 1° of visual angle and had a luminance of 10 cd/m^2 , as measured by a Minolta LS-100 luminance meter. At this luminance, all stimuli on the display were clearly visible. Distractor items were patches of random dots formed by randomly placing 200 dots (each of which were $0.002^\circ \times 0.002^\circ$) in a notional area of approximately $1^\circ \times 1^\circ$. Target items consisted of one of five outline shapes: square, cross, triangle, diamond, and circle. The background and surrounding visual field were dimly lit by an incandescent fixture located in the ceiling.

2.3. Procedure

There were two conditions: experimental and control. Each condition was run in a separate block of trials. In both conditions, an RSVP stream of random-dot distractors was displayed in the centre of the screen. In the control condition, a single target shape was presented, embedded within the stream. In the experimental condition, two target shapes were embedded in the stream, separated by a variable number of distractors. These conditions are illustrated in Fig. 1 (Panel A).

In each condition, trials began with a small fixation dot that was presented in the centre of the screen, indicating where the RSVP items would be displayed. Observers were instructed to maintain their eye gaze on the location of the fixation dot and start the trial by pressing the space bar. Immediately after the offset of the fixation dot, the RSVP stream was presented in the centre of the screen. Each item was displayed for

40 ms and was separated from the next item by an ISI of 60 ms during which the display was blank. This yielded a presentation rate of 10 items/second. Under these presentation conditions, the distractor sequence appeared as a series of discrete patches, rather than generating the percept of a single patch of randomly-moving dots.

The RSVP stream always began with five or eight distractors, followed by the first target. The first target consisted of one of the five outline shapes chosen at random with replacement. In the experimental condition, a second target was also presented that consisted of one of five shapes chosen at random with replacement. The choice of T2 was constrained so that it was never the same shape as T1. The first and second targets were separated by zero (SOA = 100 ms; Lag 1), two (SOA = 300 ms; Lag 3), six (SOA = 700 ms; Lag 7), or thirteen (SOA = 1400 ms; Lag 14) distractors. The second target was always followed by a single random-dot distractor that acted as a mask. The control condition was identical to the experimental condition except that the T1 item was omitted from the stream and replaced by a distractor.

After the final distractor was presented, the screen went blank and observers were required to identify the shape(s) that had been presented. Before the experiment began, observers were instructed to identify both shapes as accurately as possible, with an emphasis placed on first-target accuracy when there were two shapes. Responses were recorded using a custom-designed button box. Each button on the box was labelled with a picture of one of the possible target shapes, so that observers did not need to be able to name the shape in order to do the task. In the control condition, observers pressed one button corresponding to the single shape presented. In the experimental condition, observers pressed two buttons corresponding to the shapes that were presented during the trial. Responses were scored as correct regardless of whether or not shapes were identified in the order that they were presented. Thus, if T1 was a triangle and T2 was a circle, responses of triangle-circle and circle-triangle were both counted as correct identifications of both targets. After responses were recorded, the fixation dot reappeared to indicate that the next trial was ready to begin.

Both the control and experimental conditions consisted of 10 practice trials, followed by 100 experimental trials. In the experimental condition, this corresponded to 25 trials at each of the four T1–T2 lags. In the control condition, this corresponded to 25 trials in which the single target was presented at a location in the stream equivalent to where T2 would have appeared in the experimental condition at either Lag 1, 3, 7, or 14. The purpose of this was to equate the number of distractors presented prior to the target in the control condition with the number of items presented prior to T2 in

