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## Sequential object recognition deficits in normal readers<sup>☆</sup>

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### ABSTRACT

The present work examined the relationship between sequential object recognition and variations in normal reading ability. A group of normal readers completed a battery of tests examining nonverbal intelligence, rapid-automatized naming, reading ability, and an attentional blink (AB) task in which they were asked to identify two sequential targets embedded amongst distractors. Consistent with previous studies, all participants showed a significant AB, with second-target identification improving as inter-target interval increased. More critically, low-normal readers showed a larger AB than high-normal readers. Considered in context with earlier work, these results imply that the ability to allocate capacity-limited processing resources to sequential visual inputs is linked to reading proficiency across the range of both disabled and normal readers.

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### 1. Introduction

The ability to navigate through an airport, study a manual in preparation for a road test, or make a selection from a wine menu depends on reading. Although most of us develop this essential skill, approximately 15% of the population has significant impairments in reading achievement disproportionate to their chronological age, measured intelligence, and educational opportunities (DSM-IV; American Psychiatric Association., 1994). This disorder, known as dyslexia, is characterized not only by impairments in reading, but also frequently by problems with writing, spelling, short-term memory, and motor movements (Farmer & Klein, 1995; Rapala & Brady, 1990).

The heterogeneous nature of symptoms in dyslexia has led to a number of different theoretical explanations for the disorder. Perhaps the most prominent of these is the phonological hypothesis, which suggests that dyslexics are impaired in their ability to map letters and syllables onto speech sounds. However, while there is little doubt that phonology plays an important role in reading, there is ample evidence to suggest that phonological deficits alone cannot explain all cases of dyslexia. For example, (Castles & Coltheart, 1993; Castles & Coltheart, 1996) documented a 9-year old boy with surface dyslexia who could read regular words and

pseudowords, but showed profound difficulties reading irregular words and had poor lexical and whole-word recognition skills.

In light of these and similar findings, numerous additional deficits have also been linked with dyslexia. For example, (Tallal, 1984; see also Farmer & Klein, 1995) argued that poor phonological skills in dyslexia stem from a general temporal processing deficit in auditory and visual modalities. On a related note, a number of researchers (e.g., Hogben, 1997; Lovegrove, Martin, & Slaghuis, 1986; Skottun, 1997) have suggested that dysfunctions in the magnocellular pathway result in insufficient inhibition of parvocellular visual processing (which is required for word recognition). As a result, during saccades, both visual subsystems are active resulting in a scrambling of visual information obtained from one fixation to the next.

Most recently, several studies have proposed an important role for capacity-limited visual processing resources (i.e., visual attention) in reading. These accounts appeal to the notion that efficient scanning of printed material requires the visual system to selectively encode relevant pieces of information, while excluding competing irrelevant information. This is assumed to require covert shifts of attention from word to word (Casco, Tressoldi, & Dellantonio, 1998), followed by an overt eye movement (Roach & Hogben, 2004). Consistent with a link between visual attention and reading, Casco et al. (1998) showed a relationship between target detection speed in a difficult search task that required effortful shifts of attention from item to item in a display, reading rates and reading errors. Similarly, Heiervang and Hugdahl (2003) found that a peripheral visual cue that validly predicted target location on 80% of trials was less beneficial for dyslexics than normal readers. This implied that readers with dyslexia were less able to use the information from the cue to allocate visual attention.

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Given the link between reading ability and performance on tasks requiring participants to allocate attentional resources across space, it seems plausible that a relationship might also exist between reading ability and performance on tasks requiring allocation of attention over time to sequential stimuli. As discussed by Visser, Bischof, and Di Lollo (2004), this proposal is broadly consistent with studies showing correlations between reading performance and visual attention shifts (Asbjornsen & Bryden, 1998), the hypothesized link between reading and temporal processing (Farmer & Klein, 1995; Tallal, 1984) and the fact that dyslexia has already been associated with deficits in both temporal processing and visual attention.

