Vision Research 115 (2015) 8–16

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The attentional blink is related to phonemic decoding, but not sight-word recognition, in typically reading adults

Maree M. Tyson-Parry [a,b], Jessica Sailah [a,b], Mark E. Boyes [c,d], Nicholas A. Badcock [b,*]

[a] Department of Psychology, Macquarie University, Australia
[b] ARC Centre of Excellence in Cognition and its Disorders, Department of Cognitive Science, Macquarie University, Australia
[c] School of Psychology and Speech Pathology, Faculty of Health Sciences, Curtin University, Perth, Australia
[d] Centre for Evidence-Based Intervention, Department of Social Policy and Intervention, University of Oxford, United Kingdom

ARTICLE INFO

Article history:
Received 4 November 2014
Received in revised form 13 July 2015
Accepted 6 August 2015
Available online 22 August 2015

Keywords:
Attentional blink
Visual attention
Reading
Phonemic decoding
Sight-word reading
Dual-route coding

ABSTRACT

This research investigated the relationship between the attentional blink (AB) and reading in typical adults. The AB is a deficit in the processing of the second of two rapidly presented targets when it occurs in close temporal proximity to the first target. Specifically, this experiment examined whether the AB was related to both phonological and sight-word reading abilities, and whether the relationship was mediated by accuracy on a single-target rapid serial visual processing task (single-target accuracy). Undergraduate university students completed a battery of tests measuring reading ability, non-verbal intelligence, and rapid automatised naming, in addition to rapid serial visual presentation tasks in which they were required to identify either two (AB task) or one (single target task) target/s (outlined shapes: circle, square, diamond, cross, and triangle) in a stream of random-dot distractors. The duration of the AB was related to phonological reading ($n = 41$, $\beta = -0.43$): participants who exhibited longer ABs had poorer phonemic decoding skills. The AB was not related to sight-word reading. Single-target accuracy did not mediate the relationship between the AB and reading, but was significantly related to AB depth (non-linear fit, $R^2 = .50$): depth reflects the maximal cost in T2 reporting accuracy in the AB. The differential relationship between the AB and phonological versus sight-word reading implicates common resources used for phonemic decoding and target consolidation, which may be involved in cognitive control. The relationship between single-target accuracy and the AB is discussed in terms of cognitive preparation.

1. Introduction

Visual temporal attention, the ability to process visual information over time, has been related to reading proficiency. This relationship has been found in both individuals with reading disorders (i.e., dyslexia; e.g., Hari, Valta, & Uutela, 1999) and typical readers (i.e., low and high-normal range; La Rocque & Visser, 2009). However, there remain a number of unanswered questions about the relationship between visual temporal attention and reading. This paper will examine whether visual temporal attention is related to both phonological and sight-word reading, and whether this relationship is mediated by accuracy on a single-target task.

1.1. The attentional blink

Deficits in visual (see Valdois, Bosse, & Tainturier, 2004 for a review) and temporal attention (see Farmer & Klein, 1995 for a review) have independently and in combination (see McLean, Castles, Coltheart, & Stuart, 2010) been associated with reading impairment. Visual temporal attention is typically measured using dual-target rapid serial visual presentation (RSVP, for an illustration see Fig. 1) tasks (henceforth dual-target tasks). These tasks require the identification of two targets embedded in a sequence of rapidly presented items. The first target (T1) is typically reported with high accuracy, but identification of the second target (T2) is markedly impaired when T2 is presented within 200–500 ms of T1. This phenomenon is termed the *attentional blink* (AB; Raymond, Shapiro, & Arnell, 1992).