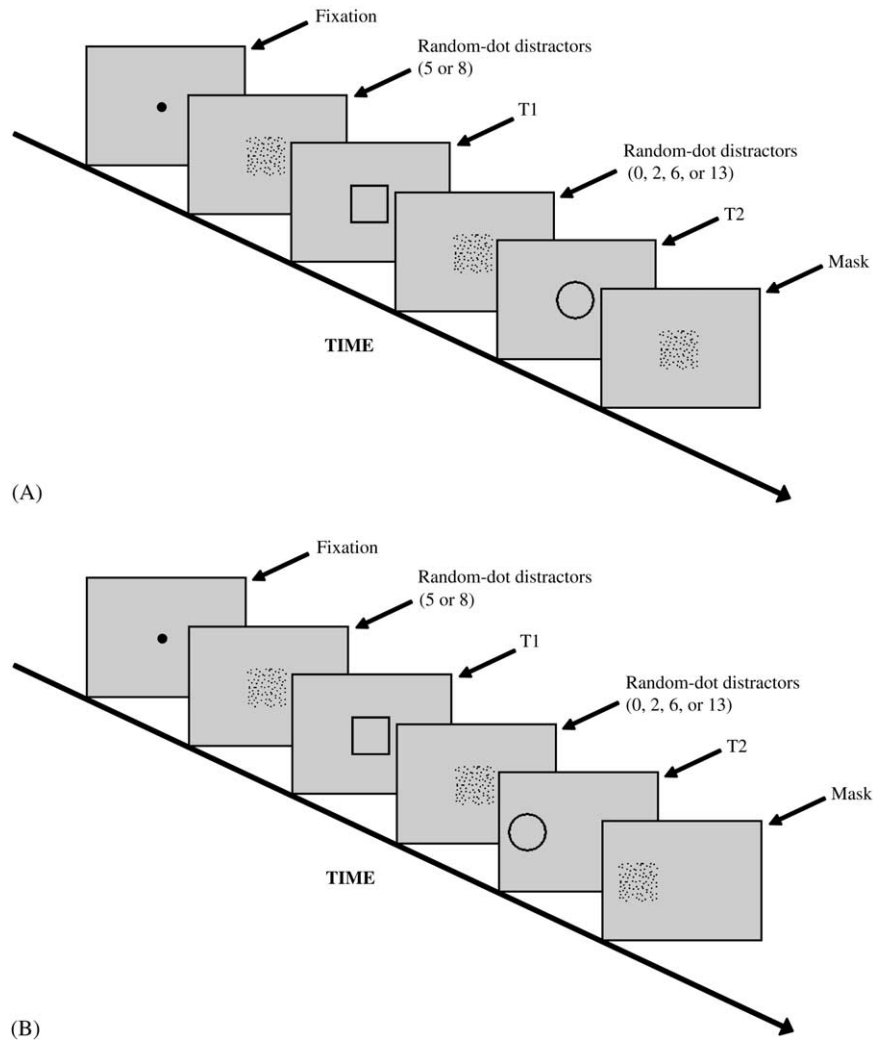


Fig. 1. Schematic diagram of stimulus presentation sequence in Experiment 1 (Panel A) and Experiment 2 (Panel B). Actual stimuli were gray and presented on a black background. Note in Panel B that T2 and the trailing mask were shifted above, below, left, or right of the preceding RSVP sequence. In the control condition in each experiment, the presentation sequence was the same but the first target was omitted.

the experimental condition, so as to better estimate the level of T2 performance had T1 been omitted from the RSVP stream.

3. Results

3.1. Control condition (single target)

Mean percentages of correct identification were 98.0, 96.9, and 97.3 for the age-matched group, reading-matched group, and group with dyslexia respectively. These results were analyzed in a 3 (Group: Age-matched, Reading-matched, Dyslexia) \times 4 (Notional Lag: 100, 300, 700, 1400 ms) mixed-design analysis of variance with Group as a between-subjects factor and Notional Lag as a within-subjects factor that indexed the number of distractors that preceded the target. This analysis revealed a significant effect of Notional Lag,

$F(3,99) = 4.02$, $p < 0.02$, $MS_e = 10.94$, but no other significant main effects or interactions (all $ps > 0.24$).

An examination of the data suggests that accuracy in all three groups actually improved slightly as notional lag increased. This indicates that as the number of dot distractors presented prior to the target increased, target accuracy also increased. One possible explanation for this finding is that increasing the number of distractors simply gave observers more time to prepare for the target. That is, it acted to increase general alertness in preparation for the presentation of the target (Posner, 1980). Regardless of the explanation, however, one fact is clear: identification of a single shape was unimpaired by the presence of the RSVP stream of dot distractors (this finding is similar to earlier results from Tallal, 1980 and Klein et al., 1990). This is important because it shows that impairments in T2 performance in the Experimental condition (reported below) cannot have arisen from distractor interference or masking, but rather from

the requirement to identify T1. This, in turn, points to an explanation for group differences in the magnitude of the AB in terms of differences in the efficiency of attentional allocation to sequences of targets (see Raymond et al., 1992; Seiffert & Di Lollo, 1997 for a similar argument).

3.2. Experimental condition (two targets)

Mean percentages of correct T1 identification as a function of experimental group and T1–T2 Lag are illustrated in Fig. 2. Two aspects of the data are especially notable. First, performance was greatly impaired at lag 1 relative to later lags. Second, it appears that T1 identification was generally poorer in the group with dyslexia than in either control group.

To verify these impressions, T1-accuracy scores were analyzed in a 3 (Group: Age-matched, Reading-matched, Dyslexia) \times 4 (T1–T2 Lag: 100, 300, 700, 1400 ms) mixed-design analysis of variance with Group as a between-subjects factor. This analysis revealed a significant effect of Lag, $F(3,99)=44.66$, $p<0.001$, $MS_e=50.60$, and a significant effect of Group, $F(2,33)=4.58$, $p<0.02$, $MS_e=164.43$, but no significant interaction ($p>0.38$). Post-hoc least-significant-difference analyses of the group means suggested that levels of T1 accuracy were lower in the group with dyslexia than in the age-matched controls ($p<0.01$), but no different than the reading-matched controls ($p>0.08$).

