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The Attentional Blink in Developing Readers

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The attentional blink refers to a reduction in accuracy that occurs when identifying the second of two targets presented within approximately 500 msec of each other. This research explored individual differences in the attentional blink in a sample of 86 children (aged 8–10) with normally developing reading skills. The attentional blink was examined in relation to general reading performance as well as specific orthographic and phonological reading subprocesses. No associations were evident between attentional blink duration and reading ability. However significant correlations did exist between each of the three reading measures and mean second target correct given first target correct (T2|T1) performance across all lags, with less skilled readers exhibiting inferior performance regardless of the temporal lag between first and second targets. Performance on a rapid naming task mediated some of the relationship between mean T2|T1 performance and reading, yet the association remained significant when this factor was accounted for.

The majority of young children manage to master the complex skill of reading with relative ease, yet some children struggle and suffer what is broadly termed developmental dyslexia. The *Diagnostic and Statistical Manual of Mental Disorders*

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(4th ed. [*DSM–IV*]; American Psychiatric Association, 1994) describes developmental dyslexia under the umbrella term *reading disorder*, categorized as reading achievement below that expected given the person's chronological age, measured intelligence, and age-appropriate education. The prevalence of developmental dyslexia has been estimated at 4 to 10%, making it one of the most common learning disorders in children and the subject of much research.

Numerous studies have shown a relationship between developmental dyslexia and impairments in phonological-processing skills, a broad range of abilities associated with spoken language. This includes deficits in phonological awareness—the ability to perceive and manipulate the sounds of spoken language (Byrne, 1998; Snowling, 1998; though see Castles & Coltheart, 2004) and difficulties in phonological short-term memory (Griffiths & Snowling, 2002). The presentation of reading difficulties associated with these impairments appears to predominantly involve deficits using phonological reading skills, involving the conversion of letters into sounds: Such children are typically particularly poor at reading nonwords (Rack, Snowling, & Olson, 1992).

However, the *phonological deficit hypothesis* cannot explain all of the varied patterns of impairment evident in developmental dyslexia (Valdois, Bosse, & Tainturier, 2004). In particular, some children with *surface dyslexia* show no phonological language impairments and do not appear to display the associated difficulties in phonological reading skills. These readers have relatively normal nonword reading yet have significant orthographic reading difficulties, as evidenced by poor irregular word reading (words that do not follow the normal letter-to-sound rules such as *yacht* or *iron*; Castles & Coltheart, 1993, 1996; Hanley & Gard, 1995; Valdois et al., 2003; Valdois et al., 2004). They also make phonologically plausible regularisation errors when they read, such as reading *flood* as *flude* (Castles & Coltheart, 1996; Romani & Stringer, 1994; Romani, Ward, & Olson, 1999). Cases such as these have led some theorists to advocate that a second core nonphonological disorder is necessary to explain the various patterns of impairment displayed in developmental dyslexia (Valdois et al., 2004).

Recent investigations into a possible alternative deficit have focused on visual attention impairments, which have been reported to be present in some cases of developmental dyslexia. Of importance, this work has suggested that visual attention deficits and phonological deficits may be independent predictors of surface and phonological dyslexia respectively, both in individual case studies (Valdois et al., 2003) and in studies comparing dyslexia groups (Bosse, Tainturier, & Valdois, 2007).

Much of this research has focused on *spatial* aspects of visual attention, with some studies reporting individuals with dyslexia exhibit an abnormal asymmetric distribution of visual attention (Facoetti & Molteni, 2001; Facoetti, Paganoni, & Lorusso, 2000) as well as poor performance on serial search tasks (Marendaz, Valdois, & Walch, 1996; Valdois, 1996). However, when considering the cognitive mechanisms central to reading ability, *temporal* aspects of visual attention also seem likely to be related to the reading process (Wolf & Bowers, 1999). When children read fluently, or indeed when they are being read to during guided reading, they must attend to a series of printed words progressing in relatively rapid sequential order. It is important to note that this process requires frequent shifts in temporal attention as well as spatial attention. Indeed a variety of temporal processing deficits have already been linked to dyslexia in visual, auditory, and tactile modalities (see Farmer & Klein, 1995, for a review) and recently the role of temporal aspects of visual attention have also been explored in dyslexia. It is these temporal aspects of visual attention that form the primary focus of this study.

TEMPORAL ASPECTS OF VISUAL ATTENTION: THE ATTENTIONAL BLINK

Temporal aspects of visual attention have most commonly been investigated using the attentional blink paradigm. Here, observers are presented with a rapid-serial visual presentation (RSVP) stream containing two targets embedded in a sequence of nontarget distractors. Although the first target (T1) is detected relatively accurately, second target (T2) accuracy is markedly reduced in proportion to the temporal lag between T1 and T2. As illustrated in Figure 1, second target accuracy is poorest at relatively short lags (approximately 200–300 msec) and

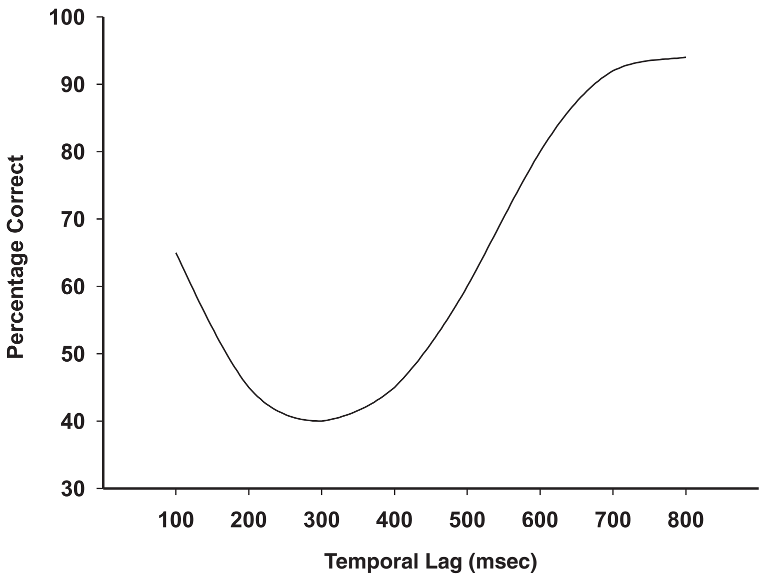

FIGURE 1 Typical pattern of performance on an attentional blink paradigm. *Note.* Line represents typical patterns of correct second target identification given correct first target identification in a dual target RSVP task.

gradually increases to asymptotic levels at longer lags (e.g. Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1994).