There are two main categories of theoretical accounts of the AB: limited capacity and selection. Both theories posit a two-stage model in which the first stage involves subconscious processing of all items in the RSVP sequence and the second stage involves

---

* Corresponding author at: Australian Hearing Hub, 16 University Avenue, Macquarie University, North Ryde, NSW 2109, Australia.
E-mail address: nicholas.badcock@mq.edu.au (N.A. Badcock).

http://dx.doi.org/10.1016/j.visres.2015.08.001

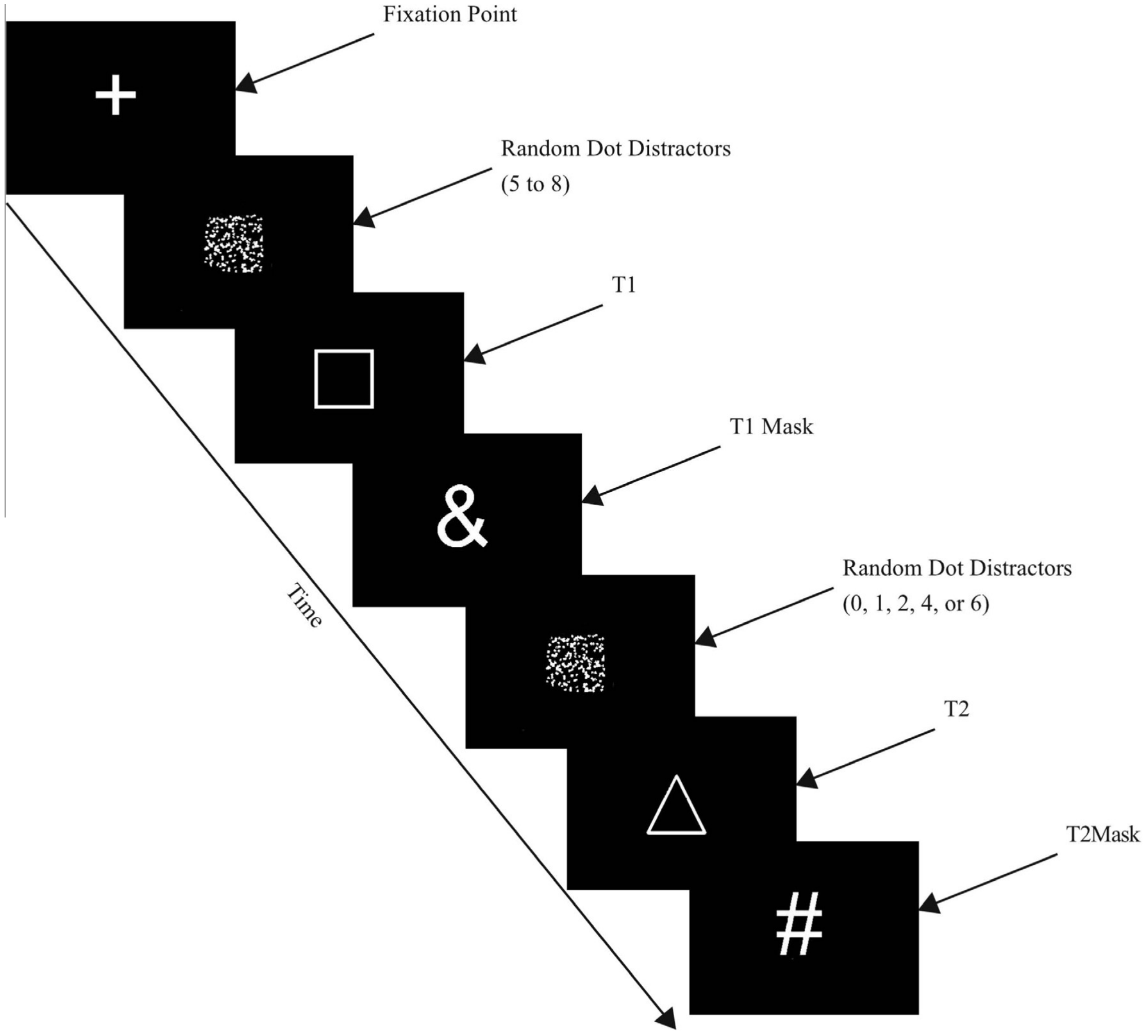

Fig. 1. Schematic representation of the rapid serial visual presentations used. Note: In the single-target condition T1 and the T1 mask were replaced by distractors.

target consolidation for conscious report. Limited capacity accounts theorise that second stage processing is capacity limited, in that resources can only be applied to one target at a time. If T2 appears while T1 is being consolidated for conscious report, T2 is queued until T1 processing is finalised. Whilst queued, T2 may be subject to interference or forgetting (Chun & Potter, 1995). Selection accounts posit that second stage processing involves targets being selected for conscious report by passing through a filter attuned to target features. When a target is detected, the system switches from monitoring to consolidation, resulting in a temporary loss of control of the filter. If T2 is presented before control of the filter is reasserted, T2 may be missed. The longer the time-interval between the targets, the higher the likelihood that control will be reasserted and T2 selected (Di Lollo, Kawahara, Ghorashi, & Enns, 2005).