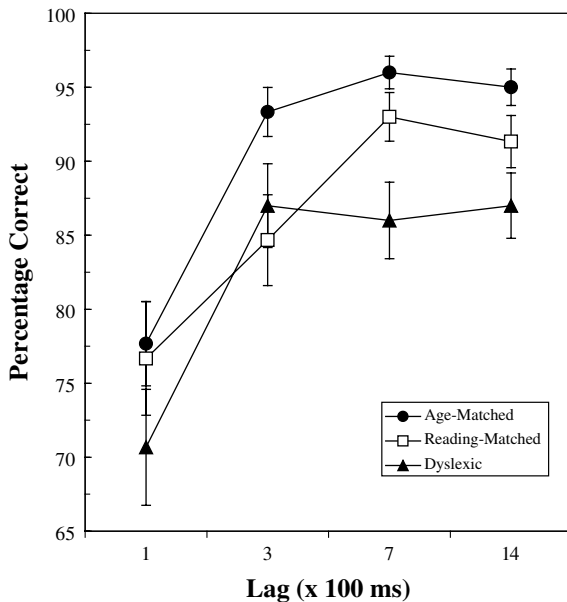


Fig. 2. Mean accuracy of T1 identification as a function of the temporal lag between T1 and T2 in Experiment 1. Closed circles represent scores in the age-matched control group. Open squares represent scores in the reading-matched control group. Closed triangles represent scores in the group with dyslexia. Error bars represent the standard error rate averaged across lags for each group.

There was also no difference between the age-matched and reading-matched controls ($p>0.25$). These results will be discussed further after examining the T2 accuracy data.

Estimates of T2-identification were based exclusively on trials in which T1 had been identified correctly. This procedure is commonly adopted in AB experiments on the grounds that, on incorrect trials, the source of error is unknown, so the effect of T1 on the processing of T2 cannot be estimated. Mean percentages of correct T2 identification as a function of experimental group and T1–T2 lag are illustrated in Fig. 3. An examination of this figure suggests that T2 accuracy improved gradually as lag increased—this is consistent with the presence of an AB deficit in all three groups. Moreover, it appears that the overall level of T2 accuracy was lower in the group with dyslexia and the reading-matched control group than in the age-matched control group.

To verify these impressions, T2-accuracy scores were analyzed in a 3 (Group: Age-matched, Reading-matched, Dyslexia) \times 4 (Lag: 100, 300, 700, 1400 ms) mixed-design analysis of variance with Group as a between-subjects factor. This analysis revealed a significant effect of Lag, $F(3,99)=3.99$, $p<0.02$, $MS_e=53.39$, and a significant effect of Group, $F(2,33)=3.91$, $p<0.04$, $MS_e=177.17$, but no significant interaction ($p>0.93$). Least-significant difference post-hoc tests were conducted in order to investigate the nature of the differences between the three groups. The difference between

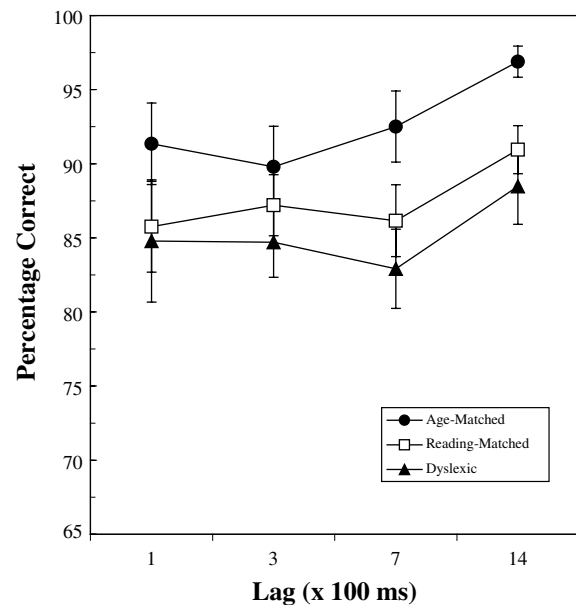


Fig. 3. Mean accuracy of T2 identification, given correct identification of T1, as a function of the temporal lag between T1 and T2 in Experiment 1. Closed circles represent scores in the age-matched control group. Open squares represent scores in the reading-matched control group. Closed triangles represent scores in the group with dyslexia. Error bars represent the standard error rate averaged across lags for each group.

age-matched and reading-matched groups was marginally significant (mean difference = 5.12, $p < 0.07$), and the difference between the age-matched group and the group with dyslexia was significant (mean difference = 7.42, $p < 0.01$). However, there was no difference between the reading-matched and group with dyslexia ($p > 0.40$).

The present results clearly demonstrate a greater AB deficit for children with dyslexia relative to their age-matched peers. This deficit is unlikely to be due to language-specific factors because targets were outline shapes that did not need to be named, rather than alphanumeric characters. Neither can it be attributed to interference between targets and distractors because single-target performance was highly accurate in all groups. Rather, consistent with Hari et al. (1999), the option is supported that identification of T1 engages attentional resources for a longer period of time in the group with dyslexia (i.e. increased dwell time of attention).

It should be noted, however, that the AB in our sample was of a much longer duration. Whereas in Hari et al. (1999), adult dyslexic performance was equivalent to age-matched controls at a T1–T2 lag of approximately 700 ms, children with dyslexia still showed significant decrements in performance at a lag of 1400 ms. This implies that for children with dyslexia, target identification requires attentional resources for a substantially longer period than their adult counterparts.