Theoretical accounts of the attentional blink share broad similarities, focusing on the limited capacity of temporal attentional processing and the role of two sequential processing stages (Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1995). For example, in the two-stage model of Chun and Potter, an initial rapid detection stage processes the features of incoming stimuli in order to identify potential targets (Stage-1). Although this processing is fast and efficient, stimulus representations at this stage are short-lived and vulnerable to overwriting by subsequent inputs. Thus, a second capacity-limited processing stage (Stage-2) is required for target identification and report. This Stage-2 processing phase requires the rapid access to, and sufficient activation of, an individual's stored cognitive representations of T1 and T2 to allow for the conscious report of the target. If T2 is presented before Stage-2 processing of T1 is completed, insufficient resources are available leaving T2 vulnerable to decay or overwriting (Chun & Potter, 1995). On this account, T2 accuracy improves as the temporal lag between T1 and T2 increases because of the likelihood that T1 processing will be complete by the time T2 is presented. An important corollary of this logic is that the duration of the attentional blink provides an estimate of the *attentional dwell time* for T1, that is, how long attention must be devoted to the first target in order for its representation to be encoded for conscious report.

The relationship between the attentional blink and dyslexia was first examined by Hari, Valta, and Uutela (1999), who compared the attentional blink of a group of adults with dyslexia to a group of normal readers. They found that although both groups exhibited a substantial attentional blink (suggesting both control and dyslexia groups used a similar approach to identify the sequential targets), the magnitude of the attentional blink of the dyslexia group was significantly longer (700 msec) than that of the control group (540 msec). Hari et al. (1999) concluded that the identification of visual stimuli requires adults with dyslexia to deploy their attention for significantly longer than adults with normal reading ability.

A potential problem with the Hari et al. (1999) study is that it utilized letter-stimuli as targets, which may have confounded attentional deficits with lexical processing impairments. To address this concern, Visser, Boden, and Giaschi (2004) modified the design of Hari et al. to use nonlinguistic stimuli (shapes). The results were similar to those of Hari et al., with the attentional blink in the dyslexia group significantly longer than that of age-matched controls (more than 1,400 msec), indicating that attentional blink differences were not indicative of poor readers' inferior processing of linguistic stimuli. Similar findings were also reported in two recent studies by Lum, Conti-Ramsden, and Lindell (2007) exploring the attentional blink in Specific Language Impairment (SLI; a disorder highly comorbid with developmental dyslexia), and Buchholz and Davies (2007) examining individual dyslexic cases. However, results have not been entirely uniform, with a study by Lacroix et al. (2005) finding that a group of adolescents with dyslexia showed a shallower attentional blink than a control sample of normal readers.

There has also been a large degree of variability in the magnitude of the reported deficit, ranging from 600 to 800 msec to more than 1,400 msec. This variability, although possibly because of differences in task complexity, may also be because of variations in the nature of the reading impairments represented in the different samples. As outlined previously, different subprocesses are involved in reading, and these are differentially impaired in individuals with dyslexia; however, these different components of reading skill have not been distinguished in previous research. Each of the studies previously outlined has been conducted with heterogenous samples of individuals with dyslexia: Participants were not identified based on having specific phonological or orthographic reading impairment (each of the participants in Buchholz and Davies's, 2007, study exhibited significant phonological deficits). Thus, a more detailed analysis of the relationship between the attentional blink and impairments in different reading subprocesses is required to advance our understanding of how attentional blink deficits influence reading performance.

A further question concerns whether the attentional blink deficits reported in dyslexia are evident only in severe reading impairment or whether attentional blink differences associated with reading ability are also found in unimpaired readers. That is, do individual attentional blink differences also predict significant variance in reading ability within a sample of children with normally developing reading skills? If attentional blink deficits are only evident in dyslexia, this would suggest that there is a discontinuous relationship between reading achievement and visual temporal attention, with attentional blink deficits only being apparent in children who fall below some threshold level of reading achievement. In contrast, if attentional blink and reading achievement are also found to be associated in normally developing readers, this would suggest a continuous relationship between the two variables, with visual temporal attention abilities influencing reading performance across the full range of achievement levels. The answer to this question will inform theories as to the mechanism by which visual temporal attention might affect the process of reading acquisition.

Also relevant to the question of the mechanism by which visual temporal attention might affect reading acquisition is the possible mediating role played by another factor known to be relevant to reading acquisition—naming speed.

THE ATTENTIONAL BLINK AND NAMING SPEED

Naming speed is most commonly assessed via rapid automatized naming (RAN) tasks. These tasks, originally developed by Denckla and Rudel (1976), require observers to name a series of stimuli (i.e., letters, numbers, colors, or shapes) as quickly as possible, with the time it takes them to do so being recorded. Numerous studies suggest that RAN performance is impaired in dyslexia (Ho, Chan, Tsang,

& Lee, 2002; Wimmer, Mayringer, & Landerl, 2000; Wolf & Bowers, 1999) and that it is a significant predictor of reading in samples of individuals with unimpaired reading skills (Neuhaus, Foorman, Francis, & Carlson, 2001; Wile & Borowsky, 2004; Wolf & Bowers, 1999).

As Visser et al. (2004) noted, there would appear to be significant overlap in the cognitive and attentional processes involved in RAN and those involved in attentional blink tasks. Both involve the rapid access to, processing of, and report of stored representations. On this basis, Visser et al. (2004, p. 2521) speculated that the attentional blink may be accounting for a "small slice" of those processes central to RAN and that RAN performance may play a mediating role in associations between the attentional blink and reading. Although recent research has failed to identify correlations between RAN and the attentional blink, significant correlations have been reported between RAN and single-target as well as T1 identification (Arnell, Howe, Joanisse, & Klein, 2006), however these associations have yet to be explored in relation to reading subprocesses.