To investigate such a link, a number of studies have employed a rapid serial visual presentation (RSVP) paradigm consisting of two target items embedded in a stream of distractors with all items presented in the same spatial location at a rate of about 10 Hz. Under these conditions, while identification of the first target (T1) is nearly perfect, identification of the second target (T2) varies with inter-target interval (lag). Performance is lowest at lags of 200–300 ms, and steady improvement to the level of T1 by about 700 ms (e.g., Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992; Visser et al., 2004). This pattern of improving performance over lags is referred to as the attentional blink (AB).

The AB has conventionally been attributed to an inability to process T2 at brief lags while attentional resources are occupied with T1 (e.g., Chun & Potter, 1995; Jolicoeur, 1998; Visser, 2007). Several pieces of evidence are consistent with this interpretation. First, the AB is reduced or eliminated, under identical stimulus presentation conditions, if observers are simply asked to ignore T1 (Chun, 1997; Dell'Acqua & Jolicoeur, 2000; Jolicoeur & Dell'Acqua, 1998; Raymond et al., 1992). This implies that resources must be engaged by a prior target stimulus for T2 impairments to occur. Second, numerous studies have shown that the AB can be found when targets are presented to different sensory modalities (e.g., auditory/visual: Arnell & Jolicoeur, 1999; Arnell & Larson, 2002; Dell'Acqua & Jolicoeur, 2000; Potter, Chun, Banks, & Muckenhoupt, 1998; auditory/tactile: Dell'Acqua, Turatto, & Jolicoeur, 2001; visual-tactile: Soto-Faraco et al., 2002). These robust cross-modal deficits implicate an important role for central resource limitations in the AB. Finally, neurophysiological investigations of the AB have consistently shown a link with mechanisms involved in spatial selection and working memory (e.g., Martens, Munneke, Smid, & Johnson, 2006; Vogel, Luck, & Shapiro, 1998; Jolicoeur, Sessa, Dell'Acqua, & Robitaille, 2006; Marois, Yi, & Chun, 2004).

One of the first studies to look at the AB and reading was done by Hari, Valta, and Uutela (1999) who evaluated a population of adults with dyslexia with 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 an RSVP stream of black-letter distractors at a central fixation location, along with a single white letter (T1) and a black 'X' (T2). Both the control and dyslexic groups showed pronounced ABs suggesting 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 a lag of approximately 1200 ms, compared to the control group whose performance asymptoted at a lag of approximately 700 ms.

In a similar vein, Visser et al. (2004) compared the AB in three groups of children: those with dyslexia, reading-matched controls, and age-matched controls. To eliminate possible group differences in linguistic ability, observers were presented with an RSVP stream of random-dot distractors along with two target shapes. In the first experiment, when all items were presented at the same location, the dyslexic and reading-matched control groups showed similar AB deficits that were both larger than the age-matched controls.

In the second experiment, when T1 and T2 were presented in different locations, the dyslexic group was significantly worse than both control groups. Taken together, this implied that children with dyslexia had a more pronounced AB that was particularly exacerbated when attention had to be shifted both over time and across space.

The studies of Hari et al. (1999), Visser et al. (2004) and analogous results from Lum, Conti-Ramsden, and Lindell (2007) and Buchholz and Davies (2007) all point to a reliable relationship between allocation of visual attention over time to sequential objects and reading impairment. However, what is not known is whether this relationship extends across the range of normal reading proficiency. One possibility is that to attain a normal level of reading proficiency, there is a certain minimum level of visual attention skill required. Once this minimum level of skill is achieved, no further benefits to reading accrue for those who are far above the minimum versus those who are only slightly above the minimum. On this view, while dyslexics and normal readers show a difference on tasks such as the AB, no such differences would be found across the range of normal reading proficiency. A second possibility is that the relationship between visual attention and reading is a continuous one, and that the difference between dyslexics and normal readers on tasks such as the AB reflect a more general relationship between reading skill and visual attention. On this view, differences on visual attention tasks should also be found across the range of normal reading proficiency. For example, highly proficient readers should show a smaller AB than less-skilled readers.