Although clearly poorer than their age-matched counterparts, children with dyslexia performed similarly to the reading-matched group of younger children. Given that observers in the reading-matched group were at the same reading level as the group with dyslexia but were significantly younger, this outcome suggests that deficits in the group with dyslexia might stem from developmental delays. If true, then it might be expected that as they grow older, the group with dyslexia would begin to show an AB deficit closer in magnitude to their same-age peers. This hypothesis would also explain the shorter AB found by Hari et al. (1999) in adults with dyslexia. Because this sample was older, some of them may have at least partially overcome their attentional deficits and thus ameliorated the severity of the AB.

In addition to deficits in T2 identification, there is also evidence that T1 performance was impaired in the group with dyslexia (and to a lesser extent in the age-matched control group). Such impairments cannot be attributed to interference from distractors or masking because these factors did not influence single-target identification (i.e. in the control condition). Instead, deficits in T1 performance must have arisen from the requirement to identify both targets. Because targets were presented in close temporal succession, they may have competed for access to attentional resources. This reasoning is consistent with the arguments of Hari et al. (1999) as well as recent work by Potter, Staub, and

O'Connor (2002) who showed competition for attentional resources between T1 and T2 in college undergraduates when the targets were separated by 50–150 ms. It is possible that this window of competition is much longer in children with dyslexia, thereby yielding mutual impairments even when targets are separated by several hundred milliseconds.

Alternatively, a number of researchers have implicated interference amongst items in visual short-term memory (VSTM) as a causal mechanism in the AB (Isaak, Shapiro, & Martin, 1999; Raymond et al., 1995; Shapiro, Raymond, & Arnell, 1994). On this account, rapid visual inputs must be stored temporarily in VSTM in order to avoid overwhelming limited-capacity high-level processing resources. While in VSTM, these items compete among themselves for access to high-level resources. While this competition is normally decided in favour of T1 at the expense of T2, thereby yielding an AB deficit, in children with dyslexia, the winner may not be as clear-cut. Instead, both T1 and T2 may suffer when two targets are presented in rapid succession.

One other aspect of the results that deserves discussion concerns the finding that T1 accuracy at Lag 1 was significantly more impaired than at any of the later lags. This result likely arises from the same mechanisms that lead to a phenomenon known as “Lag-1 sparing” (Potter, Chun, Banks, & Muckenhoupt, 1998; Visser, Bischof, & Di Lollo, 1999). Lag-1 sparing refers to the finding that T2 accuracy is often better when it follows T1 directly than when T1 and T2 are separated by an intervening distractor. This result has been explained in terms of “sluggish” attentional gate that opens for T1 but then closes slowly, thus allowing T2 to gain access to high-level processing when it follows T1 directly.

Importantly, there is evidence that the conditions that yield Lag-1 sparing can also produce interference between T1 and T2 (i.e. a “two-object cost”, see Duncan, 1980; see also, Potter et al., 2002). This interference at Lag 1 is less costly for T2 than an outright delay in processing, such as occurs at Lag 3. Thus, T2 accuracy at Lag 1 is “spared”. On the other hand, interference at Lag 1 yields a deficit in accuracy relative to Lag 3 where no interference between targets usually occurs. One novel aspect of the present results is that interference was much more harmful to T1 than in previous studies with college undergraduate samples. For example, whereas T1 accuracy is typically greater than T2, in the present experiment, overall accuracy for T2 was 87% at the shortest lag, but only 75% for T1. Given that a similar pattern occurred in all three groups, it may be attributable to the younger age of our sample. This, in turn, suggests that there are differences in processing styles and abilities as a function of age that merit further empirical investigation.

In Experiment 2, we wished to extend our findings to a situation more closely akin to reading—namely, to a case in which attentional shifts were required both over time and across space. Although, these two types of shifts are typically examined in isolation, it is likely that both are involved in reading. For example, to read a sentence, each word must be attended in correct sequence while attention is shifted across the page in order to view each word. Given the importance of simultaneously allocating visual attention over time and across space for reading, it is crucial to determine whether children with dyslexia are impaired in this respect. To evaluate this issue, in Experiment 2, we modified the AB paradigm used in Experiment 1 by displaying the first target along with an RSVP stream at a central fixation, and the second target at an adjacent peripheral location. Under these conditions, successful identification of the second target required both a temporal and a spatial reallocation of attentional resources.

4. Experiment 2

4.1. Participants

The 36 children who participated in Experiment 1 participated in Experiment 2.

4.2. Apparatus and stimuli

Apparatus and stimuli were identical to Experiment 1.

4.3. Procedure

There were two conditions: experimental and control, each ran in a separate block of trials (see Fig. 1; Panel B). In both conditions, an RSVP stream of random-dot distractors was displayed in the centre of the screen. In the control condition, a single target shape was presented, either above, below, left, or right of the central stream. The centre-to-centre separation between the stream and the eccentric target was approximately 3° . A single random-dot distractor, displayed in the same location, always followed the eccentric target and acted as a mask. In the experimental condition, the first target shape was embedded in the central stream of distractors, while the second target was presented either above, below, left, or right of the stream. As in the control condition, the centre-to-centre separation between the stream and the eccentric target was approximately 3° and a single distractor that acted as a mask always followed the second target.