Furthermore, evidence indicates that although RAN performance correlates significantly with both irregular and nonword reading skills, the correlations are significantly higher with irregular word reading (Wile & Borowskey, 2004; Wolf & Bowers, 1999). It follows from this that, if RAN performance does tap similar processes to those involved in the attentional blink, there may be a stronger association between the attentional blink and orthographic reading skills (as measured by irregular word reading) than between the blink and phonological reading skills (as measured by nonword reading).

AIMS OF THE CURRENT RESEARCH

In summary, although there is some reported evidence for impairment in temporal visual attentional processes in dyslexia, many questions remain about the exact nature of this impairment and how it might affect reading. The present work aimed to address these issues in three ways. First, we examined the relationship between the attentional blink and reading performance in a sample of normally developing readers. Past research in this field has investigated only the attentional blink in dyslexia and it remains unclear whether the association extends to normal variation in reading achievement in children learning to read. Second, we explored the association between the attentional blink and both orthographic and phonological reading processes. Previous studies investigating the attentional blink have only examined general reading impairment, without investigating the possibility of a more exclusive relationship between the attentional blink and specific reading subprocesses. Finally, we examined the possible mediating effects of RAN on the relationship between attentional blink and reading ability. No research to date has explored associations between the attentional blink and RAN in relation to reading but, given the apparent similarities in the temporal attentional demands of the two tasks, it is plausible that any relationship evident between the attentional blink and reading, particularly orthographic reading processes, may be mediated by RAN.

In addressing these aims, the current study implemented a nonlinguistic attentional blink paradigm similar to that of Visser et al. (2004) in a sample of children with normal reading ability. Children between ages 8 and 10 were selected because they are in the process of learning to read but are not yet proficient, and as such there is commonly large variability in performance across participants of this age. Reading ability was assessed using measures of general single-word reading ability but also specific assessments of reading subprocesses (irregular and nonword reading). Children's RAN performance was also assessed to determine whether any associations existed between rapid naming ability and the attentional blink, and whether attentional blink performance accounted for any unique variance in reading ability, independent of RAN.

METHOD

Participants

Participants comprised of 86 Grade 3 and 4 children (45 male, 41 female) between ages 8 and 10 years (average age = 8.99 years). Children were drawn from three schools located in Melbourne, Victoria, Australia.

Materials

Reading measures. Reading materials consisted of three measures; the Word Identification subtest of the Woodcock Reading Mastery Test–Revised (Woodcock, 1987), and a modified form of the Castles and Coltheart (1993) Word/Nonword Test including both irregular and nonword items.

The Woodcock Word Identification subtest was included as a measure of children's general single-word reading ability. The test requires children to read aloud a series of words ordered by difficulty with ceiling reached after six consecutive errors.

The Word/Nonword Test attempts to isolate specific orthographic and phonological reading skills by assessing children on their reading aloud of a set of 40 irregular and 40 nonwords. Irregular words (e.g., *blood*) cannot be read correctly via phonological decoding skills and so provide a measure of orthographic reading skill, while nonwords (e.g., *gop*) cannot be recognized via whole word orthographic skills and must be read via phonological decoding. The items were printed individually on 10 cm × 14 cm index cards, in lowercase 24-point Arial font. All 80 items were presented one at a time, in mixed order and the children were asked to attempt to read each item aloud. They were advised that some of the words would be familiar everyday words, but others would be nonsense or made-up words. Mixed presentation of the words and nonwords was used to ensure that children could not use a guessing strategy such as could be used if they knew that a presented item would always be a word.

Nonverbal IQ. The Raven's Coloured Progressive Matrices (Raven, 1956) task was used to assess nonverbal reasoning ability. The group form of Raven's Matrices was implemented to minimise the total time required for participant testing.

Rapid naming. The majority of previous studies exploring rapid naming in reading development have included letter or digit stimuli based RAN tasks (see Denkla & Cutting, 1999, for a review); however in the current study a color-based RAN task was implemented to determine whether basic rapid naming ability, independent of differences in alphanumeric ability, accounted for any variance in performance on a similarly nonlinguistic stimuli based attentional blink task. The RAN task consisted of 36 colored circles (red, black green, yellow, blue, or white) appearing in a grid sorted randomly in six rows of 6, presented on the same monitor used in the attentional blink task. Participants were instructed to try and correctly name aloud all the colors in the grid as rapidly as they could without making any mistakes. The experimenter carefully observed the participants' responses to ensure they were correctly identifying the colored circles. The total time participants took to name all 36 items was recorded in milliseconds. The task was completed twice, using two different color grids, with the two grids being presented in a random order across participants.

Attentional blink. The attentional blink task consisted of separate control and experimental conditions, in which either one or two targets were presented amongst an RSVP stream of distractors. Targets consisted of five shapes (square, cross, triangle, diamond, and circle) that measured approximately 1º of visual angle. The surrounding room was kept dimly lit to ensure all stimuli were clearly visible and observers were seated approximately 60 cm from the monitor.