The present work was designed to test these alternatives. We compared performance on an AB task between low-skill and high-skill readers, all of whom scored within the normal range of reading proficiency on standardized tests (subsequently, we refer to these groups as low-normal and high-normal). To anticipate the results, we found reliable differences in AB performance between reading groups even when other variables such as nonverbal intelligence, age, and speed of memory retrieval were controlled for. This implies that the ability to allocate visual attention over time is related to reading proficiency across a range of abilities.

## 2. Methods

### 2.1. Participants

Eighty-seven university students (78.2% women; 21.8% men) participated in the study. Age ranged from 18 to 41 years ( $M = 21.27$ ,  $Mdn = 20.00$ ,  $SD = 4.15$ ; women:  $M = 21.37$ ,  $Mdn = 19.96$ ,  $SD = 4.39$ ; men:  $M = 20.94$ ,  $Mdn = 20.00$ ,  $SD = 3.27$ ). Participants received course credit in exchange for participation in a 1-h session. All participants reported normal or corrected-to-normal (i.e., eye glasses or contact lenses) vision.

### 2.2. Measures

#### 2.2.1. Reading efficiency

The phonemic decoding efficiency subtest from the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999) was used. This test measured observers' ability to rapidly name as many non-words as possible (top score of 63) without errors in 45 s. Non-words were divided into three equal lists printed vertically on a white form. Participants were instructed to read down each list, pronouncing items based on their common sounds, and skipping any items they could not pronounce. Participants were asked to stop reading after 45 s and a line was drawn after the last non-word read. If all the items were read in less than 45 s, the time required was noted. Incorrect responses were given for inaccurately pronounced non-words and non-words that had been skipped.

### 2.2.2. Nonverbal intelligence

Nonverbal intelligence was assessed using the nonverbal subtest of the Kaufman Brief Intelligence Test (Kaufman & Kaufman, 2004). This subtest was composed of 46 matrices involving meaningful and abstract visual stimuli. Participants were required use fluid thinking and problem solving abilities to identify relationships and complete visual patterns in either  $2 \times 2$  or  $3 \times 3$  matrices. Each matrix had one missing item and participants were instructed to choose one of six possible items to complete it. A score out of 46 was recorded.

### 2.2.3. Rapid-automatised naming (RAN)

Two measures were used to assess naming speed in participants: one involving letter stimuli and one without. Performance on these types of tasks have been shown to be related to reading ability (Kail & Hall, 1994; Wolf & Obregon, 1992) as well as a number of skills associated with reading performance such as phonological processing (Wagner & Torgesen, 1987), mastery of orthography–phonology relationships (Wolf, 1991) and general processing speed (Kail, Hall, & Caskey, 1999).

The first measure (RAN-Letters) was the rapid letter naming subtest from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen & Rashotte, 1999). Participants were asked to read aloud, as quickly as possible, 72 items composed of six black randomly arranged letters (*a, c, k, n, s, and t*) divided into four rows and nine columns on two white pages. Participants were instructed to read across the top row of the first page from left to right before going onto the second row and so on. Once each letter on the first page was named, the same procedure was completed with the second page. The cumulative time taken to name both pages was recorded, along with the number of errors.

The second measure (RAN-Colours) was similar to the CTOPP, but involved naming colours rather than letters in order to estimate naming speed for non-linguistic stimuli. This task consisted of a computer display composed of a  $6 \times 6$  matrix of solid coloured dots ( $1^\circ \times 1^\circ$ ) presented on a white background. Participants named the colour of each dot (i.e., black, blue, green, red, white, yellow) in the matrix, as quickly and accurately as possible, starting at the top left corner and proceeding across the first row, moving to the second row and so on. Participants began the task by pressing the space bar to initiate display of the matrix, and pressed the space bar again when they had completed naming the colour of all the dots. The researcher noted errors while the computer recorded the interval between the presses of the spacebar as an estimate of processing speed. Each participant completed two trials with a different pattern of dots in counter-balanced order.