1.2. The AB and reading

The relationship between the AB and reading was first explored by Hari et al. (1999) who reported that participants with dyslexia exhibited a significantly longer AB (700 ms) compared with typical (540 ms), interpreted as prolonged attentional dwell time. Whilst considerable variance in the size of the AB is present within studies, the majority of evidence indicates that people with dyslexia have deficits performing dual-target tasks (see McLean et al., 2010 for a review). However McLean et al. (2010) demonstrated that whilst group differences between dyslexic and typical readers were present on dual-target tasks, the differences rarely interacted with inter-target-interval (ITI), the time period between targets. Rather McLean et al. found that dyslexic readers exhibited poorer overall accuracy for T2 report, regardless of ITI. Hence, where previous studies had observed that the performance of participants with dyslexia was impaired at later ITIs than controls, this was a reflection of poorer overall performance by the dyslexic group and not indicative of a prolonged AB. This same relationship between T2 accuracy and reading has been found in normally developing readers, with better readers exhibiting higher T2 accuracy at all ITIs, but no differences in the AB per se (McLean, Stuart, Visser, & Castles, 2009). In typically reading adults, however, a different relationship has been reported.

La Rocque and Visser (2009) explored the relationship between reading and the AB in typically reading adults finding that low-normal readers had a significantly deeper AB than high-normal readers. It therefore appears that the relationship between reading and the AB may be different for typically reading adults relative to developing or dyslexic readers. However, La Rocque and Visser only tested the relationship between the AB and phonological reading. It is not known whether sight-word reading is also related to the AB in typically reading adults.

1.2.1. Phonological and sight-word reading and the AB

One model of reading suggests that printed words are read via two reading routes – the non-lexical or phonological and the lexical or sight-word (see Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). The phonological route relies on the knowledge of the letter-sound correspondences to decode words. This route is used for reading nonwords (e.g., bormil) or novel words that can be pronounced correctly from the letter-sound correspondences. The sight-word route relies on accessing memories of known words and is best assessed by irregular word reading: That is, reading words that cannot be pronounced from the letter-sound correspondences (e.g., yacht). Deficits in either or both routes result in characteristic patterns of reading impairment (see Coltheart et al., 2001). With two notable exceptions (McLean et al., 2010, McLean, Stuart, Visser, & Castles, 2009), studies of the AB and reading have not differentiated between phonological and sight-word reading. McLean et al. (2009) examined whether the relationship between the AB differed for phonological or sight-word reading skills in developing readers (i.e., children). They found no relationship between either reading route and the AB. However they did find that T2 accuracy was equally impaired at all ITIs for poorer readers for both reading routes. The same pattern of results was found comparing dyslexic and normally developing readers (McLean et al., 2010).

The maximum cost in T2 accuracy during the AB is referred to as AB depth. Whilst there is evidence that AB depth is related to phonological reading in typically reading adults (La Rocque & Visser, 2009), the relationship between the AB and sight-word reading has not been tested. Evidence of a differential relationship between the two reading abilities and the AB may shed light on the cognitive processes that underpin the relationship between the AB and reading. The relationship between the AB and reading may, however, be mediated by performance on a single-target RSVP (henceforth single-target task).

1.2.2. Reading, single-target accuracy, and the AB

An assumption of investigations of the AB and reading is that the dual-target RSVP paradigm is a test of temporal attention. One reason for this is that groups separated by reading abilities show very little difference on single-target RSVP tasks; therefore, it must be dual-target interference that is related to reading. However, McLean et al. (2010) found lower single-target accuracy in their dyslexic sample and, when factored into the dual target analyses, this accounted for between group differences. This suggests that some general factor, perhaps task vigilance, rather than temporal attention may underpin the relationship between the AB and reading. This remains to be tested in typically reading adults.