All other aspects of the procedure were identical to Experiment 1.

5. Results

5.1. Control condition (single target)

Mean percentages of correct identification were 98.3, 94.7, and 97.0 for the age-matched group, reading-matched group, and group with dyslexia respectively. Performance was analyzed in a 3 (Group: Age-matched, Reading-matched, Dyslexia) \times 4 (Notional Lag: 100, 300, 700, 1400 ms) mixed-design analysis of variance with Group as a between-subjects factor. This analysis revealed no significant main effects or interactions (all p 's > 0.05). This indicates that identification accuracy for a single eccentric target was uniformly high in all three groups. Moreover, as in Experiment 1, the high accuracy with which the single target was identified from amongst distractors implicates attention as the causal agent in dual-target impairments reported below, rather than low-level factors such as visual masking.

5.2. Experimental condition (two targets)

Mean percentages of correct T1 identification as a function of experimental group and T1–T2 Lag are illustrated in Fig. 4. An examination of this figure suggests that overall T1 performance improved gradually as lag increased, but that T1 identification was more accurate in the age-matched control group than either the reading-matched group or the group with dyslexia.

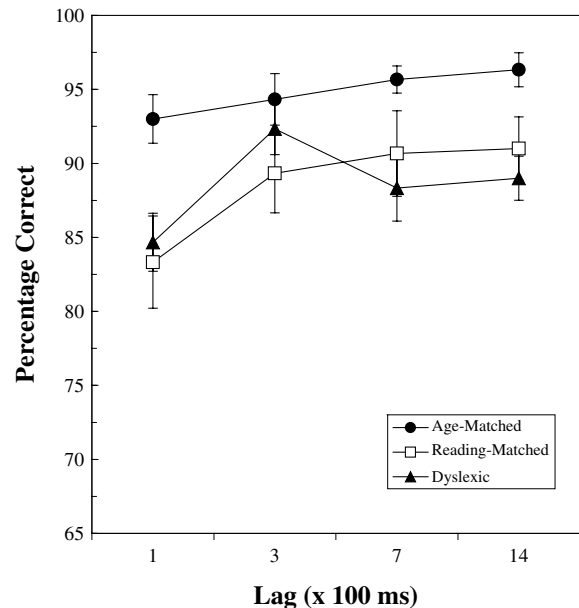


Fig. 4. Mean accuracy of T1 identification as a function of the temporal lag between T1 and T2 in Experiment 2. Closed circles represent scores in the age-matched control group. Open squares represent scores in the reading-matched control group. Closed triangles represent scores in the group with dyslexia. Error bars represent the standard error rate averaged across lags for each group.

To verify these impressions, T1-accuracy scores were analyzed in a 3 (Group: Age-matched, Reading-matched, Dyslexia) \times 4 (Lag: 100, 300, 700, 1400 ms) mixed-design analysis of variance with Group as a between-subjects factor. This analysis revealed a significant effect of Lag, $F(3,99)=6.72$, $p<0.001$, $MS_e=30.03$, and a significant effect of Group, $F(2,33)=4.37$, $p<0.03$, $MS_e=126.49$, but no significant interaction ($p>0.36$). Subsequent post-hoc least-significant-difference tests indicated that accuracy in the age-matched group was significantly higher than in the reading-matched control group ($p<0.03$) and the group with dyslexia ($p=0.01$). However, there was no difference between the reading-matched group and the group with dyslexia ($p>0.70$). These results will be discussed further after examining the T2 accuracy data.

As in Experiment 1, estimates of T2-identification were based exclusively on trials in which T1 had been identified correctly. Mean percentages of correct T2 identification as a function of experimental group and T1–T2 lag are illustrated in Fig. 5. An examination of this figure suggests that T2 accuracy improved gradually as lag increased. This is consistent with the presence of an AB deficit in all three groups. Moreover, it appears that the overall level of T2 accuracy was lowest in the group with dyslexia, somewhat higher in the reading-matched control group, and highest in the age-matched control group.

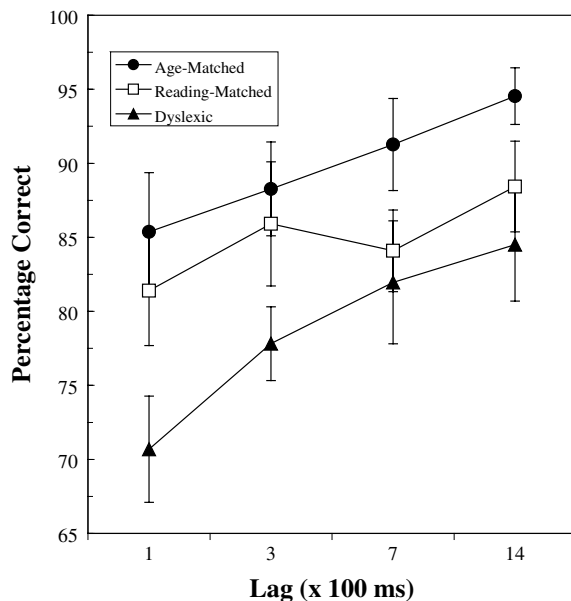


Fig. 5. Mean accuracy of T2 identification, given correct identification of T1, as a function of the temporal lag between T1 and T2 in Experiment 2. Closed circles represent scores in the age-matched control group. Open squares represent scores in the reading-matched control group. Closed triangles represent scores in the group with dyslexia. Error bars represent the standard error rate averaged across lags for each group.