### 2.2.4. Visual attention (AB) task

All stimuli were displayed on an NEC MultiSync FE 992 monitor running at a refresh rate of 100 Hz, slaved to a Pentium IV computer running Presentation software (Version 9.04, Neurobehavioral Systems). Target items consisted of five white outlined shapes: square, cross, triangle, diamond, or circle. Distractors, consisting of random-dot patches, were formed by placing 200 dots randomly ( $0.002^\circ \times 0.002^\circ$  each) in a notional area of approximately  $1^\circ \times 1^\circ$ . Each target was masked by a keyboard symbol drawn from the set %, &, and #, presented immediately following the target (see below). Targets and masked subtended approximately  $1^\circ \times 1^\circ$ . All participants received written and verbal instructions prior to beginning the task asking them to identify both targets as accurately as possible with an emphasis on T1 accuracy.

Each trial began with the presentation of a white fixation cross at the centre of the display. Participants were instructed to fixate on this cross and press the spacebar to initiate a trial. Once the space bar was pressed, the fixation cross was replaced by the presentation of an RSVP stream. Each item in the stream was pre-

sented for 40 ms and separated from the next item by a 60 ms blank display yielding an inter-item stimulus onset asynchrony (SOA) of 100 ms. The RSVP began with five to eight sequential random-dot distractors, followed by T1. The second target was separated from T1 by an SOA of 100 ms (Lag 1), 200 ms (Lag 2), 300 ms (Lag 3), 500 ms (Lag 5), or 700 ms (Lag 7). Thus, at lag 1, T2 was presented directly after T1, without an intervening mask, while at lag 2, the targets were separated by the T1 mask alone. At all other lags, a mask and either 1, 3, or 5 distractors followed T1. The last item in the RSVP stream, presented immediately following T2, was always a keyboard symbol mask. Targets and masks were chosen randomly with replacement with the constraint that a target or mask could not be used twice in a single trial.

Once the final distractor was presented, the monitor went blank indicating to participants that it was time to make their responses. Identification of each target was made by pressing one of five marked keys on the keyboard that corresponded to the five possible shapes. Responses were scored as correct regardless of whether or not the shapes were identified in the same order that they were presented. After a response was made for both targets, the fixation cross reappeared in the centre of the monitor, indicating the next trial was ready to begin. Participants completed 125 trials, equally divided between each T1–T2 lag.

### 2.3. Procedure

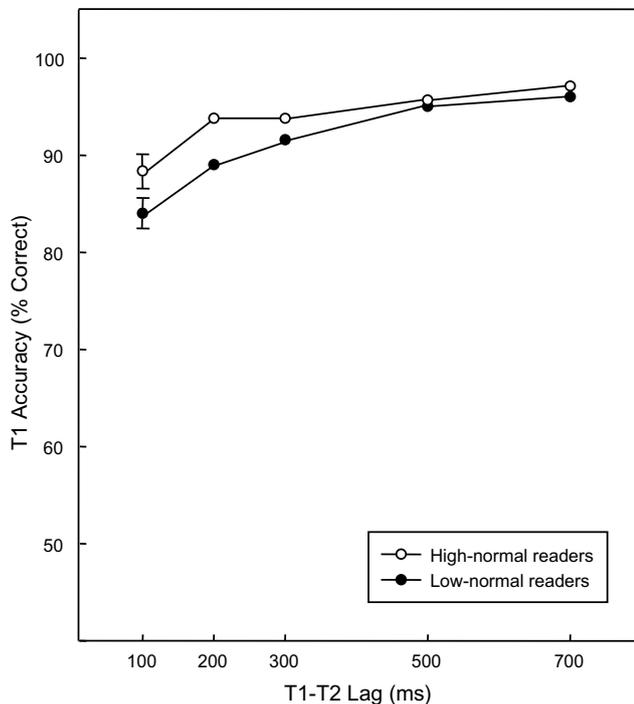
Participants completed the battery of written, verbal and computerized tasks during a 1-h experimental session. The computerized task was completed in a quiet and darkened room, with participants seated comfortably at a desk approximately 60 cm from the computer monitor. The non-computerized tasks were given in a small, brightly lit room. To control for the effects of presentation order, the computerized and non-computerized tasks were counter-balanced separately, with half of participants receiving the non-computerized tasks first, while the other half received the computerized tasks first.