Children were instructed that a series of random-dot patches, keyboard symbols, and shapes would appear on the screen one after the other and that they should try to identify only the shapes as best they could. At the beginning of each experimental trial, participants were asked to focus their gaze on a small fixation point presented at the center of the screen. Once the child's attention was focused on the fixation point, a keystroke by the experimenter initiated the RSVP stream. As illustrated in Figure 2, the RSVP began with a series of five to eight random-dot distractor items, with each item being displayed for 20 msec and separated by an inter-stimulus interval of 80 msec during which the display was blank. Distractors consisted of random-dot patches comprising 200 small dots scattered randomly

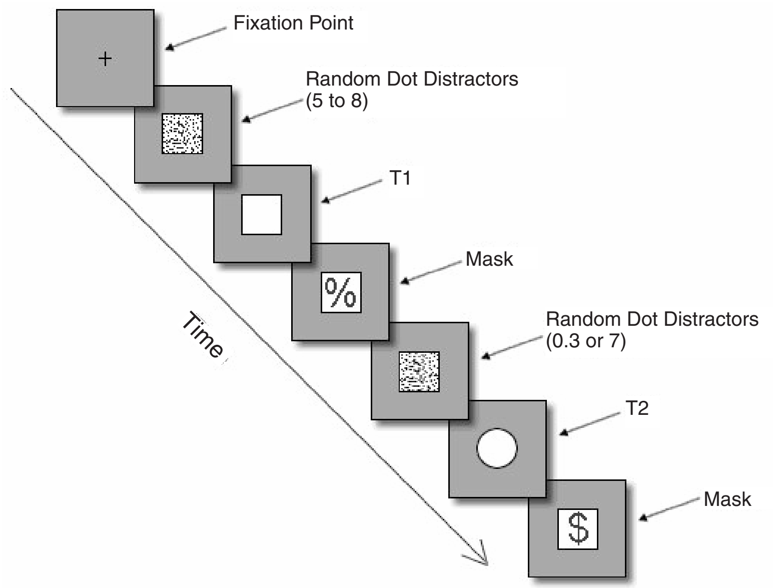

FIGURE 2 Schematic diagram of stimulus presentation sequence. *Note.* Actual stimuli were grey and displayed on a black background. In the single-target condition, the presentation sequence was identical except the first target was replaced with a distractor.

across a notional square of approximately 1° × 1°. All stimuli were displayed on a 17-in. monitor running at a refresh rate of 100 Hz. The first target consisted of a shape chosen randomly without replacement from the available set of five. The second target (T2) was another shape chosen randomly with the proviso that it could not be identical to the first. It followed the first shape after either zero distractors (temporal lag = 100 msec), two distractors (temporal lag = 300 msec) or six distractors (temporal lag = 700 msec). Both T1 and T2 were followed by a mask (selected randomly from the keyboard symbols &, $, or %).

Participants were instructed to identify the two targets by pressing marked keys on a computer keyboard (participants were not required to respond aloud, removing the effect of any verbal difficulties). Participants were told to respond to the two targets in the same order that they were presented, with a greater emphasis placed on correctly identifying the first target; however, as in the original study by Visser et al. (2004), responses given in reverse order were also scored as correct. A small pilot study was conducted to ensure both the stimuli and task difficulty were suitable for young children.

The control condition was identical to the experimental condition, except that a random-dot distractor was presented in place of the T1 shape resulting in a single-target RSVP task. The experimental and control conditions of the attentional

TABLE 1
Summary Statistics

	M	*SD*	*Range*
Age (years)	8.98	4.97	2.08
Raven's Matrices PR	71.74	21.86	91.60
Woodcock Word Identification PR	71.98	27.33	94.90
Irregular Word Reading RS	22.75	4.30	22.00
Nonword Reading RS	28.89	8.25	35.00
Rapid Naming (sec)	31.60	6.36	31.83

Note. PR = percentile rank; RS = raw score.

blink task were run in separate blocks of trials, with the order of the two blocks randomized across participants. In total, the control condition consisted of 45 trials and the experimental condition consisted of 75 trials. Participants were offered a short break in between the experimental and control trials to ensure that they remained actively focused throughout the task.

RESULTS

Summary Statistics

All 86 participants were included in the analysis, however 10 participants were unavailable to complete Raven's Matrices, and these missing values were estimated using a multiple regression technique.[1] Table 1 presents summary statistics of participants' performance across the reading, Raven's Matrices, and RAN measures. Standardized scores were used for both the Word Identification subtest (Woodcock, 1987) and Raven's Matrices; however, only raw scores were available for irregular word and nonword reading. Results revealed a wide range of reading ability, although overall reading and nonverbal reasoning scores were found to be slightly above average compared to published norms (Cotton et al., 2005; Woodcock, 1987). Total time (in milliseconds) to complete the two RAN trials was averaged to gain a single RAN measure for each participant. The RAN task appeared to have a strong internal reliability with highly significant correlations evident between the two RAN trials (r = .939) indicating that children understood the task and performed consistently across trials.

[1]Missing values were estimated using a multiple regression technique including Age, and each of the three reading measures as predictor variables. All significant findings remained when these ten participants were excluded from the analysis.

RSVP Task Performance

Initial analyses were carried out on participants' single-target performance to determine whether participants were capable of identifying targets amongst distractors in a RSVP stream. Children performed extremely well in the single-target condition, with mean performance across all lags 92%. Furthermore, there were no significant differences in single-target performance as a function of the fore-period or lag created by replacing T1 with a distractor, $F(2, 85) = 0.425$, $p > .05$. Figure 3 illustrates the children's performance on T1 as a function of the lag between the two targets and again indicates that the majority of children were capable of identifying individual targets among distractors. At this stage 2 participants were excluded from the analysis as they failed to correctly identify T1 on at least 50% of trials (these participants also exhibited very poor single-target performance). Consistent with the findings of Visser et al. (2004), a significant effect for lag was also evident, $F(2, 85) = 4.104$, $p < .01$, with participants exhibiting poorer T1 performance at earlier lags, particularly at 100 msec.[2]

Figure 4 presents a summary of participants' attentional blink performance. Performance was assessed by calculating the mean percentage of correct T2 identification, given the correct identification of T1 (T2|T1), at each lag (100 msec, 300 msec, and 700 msec). This is the typical methodology used in attentional blink studies (Raymond et al., 1992; Shapiro et al., 1994) and ensures that only trials in which observers had attended to T1 are included. It can be seen from Figure 4 that the children displayed a relatively shallow attentional blink compared to past studies using adult participants (Raymond et al., 1992; Shapiro et al., 1994), although it is interesting to note that previous studies exploring the attentional blink in young children have also recorded similarly shallow blink effects (C. R. Li, Lin, Chang, & Hung, 2004; Visser et al., 2004). Nevertheless, there was a highly significant increase in participants T2|T1 performance across lags, $F(2, 83) = 8.317$, $p < .01$.