To verify these impressions, T2-accuracy scores were analyzed in a 3 (Group: Age-matched, Reading-matched, Dyslexia) \times 4 (Lag: 100, 300, 700, 1400 ms) mixed-design analysis of variance with Group as a between-subjects factor. This analysis revealed a significant effect of Lag, $F(3,99)=8.50$, $p<0.001$, $MS_e=73.58$, and a significant effect of Group, $F(2,33)=4.80$, $p<0.02$, $MS_e=310.28$, but no significant interaction ($p>0.65$). Least-significant difference post-hoc tests were conducted in order to investigate the nature of the group differences. There was no significant difference between the reading-matched and age-matched groups ($p>0.18$). However, the difference between the group with dyslexia and the reading-matched group was highly significant (mean difference = 11.12, $p<0.01$), and the difference between the group with dyslexia and the age-matched group was marginally significant (mean difference = 6.22, $p<0.10$). Follow-up analyses conducted separately at each lag indicated significant differences at Lag 1, $t(22)=2.16$, $p=0.02$, and Lag 3, $t(22)=1.70$, $p=0.05$, but not at Lag 7, $p=0.33$, or Lag 14, $p=0.20$ (all tests one-tailed).

The results of Experiment 2 bear striking similarities to those of Experiment 1. Again, identification of a single (eccentric) target was similar across all groups. In contrast, when two targets, separated in space and time, had to be identified, accuracy for both was impaired. Notably, overall levels of T2 accuracy were lower in this experiment than in Experiment 1. This suggests that the necessity to shift attention across space and over time was more demanding than simply shifting attention over time, thus producing larger impairments.

Importantly, there is also some evidence that overall T2 accuracy was poorer in the group with dyslexia than in both control groups. This contrasts with Experiment 1 in which performance in the group with dyslexia was poorer than the age-matched control group, but no different than the reading-matched control group. This difference suggests that impairments in target identification when both spatial and temporal shifts of attention are necessary may not be due solely to delays in the development of reading ability. If this were the case then performance should have been similar in the group with dyslexia and the reading-matched group (who had the same reading ability, but were younger). Rather it seems prudent to consider the possibility that the AB shown in Experiment 2 reflect unique impairments associated with dyslexia. This suggestion is consistent with earlier evidence that attentional control mechanisms are impaired in dyslexia (e.g. Lovegrove et al., 1986). However, clearly additional work is necessary before strong conclusions can be made.

One final issue concerns T1 accuracy at Lag 1. Whereas, in Experiment 1, T1 accuracy was much reduced at Lag 1 relative to later lags, this pattern was much less evident in Experiment 2. Moreover, whereas

T2 accuracy showed evidence of Lag-1 sparing in Experiment 1, T2 accuracy was poorest at Lag 1 in Experiment 2. These differences in T1 and T2 performance are likely due to the fact that T1 and T2 were presented in different spatial locations. In a review of published AB studies, Visser et al. (1999) found that Lag-1 sparing never occurred when targets were in different spatial locations. They attributed this to the need to shift attention between spatial locations which, in turn, prevented T1 and T2 from passing the same attentional gate.

6. General discussion

When two targets appear in rapid succession at the same spatial location, children with dyslexia showed a larger AB deficit relative to their age-matched peers (Experiment 1). Moreover, this difference is greater when the two targets are presented in different spatial locations, thus necessitating a shift of attention over time and space (Experiment 2). Importantly, these results are unlikely to be due to specific deficits in linguistic processing (e.g. Snowling, 2000) because targets were shapes while distractors were patches of random dots. They also cannot be attributed to factors such as distractor interference or decreased vigilance because identification of a single shape amongst distractors was unimpaired in the group with dyslexia. This bolsters our claim that children with dyslexia are less able to rapidly reallocate attention to rapidly-sequential targets.

Although broadly similar to previous findings using an adult group with dyslexia (Hari et al., 1999), our results also indicate important differences. Foremost amongst these is a difference in the duration of impairment. In an adult group with dyslexia, the magnitude of the AB was greater than in an age-matched control group up to a T1–T2 SOA of approximately 700 ms. In contrast, in our children with dyslexia, performance was still inferior to the age-matched controls at a T1–T2 SOA of 1400 ms. Thus differences in the magnitude of the AB persist for almost twice as long in the younger group.