## 3. Results

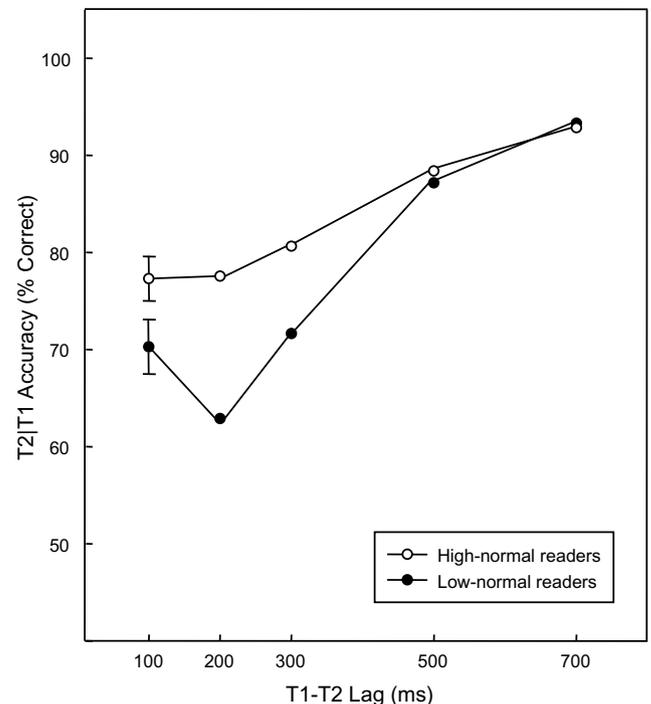
Data from four participants were omitted from analysis because they did not complete all measures. The remaining participants were categorized into groups based on reading efficiency. To create reading efficiency groups, we used the norms from the TOWRE manual to classify participants as low-normal or high-normal readers based on their standard scores. We classified low-normal readers as those whose standard scores ranging from 90 to 99.99 ( $n = 26$ ). We classified high-normal readers as those whose standard scores were 100 or higher ( $n = 41$ ). Because we were only interested in the role of visual attention in normal readers, we excluded participants ( $n = 16$ ) who fell below the cut-off point for average reading skill ( $<90$ ).

Mean T1 accuracy scores were calculated separately as a function of T1–T2 lag and reading ability, and are displayed in Fig. 1. These scores were submitted to a (T1–T2 lag: 100, 200, 300, 500, 700 ms)  $\times$  2 (Reading Ability: Low-normal, High-normal) repeated-measures analysis of covariance (ANCOVA) with age, nonverbal intelligence, RAN-Letters standardized scores, and RAN-Colours mean response times (averaged across both trials) entered as covariates. Both RAN scores were used as covariates in the analysis because they showed a relatively low correlation (0.32), and thus seemed to tap at least some distinct processes.

Degrees of freedom were adjusted using the Huynh–Feldt procedure. The analysis revealed no significant main effect of Lag,  $F(2.83, 172.47) = 0.67, p = .57, \eta^2 = .011$ , but a marginally significant main effect of Reading Ability,  $F(1, 61) = 3.87, p < .06, \eta^2 = .060$ ,



**Fig. 1.** Mean T1 accuracy as a function of inter-target lag, reading ability, and phonological ability. Error bars represent one standard error of the mean averaged across all data points for a particular level of reading ability.



**Fig. 2.** Mean T2 accuracy (given T1 correct) as a function of inter-target lag, reading ability, and phonological ability. Error bars represent one standard error of the mean averaged across all data points for a particular level of reading ability.

indicating T1 performance was somewhat poorer in the low-normal group. The interaction between Lag and Reading Ability also failed to reach significance,  $F(2.83, 172.47) = 2.12$ ,  $p = .10$ ,  $\eta^2 = .034$ .