Individual indices of attentional blink duration were calculated for use in regression analyses by measuring the gradient of each participant's T2|T1 performance between lags of 300 msec and 700 msec (i.e., performance at 700 msec–performance at 300 msec). A similar procedure was implemented by Arnell et al. (2006) and is designed to estimate the rate at which each participant recovered

[2]Main effects for lag in relation to T1 performance have typically been attributed to similar mechanisms to those behind lag-1 sparing (Visser et al., 2004). This is a phenomenon where T2 accuracy is relatively spared when occurring directly after T1 as attention can be allocated to both targets together (Potter, Chun, Banks, & Muckenhoupt, 1998; Visser, Bischof, & Di Lollo, 1999). As targets in the current paradigm were followed by a mask it is less likely that both targets could be processed together, yet competition between two targets presented within such close temporal proximity may still have consequences for both T1 and T2 identification. This notion is partially supported in that participants averaged a greater number of temporal order judgment errors at lags of 100 msec (2.011) compared to lags of 300 msec (0.674), $t(84) = 6.321$, $p < .01$, or 700 msec (0.337), $t(84) = 8.337$, $p < .01$.

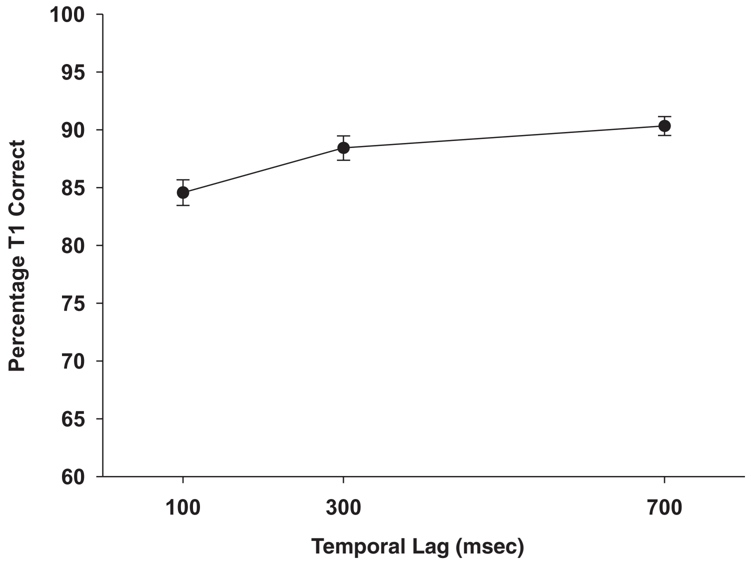

FIGURE 3 T1 performance. *Note.* Mean accuracy of T1 identification as a function of the temporal lag between T1 and T2. Error bars represent one standard error.

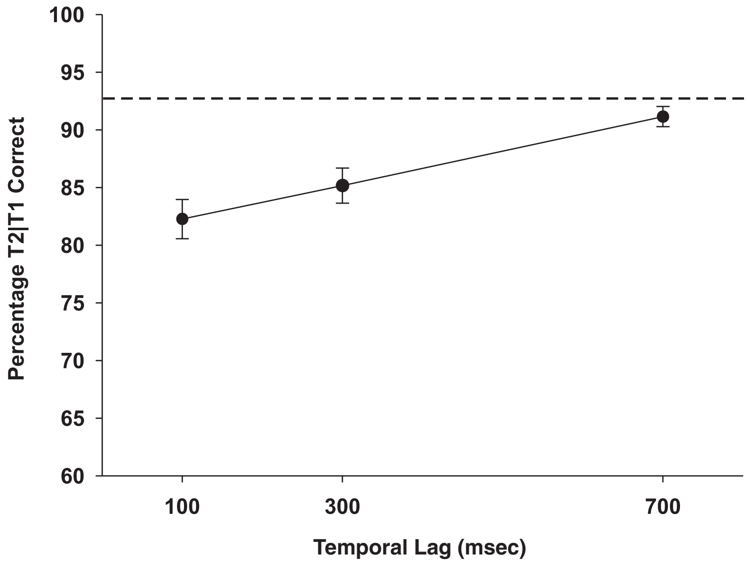

FIGURE 4 Attentional blink performance. *Note.* Unbroken line indicates mean T2|T1 percentage correct as a function of the temporal lag between T1 and T2. Broken line indicates mean percentage correct in the single target condition. Error bars represent one standard error.

from their attentional blink phase. However it is important to note that individual differences in overall T2|T1 performance are likely to have a significant influence on gradient estimates of attentional blink duration. Participants with poorer T2|T1 performance during their attentional blink phase will have significantly more percentage points to gain when recovering from their attentional blink than those who have performed better across all lags. To control for this, the analyses also included a measure of general dual-target RSVP performance, calculated as the mean T2|T1 percentage across each of the three lags. The use of these two measures together provides an accurate estimate of attentional blink duration suitable for inclusion in regression analyses.

Initial exploration of the data was carried out using Pearson product moment correlations and a summary of these correlations is provided in Table 2. As would be expected, there were highly significant intercorrelations amongst each of the three reading measures as well as between the reading measures and Raven's Matrices (nonverbal reasoning ability). Correlations between RAN and reading ability were also evident, although the correlation with nonword reading ability narrowly failed to reach significance. These correlations are negative as RAN scores were measures of time (msec), where shorter time indicates superior performance. A notable finding is that although mean T2|T1 performance correlated significantly with each of the three reading measures, as well as RAN, the correlations between attentional blink duration and these variables failed to reach significance.