One possible explanation for this difference is that adults with dyslexia develop strategies to compensate for their reading difficulties. Such strategies might improve performance on tasks that require similar processing capabilities as those employed in reading. Another possibility is that differences between children and adults are at least partially the result of developmental delays in the children with dyslexia that are overcome by adulthood. It is notable that performance in the group with dyslexia was similar to that of the reading-matched control group who were several years younger. This suggests that the ability to shift attention over time in our dyslexic group was on par with children several years their junior. Put differently, as suggested by Hari et al.

(1999), the dwell time of attention for children with dyslexia may be slowed to a level that is similar to younger children who read at the same level.

Another novel aspect of the present findings is that identification impairments were evident for both T1 and T2. This pattern of results is different than many previous studies with college undergraduates (e.g. Chun & Potter, 1995; Raymond et al., 1992; Visser et al., *in press*) in which identification deficits were limited to T2. The most likely explanation for this result is that it reflects a period of prolonged competition between T1 and T2 for access to high-level processing. Such a competition could occur in at least two ways. One possibility, as suggested by Potter et al. (2002), is that “attention is labile” and that either T1 or T2 can produce involuntary shifts of attention to itself at the expense of the other target. As a result, temporal lags at which T1 would normally capture attention quite easily may instead result in a competition with T2 that produces more errors for T1. Another possibility is that targets may experience a prolonged period of delay in a visual short-term memory store (e.g. Shapiro et al., 1994). Such a delay would result in competition amongst target representations for access to attentional resources and reduce identification accuracy for both targets. Both of these options are plausible, and they remain to be evaluated in future experiments.

One other potential explanation for the high level of T1 errors is that observers adopted a deliberate strategy of sacrificing T1 accuracy in order to improve T2 performance. On this account, because identifying two targets was relatively difficult, observers chose to ignore T1 on some trials in order to improve T2 performance. If this strategy were only partially successful, however, both T1 and T2 accuracy would be expected to suffer. Although plausible, the present experiments were designed specifically to maximize T1 accuracy by instructing participants that this was their primary target. Given these instructions, it seems unlikely that participants would deliberately choose to ignore T1. Even if participants did adopt such a strategy, it is important to note that this would not undermine our main conclusion that processing T1 impairs allocation of attention to T2. This is because adopting a strategy to maximize T2 accuracy by not attending to T1, is itself indicative that T1 processing impairs T2 identification. To wit, if observers were having no difficulty identifying both targets, they would not have to adopt a strategy of sacrificing T1. Viewed from this perspective, it is clear that the presence of T1 identification deficits in dyslexia does not undermine the conclusion that this group has difficulty reallocating to attention to rapidly-sequential targets.

Perhaps the most interesting aspect of our findings are indications that T2 identification in the group with dyslexia was more impaired than either control group

when the second target was presented in a different location than the first. This experimental condition was designed to approximate the attentional requirements of reading—namely, the need to shift attention both across space and over time. Thus, the presence of a pronounced deficit in this condition provides stronger evidence for a link between attention deficits and reading difficulties in dyslexia. Moreover, that performance was marginally worse in the group with dyslexia than either control group suggests deficits that go beyond what is explainable purely in terms of developmental delays in reading. Rather, the group with dyslexia may have impairments in their ability to simultaneously shift attention over time and space that are linked specifically to dyslexia.

6.1. Relationship to other dyslexia research

Researchers have used a variety of research paradigms to investigate reading in children with developmental dyslexia. The findings from three of these are particularly germane to the present work. The first is the Rapid Automatised Naming (RAN) procedure. In a typical RAN task, participants are asked to name out loud 50 (five rows of 10) printed items as quickly as possible. Items usually consist of colour patches, random objects, digits, or letters. Performance is assessed typically on the basis of total time required to read the items, articulation time (the total time spent speaking) and pause time (the total time taken between naming items) (e.g. Neuhaus, Foorman, Francis, & Carlson, 2001).

Studies have consistently found strong relationships between naming speed and reading skill in samples of both normal readers and readers with dyslexia (Kail & Hall, 1994; Wolf & Obregon, 1992). Additionally, RAN scores predict later reading ability in young children (Wolf, Bally, & Morris, 1986), and discriminate between different types of readers (Wolf, 1991). However, the factors that mediate this relationship are unclear because RAN performance is correlated with many variables including phonological processing (Wagner & Torgesen, 1987), verbal memory (Mann, 1984), quality of orthographic codes in memory (Perfetti, 1992), orthographic knowledge (Bowers, Sunseth, & Golden, 1999), reading automaticity (Spring & Davis, 1988), executive functioning (Denckla & Cutting, 1999), mastery of orthography-phonology associations (Wolf, 1991), generalized processing speed (Kail, Hall, & Caskey, 1999), and visual attention (Neuhaus et al., 2001).

On the face of it, given the correlations with processing speed and visual attention measures, there would seem to be some relationship between the RAN task and the AB task. In fact, it might be asked whether the AB task here amounts to a small slice of a full RAN task. Although this is an intriguing suggestion, it is difficult to judge the overlap between these two tasks

based on the current data because there are many differences between the two paradigms.