Mean T2 accuracy scores were calculated exclusively using trials on which T1 had been identified correctly. The reasoning behind this is that if T1 is recalled incorrectly, the effect of T1 processing on T2 processing is unknown and cannot be estimated. Mean T2 accuracy scores (shown in Fig. 2) were submitted to a 5 (T1–T2 lag)  $\times$  2 (Reading Ability) ANCOVA identical to that used for T1 accuracy. Degrees of freedom were adjusted using the Huynh–Feldt procedure. The analysis revealed a non-significant main effect of Lag,  $F(2.76, 168.55) = 2.14$ ,  $p = .102$ ,  $\eta^2 = .034$ , but within-subjects contrasts showed a significant quadratic component,  $F(1, 61) = 4.65$ ,  $p < .04$ ,  $\eta^2 = .071$  to the variation in T2 accuracy across Lag. This analysis confirms that T2 accuracy improved significantly over lags—the empirical signature of the AB deficit. There was also a main effect of Reading Ability,  $F(1, 61) = 6.34$ ,  $p < .02$ ,  $\eta^2 = .094$ , indicating that overall T2 accuracy was poorer in the low-normal reading group. Finally, there was a significant interaction between Lag and Reading Ability,  $F(2.76, 168.55) = 3.64$ ,  $p < .02$ ,  $\eta^2 = .056$ , indicating that the magnitude of the AB was significantly larger in low-normal readers than high-normal readers.

Analysis of T2 accuracy scores clearly indicates that low-normal readers show a larger AB than high-normal readers. This result mirrors differences found between dyslexics and normal readers and suggests that performance on the AB task indexes variability in reading within the normal range. That said, examination of Fig. 2 indicates at least one difference between earlier studies involving dyslexia and our results. In this experiment, low-normal readers perform similarly to high-normal readers on T2 past Lag 5, whereas readers with dyslexia never reach the performance level of normal readers (e.g., Hari et al., 1999; Visser et al., 2004). Put differently, the AB appears to differ in depth between groups of low-normal and high-normal readers, whereas it differs in duration between impaired and normal readers.

To confirm this impression, we conducted separate univariate analyses of variance with reading ability as the independent variable and AB depth and AB duration as the dependent measures. We estimated AB depth as the lowest accuracy of T2 at one of the five lags while AB duration was estimated as the lag at which T2 accuracy met or exceeded T1. As in the ANCOVAs reported above, we used age, nonverbal intelligence, RAN–Letters standard scores, and RAN–Colours mean response times as covariates. As expected, the analysis of AB depth revealed a significant main effect of Reading Ability,  $F(1, 61) = 4.96$ ,  $p = .03$ ,  $\eta^2 = .075$ . In contrast, no significant main effect of Reading Ability was found in the analysis of AB duration ( $p > .85$ ). We interpret this difference in more detail in Section 4.

#### 4. General discussion

When two targets were presented in an RSVP stream, participants displayed differences in the magnitude of the AB deficit depending on their level of reading skill. Specifically, low-normal readers showed larger ABs compared to high-normal readers. These findings are unlikely to be due to difficulties in identifying targets amongst RSVP distractors or interference from distractors because, despite differences in reading skill, participants did not vary significantly on T1 accuracy. Specific deficits in linguistic processing are also an improbable explanation for our findings because our stimuli consisted of shapes, keyboard symbols and random-dot patches. Rather, our findings suggest readers varied in their ability to allocate visual attention over time to sequential objects.

Our findings are consistent with previous studies that found variations in the magnitude of the AB deficit between normal readers and those with dyslexia (Buchholz & Davies, 2007; Hari et al., 1999; Lum et al., 2007; Visser et al., 2004). Importantly, however, while these studies showed differences in the AB between normal and impaired readers, our study revealed differences within the

range of normal reading. This extends previous results and suggests that the ability to allocate visual attention to sequential objects may play a role in reading efficiency even when a normal level of reading has been achieved.