Multiple Regression Analyses

Predicting reading performance from the attentional blink. A series of multiple regression analyses was undertaken to determine the relationship between attentional blink performance and reading ability. Multiple regression analyses were carried out using each of the three reading measures as dependent variables, with Raven's Matrices, Single-Target Performance, and Age included as predictor variables in addition to attentional blink duration, and mean T2|T1 performance. All analyses were completed using a robust weighted regression analysis procedure[3] (Stata Corporation, 2003) to ensure any outliers or extreme scores

[3]Robust regression begins by fitting the regression, before calculating Cook's Distance (*D*) and removing cases where *D* is greater than 1. Robust regression then works iteratively, performing a regression and generating a series of weights based on absolute residuals and then regressing again, applying these weights (Stata Corporation, 2003). This process is repeated until a stable solution is obtained where the maximum change in weights drops below tolerance. These weights are derived from both Huber weights (Huber, 1964) and biweights (Beaton & Tukey, 1964), allowing for the initial Huber weighting to improve the biweight estimator. The weights created for each participant are then incorporated into a least squares multiple regression analysis to test semipartial correlations. As advocated by G. Li (1985), by using a weighted regression analysis, the effects of extreme cases are controlled so that these cases do not have a disproportionate effect on the regression function.

TABLE 2
Summary Pearson Correlations

	Age	*Raven's Matrices*	*Woodcock Word Identification*	*Irregular Word Reading*	*Nonword Reading*	*Rapid Naming*	*Single-Target Accuracy*	*T1 Accuracy*	*Mean T2|T1 Accuracy*	*AB Duration*
Age (years)	—									
Raven's Matrices PR	–.099	—								
Woodcock Word Identification PR	–.168	.445**	—							
Irregular Word Reading RS	.135	.270*	.747**	—						
Nonword Reading RS	.067	.372**	.837**	.699**	—					
Rapid Naming (sec)	.003	–.207	–.288**	–.259*	–.201	—				
Single-Target Accuracy	.127	.155	.193	.351**	.205	–.147	—			
T1 Accuracy	.014	.255*	.174	.272*	.231*	–.246*	.347**	—		
Mean T2|T1 Accuracy	–.053	.411**	.429**	.417**	.431**	–.353**	.315**	.562**	—	
AB Duration	.019	.074	.013	.075	–.014	.154	–.106	–.087	–.055	—

Note. PR = percentile rank; RS = raw score; T1 = first target; T2|T1 = T2 correct given T1 correct; AB = attentional blink.
$^{*}p < .05$. $^{**}p < .01$.

did not disproportionably influence the regression equation (G. Li, 1985). Table 3 illustrates the results of three analyses predicting Woodcock Word Identification, nonword reading accuracy, and irregular word reading accuracy. The overall models for each of the analyses were significant, Woodcock Word Identification, $F(5, 78) = 7.246$, $p < .01$, adjusted $R^2 = .273$; nonword reading, $F(5, 78) = 8.728$, $p < .01$, adjusted $R^2 = .318$; and irregular word reading, $F(5, 78) = 7.041$, $p < .01$, adjusted $R^2 = .267$; however, a large proportion of reading variance in each of these analyses was explained by nonverbal reasoning ability (Raven's Matrices). Of more theoretical relevance, although mean T2|T1 performance contributed significantly to the proportion of variance explained in all three reading measures ($p < .05$), attentional blink duration failed to account for significant variance in any of the three reading measures. Furthermore, a Williams' *t* test, a robust test of significant differences between nonindependent correlations (Steiger, 1980; Williams, 1959), also determined that the semipartial correlations between mean T2|T1 performance and reading ability were not significantly stronger for either irregular or nonword reading, $t(81) = 0.587$, $p > .05$.

One possibility is that the lack of association between attentional blink gradient scores and reading ability was due to the use of difference scores (between lags of 300 msec and 700 msec) to estimate attentional blink duration. This approach is equivalent to the use of repeated measures analysis of variance (ANOVA) where one factor (reading ability) is continuous rather than categorical. However, if component scores are unreliable, a difference score can have disproportionate unreliability because of the combination of error across two measures, and there can be regression to the mean effects (Gottman & Rushe, 1993; Harris, 1963). An alternative approach is to partial out, at a group level, the common variance between two measures and use the adjusted score on the second measure as a predictor. Addi-

TABLE 3
Robust Multiple Regression Analyses: Attentional Blink Duration and Mean T2|T1 Accuracy Predicting Reading Ability Including Age, Raven's Matrices, and Single-Target Accuracy as Covariates

	Woodcock Word Identification		*Nonword Reading*		*Irregular Word Reading*	
	p	*Semipartial Correlation*	*p*	*Semipartial Correlation*	*p*	*Semipartial Correlation*
Age	.604	–.049	.030	.201	.045	.191
Raven's Matrices	.002	.294	.001	.358	.051	.187
AB Single-Target	.329	.092	.403	.076	.023	.218
AB Duration	.732	.032	.943	.006	.186	.125
Mean T2|T1	.017	.228	.014	.227	.017	.230

Note. T2|T1 = second target correct given first target correct; AB = attentional blink.

tional hierarchical regression analyses were therefore also carried out using this approach. If attentional blink duration is indeed a reliable predictor of reading ability, then links between T2|T1 performance at lags of 700 msec should remain significant after controlling for T2|T1 performance at lags of 300 msec.

Three additional hierarchical regression analyses were conducted using the three reading measures as dependent variables and examining the variance predicted by performance at lags of 700 msec after controlling for the variance accounted for by performance at lags of 300 msec as well as additional covariates of Age, Raven's Matrices, and Single-Target Performance. Consistent with the original analyses, Table 4 indicates that, after controlling for performance at lags of 300 msec as well as additional covariates, T2|T1 performance at lags of 700 msec did not account for significant variance in any of the three reading measures.

The findings of the regression analyses can be further illustrated by a median split of skilled and less skilled readers' T2|T1 performance (see Figure 5). Given that no significant differences were evident in associations between attentional blink performance and orthographic or phonological reading ability, skilled and less skilled readers were selected based on a median split of Word Identification performance. A 2 (group: skilled vs. less skilled readers) x 3 (lag: 100 msec, 300 msec, and 700 msec) mixed design ANOVA including group as a between-subjects factor revealed a significant main effect for lag, $F(2, 82) = 8.883$, $p < .01$, and a significant main effect for group, $F(2, 82) = 12.152$, $p < .01$, yet no significant Group × Lag interaction effect, $F(2, 82) = 0.226$, $p > .05$. These findings support those of the aforementioned regression analyses indicating that less skilled readers exhibit inferior T2|T1 performance compared to skilled readers across each of the three lags yet do not show differences in attentional blink duration.