One type of difference is in the response requirements. Whereas continuous performance is required on the RAN task, with the dependent measure most commonly being overall response time, the AB task consists of discrete trials with the dependent measure being accuracy. This makes a directly comparison of results problematic. There are also clear differences in task demands between the two tasks with RAN performance requiring oral naming and the AB task requiring manual responses that did not necessarily involve object naming. This suggests the two tasks may require very different processing mechanisms. This point is bolstered by the fact that the RAN task has been shown to correlate with a variety of tasks that tap very different processing requirements.

Despite these difficulties, it is clear that future empirical work should pursue the relationship between the RAN and the AB. This might be accomplished in at least two ways (which were suggested by a helpful anonymous reviewer). First, a replication of the present AB task along with measures of RAN performance would be useful in order to examine correlations between these measures, and establish potential dissociations. Second, modifications of the AB task in order to further minimize linguistic demands (i.e. naming) would be important in order to determine how much of the AB deficit reported here depends on such task requirements. In addition, we suggest that future research should focus on measures of pause time in the RAN task because these are thought to be more accurate indexes of processing time (Neuhaus & Swank, 2002).

Another measure of reading skill that is clearly related to the present work is RSVP reading. In this task, participants are asked to read aloud a passage that is presented to them on a word-by-word basis. Presentation rates are similar to those used in the AB task. However, while AB tasks typically yield significant impairments in target identification, RSVP reading demonstrates high levels of accuracy in normal readers (Masson, 1983).

Chun and Potter (1995) suggested that these performance differences arise from two factors. One is the role of context and grammar. Whereas context and grammar may be helpful in RSVP reading, they are not present as cues in a typical AB task. This may contribute to better performance on the reading task. Additionally, Chun and Potter (1995) noted that while RSVP reading involves whole-report of every item, the AB requires participants to select relevant targets from irrelevant distractors. This selection process may create difficulties that are not present in RSVP reading, and thus may contribute significantly to the AB deficit.

On this analysis, it might be suggested that the processing deficits revealed by the AB are only marginally related to reading because they do not take into

account context and grammar and because they require observers to select stimuli from amongst distractors. On the contrary, we believe that the AB is ideally suited to studying attentional processes in reading precisely because of these reasons. To the extent that reading does depend on rapidly allocating attention to sequences of written input—a relationship supported by the correlations that have been obtained between visual attention shifts and reading performance (Asbjornsen & Bryden, 1998)—the AB represents a task that uniquely taps these processes while minimizing the contributions of other factors such as memory, and phonological processing. For the same reason, the AB task is a particularly useful tool to study the development of reading in children (both with and without dyslexia) who are just learning to read and thus have not mastered the use of grammatical and contextual constraints in reading. In this population, initial mastery of reading is likely to depend more heavily on fast and efficient of visual attention.

It should also be noted that RSVP reading is not immune to deficits similar to those that underlie the AB. Calvo, Castillo, and Estevez (1999) found that decreasing within-sentence presentation rate improved processing of RSVP items. This suggests that increasing the processing time for each item improved accuracy, which is consistent with what would be expected on the basis of the results from the AB paradigm where second target performance improves with increasing inter-target interval. Also relevant is evidence showing repetition blindness (RB) in the context of RSVP reading. Repetition blindness refers to a deficit in reporting the second of two similar or identical words when they are briefly displayed and are presented in close temporal succession (Kanwisher, 1987). The presence of RB in RSVP reading suggests that while overall performance in this task may be quite accurate, subtle difficulties similar to the AB deficit, may be present upon more fine-grained analysis.

A final area of research that is relevant to the present work involves the continuous performance task (CPT; Epstein, Conners, Sitarenios, & Erhardt, 1998). In this task, several hundred stimuli (usually letters) are presented in rapid succession, with participants monitoring the stream of stimuli for instances of a specific target stimulus. The CPT is usually conceptualized as a measure of task vigilance, with missed targets indicating that participant's attention is wandering from the task. Numerous studies have shown that CPT performance is poorer in children with dyslexia and comorbid ADHD (e.g. Kupietz, 1990). This is broadly consistent with the attentional deficits shown in the present work. Critically, however, the present results do not indicate a problem with vigilance because children with dyslexia were just as good at identifying a single target from a stream of distractors (a task roughly equivalent to the CPT) as the children in the control groups. Rather, our results

indicate deficits in allocation of attention to rapid sequences of target objects that only become apparent when multiple objects must be attended.

6.2. Concluding comments

Considered collectively, the present results indicate that children with dyslexia have difficulty rapidly allocating attention over time (and across space) in comparison to their age-matched peers. While this deficit is broadly similar to that of adults with dyslexia (Hari et al., 1999), these findings also reveal features that are unique to children. What is needed is additional research aimed at more fully understanding temporal processing deficits in dyslexia and what links may exist between these deficits and reading impairments.

Acknowledgments

This work was sponsored by research grants from the Natural Sciences and Engineering Research Council of Canada to T.A.W.V. and D.E.G, and by Grant #12-FY98-478 from the March of Dime Birth Defects Foundation to D.E.G.

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