One interesting aspect of our findings that differs from work with impaired readers concerns the temporal characteristics of the AB deficit. It has commonly been found that impaired readers produce a longer AB than normal readers. In contrast, we found that AB duration was largely equivalent between low-normal and high-normal readers. However, low-normal readers showed a significantly deeper AB. This pattern of results is also evident in a recent study by McLean, Stuart, Visser, and Castles (in press) who looked at children aged 8–10 who are just developing reading proficiency. As in the present work, AB depth uniquely predicted proficiency on three different reading measures, while AB duration was unrelated to proficiency.

Couched in the terms of previous studies, similarities in AB duration imply that all normal readers share a similar “attentional dwell time” (Duncan, Ward, & Shapiro, 1994), while differences in AB depth imply that low-normal readers commit more resources to T1 processing during this dwell time. According to conventional two-stage models of the AB (e.g., Chun & Potter, 1995; Jolicoeur, 1998), T1 processing can vary both in terms of the duration that resources may be occupied with T1 and the extent that those resources are occupied with target processing. An increase in processing duration makes it more likely that T2 will arrive while T1 is still being processed, with consequent negative effects for T2. Alternatively, an increase in the extent of resources committed to T1 will leave fewer resources available for T2, with similar negative consequences. The present findings suggest that poorer T2 performance in low-normal readers is more likely to be due to the later explanation than the former.

One other issue that is directly addressed by the present study is the relationship between performances on RAN tasks, the AB deficit, and reading proficiency. As noted earlier, a number of studies have found a strong correlation between RAN performance and reading ability amongst those with dyslexia (e.g., Kail & Hall, 1994), and that RAN performance predicts later reading ability in children (Wolf, Bally, & Morris, 1986). There is also evidence that RAN performance may be related to visual attention (Neuhaus, Foorman, Francis, & Carlson, 2001). Thus, to the extent that both RAN performance and the AB deficit are related to visual attention and reading, it might be suggested that both tasks tap entirely common processes.

The present work, however, countermands this suggestion. Our findings indicate that while RAN performance and the AB deficit may reflect some common processes related to reading (see also McLean et al., in press), they also measure unique aspects of reading ability. This conclusion follows from the fact that the differences in AB magnitude between low and high-normal readers persisted even when performance on both RAN-Letters and RAN-Colours were entered as covariates in our analyses. Interestingly, we also found relatively low correlations in our sample between performances on the RAN measures we employed. This suggests that even within RAN tasks, there may be significant differences in the types of processing mechanisms that are employed. In our study, these differences may be specifically related to the requirement to process letters in the RAN-Letters task but not in the RAN-Colours task.

On a final note, now that the relationship between the AB and reading ability seems well established across both impaired and normal populations, it is important to begin to determine just what mechanisms that are reflected in AB performance are critical in determining reading ability. While there is general agreement that the AB reflects the function of limited-capacity mechanisms in visual processing, multiple mechanisms have been implicated

including task switching (Visser, Bischof, & Di Lollo, 1999), visual masking (Giesbrecht & Di Lollo, 1998; Seiffert & Di Lollo, 1997), distractor processing (Folk, Leber, & Egeth, 2002; Visser et al., 2004), perceptual load (Giesbrecht, Sy, & Elliott, 2007), working memory updating (Vogel et al., 1998), response planning (Jolicoeur, 1998), “temporary loss of control” over a visual input filter (Di Lollo, Kawahara, Ghorashi, & Enns, 2005), and excessive allocation of resources to the AB task (Olivers & Nieuwenhuis, 2005, 2006). At present it is not known which of these mechanisms may be linked to reading, and whether different mechanisms may be implicated in dyslexia versus normal readers (although the current findings imply that there may be differences between these groups). We are currently pursuing parametric studies aimed at investigating these options more carefully, and hope that this work will provide additional and important insights into reading that will help both abnormal and normal readers become more proficient at this important skill.

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