TABLE 4
Hierarchical Regression Analyses: Reading Ability Predicted by Age, Raven's Matrices, Single-Target Accuracy, T2|T1 Accuracy at Lags of 300ms and T2|T1 Accuracy at Lags of 700 msec

	Woodcock Word Identification		*Nonword Reading*		*Irregular Word Reading*	
Block	*p*	*Semipartial Correlation*	*p*	*Semipartial Correlation*	*p*	Semipartial Correlation
1 Age	.436	–.076	.139	.147	.128	.148
2 Raven's Matrices	.006	.272	.008	.266	.057	.199
3 AB Single-Target	.372	.087	.545	.060	.022	.224
4 T2|T1 at 300 msec	.268	.108	.130	.150	.231	.101
5 T2|T1 at 700 msec	.151	.141	.186	.131	.168	.132

Note. T2|T1 = second target correct given first target correct; AB = attentional blink.

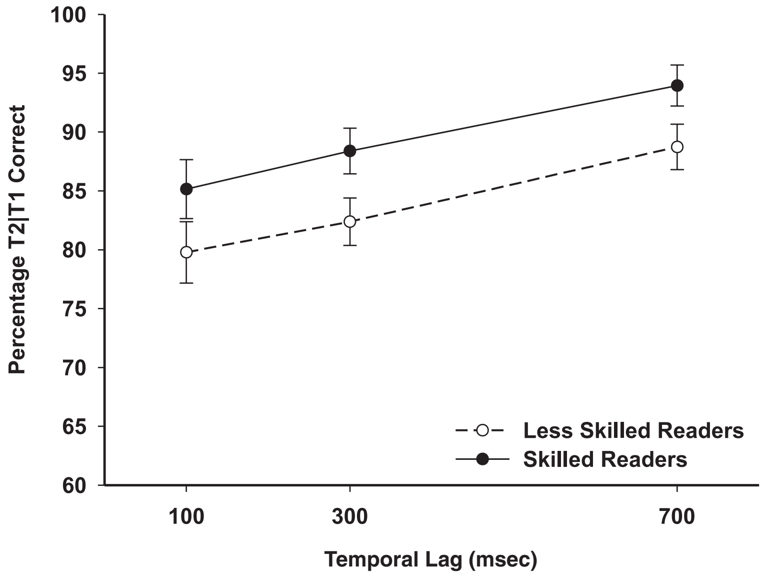

FIGURE 5 Skilled and less skilled readers attentional blink performance. Note. Unbroken line indicates mean T2|T1 percentage correct as a function of temporal lag between T1 and T2 for skilled readers. Broken line indicates mean T2|T1 percentage correct as a function of temporal lag between T1 and T2 for less skilled readers. Error bars represent one standard error.

Predicting reading performance from RAN. Further regression analyses were carried out to confirm the relationship between reading ability and performance on the RAN task. Three weighted multiple regression analyses were carried out for each of the reading measures, entering Raven's Matrices and Age as well as RAN as predictor variables. The results of these three analyses are presented in Table 5 and indicate relatively strong evidence of negative correlations between RAN scores and reading ability. Significant negative correlations were found between RAN and Woodcock Word Identification scores ($t = 2.334$, $p = .022$) as well as irregular word reading ($t = 2.340$, $p = .022$). However, RAN performance did not account for significant variance in nonword reading ability ($t = 1.450$, $p = .151$), suggesting RAN may not be as strong a predictor of phonological reading skills, although a Williams' t test did not reveal a significant difference between irregular and nonword reading correlations with RAN, $t(81) = 1.014$, $p > .05$.

Rapid Naming and the Attentional Blink

Of particular interest in this study was the relationship between attentional blink duration and RAN and whether these variables accounted for unique variance in

TABLE 5
Robust Multiple Regression Analyses: Rapid Automatized Naming Scores Predicting Reading Performance, Including Age, and Raven's Matrices as Covariates

	Woodcock Word Identification		*Nonword Reading*		*Irregular Word Reading*	
	p	*Semipartial Correlation*	*p*	*Semipartial Correlation*	*p*	*Semipartial Correlation*
Age	.760	–.034	.049	.218	.010	.283
Raven's Matrices	.001	.397	.001	.443	.001	.334
Rapid Naming	.018	–.260	.151	–.160	.029	–.241

reading ability. Initial Pearson correlations presented in Table 2 revealed no significant associations between RAN and attentional blink duration, yet significant correlations were evident between RAN and mean T2|T1 performance. Furthermore additional semipartial correlations indicated that the association between RAN and mean T2|T1 performance remained significant after controlling for Single-Target Performance, Age, and Raven's Matrices ($r = –.279$, $p = .012$). To determine whether RAN performance mediated the relationship between mean T2|T1 performance and reading, further semipartial correlations were examined between mean T2|T1 performance and the three measures of reading ability, controlling for RAN. Although reduced in magnitude, associations between mean T2|T1 performance and Word Identification ($r = .233$, $p = .037$), nonword reading ($r = .281$, $p = .012$), and irregular word reading ($r = .247$, $p = .027$) remained significant even when controlling for RAN performance as well as additional covariates of Age, Raven's Matrices, and Single-Target Performance.

DISCUSSION

The primary finding of this study was that there was no relationship between attentional blink duration and reading ability in normally developing readers. There was, however, an association between reading ability and mean T2|T1 performance across each of the three lags, yet correlations did not differ in strength between irregular and nonword reading measures. No association was evident between rapid naming and attentional blink duration, yet significant correlations were evident between RAN and mean T2|T1 performance across all lags. This association between RAN and mean T2|T1 performance did appear to play a minor mediating role in links between mean T2|T1 performance and reading ability; however, correlations remained significant when the effects of this factor were controlled for. We now consider these findings further in relation to each of our aims.

The Attentional Blink in Normally Developing Readers

The first aim of this study was to determine whether the link between the magnitude of the attentional blink and dyslexia reported in previous studies (Buchholz & Davies, 2007; Hari et al., 1999; Lum et al., 2007; Visser et al., 2004) was also evident in a sample of children with normally developing reading skills. In relation to our primary measure of blink magnitude—attentional blink duration—this does not appear to be the case, with no significant association evident between attentional blink duration and reading performance. This finding supports the notion of a discontinuous relationship between reading ability and attentional dwell time, suggesting that a prolonged attentional blink may only be evident in individuals with severe reading impairments and that variation in attentional dwell time does not play a major role in normal reading acquisition. It is important to note, however, that the attentional blink effect evident in the current study, although significant, was relatively weak, and this may have constrained the sensitivity to detect relationships between attentional blink duration and reading ability.

Given that a link between attentional blink duration and reading performance appears to be evident only within impaired reader samples, further work is required to explore the nature of the relationship within this specific population. The magnitude of attentional blink impairments reported in previous studies exploring dyslexia has varied greatly, ranging from only mild impairments between 600 and 800 msec (Buchholz & Davies, 2007; Hari et al., 1999) to very significant impairments above 1,400 msec (Visser et al., 2004). The source of this variation, and what implications, if any, it has for reading acquisition, is not known. As noted earlier, the variability may be associated with heterogeneity within the dyslexia samples; it may also be tied to the magnitude of reading impairments in these samples. Of particular relevancy to this issue, a recent study by La Rocque and Visser (2008) explored the attentional blink in a sample of adults with normal reading skills and reported that less skilled readers exhibited inferior T2|T1 performance only during the attentional blink phase. That is, less skilled readers exhibited a deeper attentional blink, despite similar performance levels at later lags. Such findings in adults with normal reading skills suggest some aspects of attentional blink performance may possibly be functionally related to the reading impairment in adult readers and future research would profitably focus on these issues.

Of further interest, the findings of the present study did indicate a significant association between reading measures and mean T2|T1 performance across all temporal lags, further suggesting there may be some aspects of attentional blink task performance that do relate to reading ability in a continuous manner. Variations in attentional blink task performance across all lags have been attributed to a number of different factors, including short-term memory, general intelligence, and vigilance (Akyürek & Hommel, 2006; Akyürek, Hommel, & Jolicœur, 2007; Colzato, Spapè, Pannebakker, & Hommel, 2007). Considering this, the correlations between mean T2|T1 performance and reading ability are perhaps not completely unexpected given that each of these factors have also been linked to reading ability (see Bowey, 2005, for a review). Indeed, in the current findings there tended to be associations between reading ability and more general RSVP performance measures such as single-target and T1 performance (see Table 2). That associations between general RSVP performance and reading ability are mediated by individual differences in general factors such as short-term memory, general intelligence, and vigilance is further supported by the finding of a significant correlation between nonverbal IQ (Raven's Matrices) and mean T2|T1 performance across all lags. However, although of interest, variations in dual-target RSVP performance across all lags cannot be attributed specifically to variations in attentional dwell time.

The Attentional Blink and Reading Subprocesses

This study also aimed to investigate the association between the attentional blink and different reading subprocesses, specifically orthographic and phonological skills. We did not find evidence for any specific associations: Attentional blink duration did not account for significant variance in either irregular or nonword reading performance and, although mean T2|T1 performance did account for significant variance in both irregular and nonword reading, neither of these correlations was significantly stronger than the other. These findings only apply to developing readers and there may be differences in adult readers' reliance on lexical and sublexical reading skills and consequently a different pattern of results. However, given that mean T2|T1 performance across lags is likely to index a range of general cognitive factors, it is perhaps not surprising that variation on this measure was equally strongly associated with measures of both reading subprocesses. Furthermore, the lack of association between attentional blink duration and performance on any reading measure means that the results of the present study cannot shed light on whether attentional blink impairments in dyslexia are associated with deficits in particular aspects of reading. As previously noted, resolving this issue will require further studies focused on examining the attentional blink in children with specific kinds of reading impairment such as surface or phonological dyslexia.

Rapid Automatized Naming and the Attentional Blink

The final aim of this study was to evaluate whether performance on the RAN task mediated any relationship found between the attentional blink and reading. As in previous studies (Neuhaus et al., 2001; Wolf & Bowers, 1999), we demonstrated an association between RAN and general reading ability, particularly irregular word reading. Of more theoretical relevance, no significant associations were found between RAN and attentional blink duration, yet correlations were evident between RAN and mean T2|T1 performance across all lags. This finding is consistent with previous research reporting significant correlations between RAN and general RSVP performance (single-target, T1 and T2 performance), yet no relationship between RAN and attentional blink duration (Arnell et al., 2006). Both of these findings suggest that RAN may play a mediating role in the relationship between general dual-target RSVP performance and reading, perhaps tapping into short-term memory, intelligence, and vigilance factors involved in all of the tasks.

However, it should be noted that the correlations between mean T2|T1 performance and reading, although diminished, remained significant when controlling for RAN performance. This may be partly due to the relatively low correlations evident between RAN and reading ability in the current study. Previous research has typically shown stronger correlations between reading and rapid naming than we found, particularly when using letter- or digit-based RAN tasks, and the use of a color-based RAN task in the current study is likely to have reduced the strength of correlations between RAN and reading ability. It is also important to note, however, that any mediating role played by RAN in the link between mean T2|T1 performance and reading has little, if any, implication for the findings of deficits in attentional blink magnitude reported in previous studies, as we found no correlation between attentional blink duration and RAN.

CONCLUSION

In conclusion, this study indicates that attentional blink duration does not predict significant variance in the reading ability of children with normally developing reading skills. However, significant variance in reading ability was explained by mean T2|T1 performance across all lags, possibly due to factors such as short-term memory, general intelligence, and vigilance. Rapid naming appeared to mediate some of the variance in reading ability explained by mean T2|T1 performance; however, correlations with reading ability remained significant even after controlling for this factor.

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