1.3. Aims

The present study has three aims. (1) To build upon the work of La Rocque and Visser (2009), which indicated that the AB is related to phonological reading in typically reading adults with poorer readers exhibiting a deeper AB than skilled readers. (2) To explore whether this relationship holds true for sight-word as well as phonological reading. (3) To determine if the relationship between the AB and reading is mediated by single-target accuracy.

2. Method

The methods are in line with the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans and were approved by the Macquarie University Human Research Ethics Committee (reference number: 5201200813). All participants provided informed written consent.

2.1. Participants

Participants comprised of 65 undergraduate psychology students (58 female) from Macquarie University between 17 and 53 years of age ($M = 20.74$, $Mdn = 18.66$, $SD = 6.05$). All participants reported that they were native English speakers with normal or corrected to normal vision and granted course credit for participation.

2.2. Measure and stimulus

The same measures used by La Rocque and Visser (2009) were conducted. Standardised administration procedures, as detailed in test manuals, were used. Scaled-scores were derived from the test manuals, however, for the reading and rapid naming tests, scores for participants older than the normative age range were based upon the maximum age-group (17–24).

2.2.1. Reading ability

The phonemic decoding and sight-word efficiency subtests of the Test of Word Reading Efficiency (TOWRE: Torgesen, Wagner, & Rashotte, 2012) were used to assess phonological and sight-word reading abilities respectively. The phonemic decoding subtest consisted of 66 nonwords. The sight-word efficiency tests consisted of 108 real words (regular and irregular). In both tests participants were required to read as many words as possible in 45 s. The phonemic decoding and sight-word efficiency subtests have reliability coefficients of .90 and .91, respectively (Torgesen et al., 2012).

2.2.2. Non-verbal intelligence

The matrices subtest of the Kaufman Brief Intelligence Test II (KBIT: Kaufman & Kaufman, 2005) was used to assess non-verbal intelligence. Participants were presented with 36 picture matrices and requested to identify the item missing from each matrix from one of four options. The reliability of the non-verbal intelligence subtest is reported to be at least .85 (Kaufman & Kaufman, 2005). The rationale for including non-verbal IQ was to control for variance due to general abilities.

2.2.3. Rapid-automatised naming (RAN)

The rapid letter naming (RAN-letter) subtest of the Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999) and a computerised rapid colour naming task (RAN-colour) were used to assess naming speed. The rationale for this was to control for variance due to processing speed (common to TOWRE and RAN), with the aim of obtaining purer estimates of the reading processes.

For the RAN-letter task, participants were instructed to read two pages each containing 36 six black letters on a white background (random sequences of the letters a, c, k, n, s, and t) as quickly as possible. The time taken to read both pages of items was converted to an aged-based scaled score. The reliability of the RAN-Letter task is .86 for individuals aged 18 years and over (Wagner et al., 1999).

The RAN-colour task used by La Rocque and Visser (2009) was replicated. The task consisted of a computerised display of a 6×6 matrix of solid coloured dots (subtending 1° of visual angle in width and height at a viewing distance of 60 cm) presented on a grey background. Participants were instructed to start at the top left hand corner and proceed to the right naming the colour of each dot (i.e., green, black, yellow, white, red, and blue) as accurately and quickly as possible. Participants commenced each trial by pressing the space bar, and were instructed to press the space bar again immediately upon finishing. Each participant completed two trials, which differed in colour configuration. The variable of interest was the average time taken to complete each trial.

2.2.4. Rapid serial visual presentation tasks

Single- and dual-target tasks were completed. The RSVP sequence included distractors, one or two targets depending on the task, and at least one mask (see Fig. 1 for a schematic diagram of a dual-target trial). In replication of La Rocque and Visser (2009), targets consisted of five shape outlines (circle, square, diamond, cross, and triangle). The masks were keyboard characters %, &, and #. Distractors were random-dot patches consisting of 200 dots (each subtending approximately $0.002^\circ \times 0.002^\circ$). All items were white on a black background presented in an area approximately subtending 1° of visual angle in width and height at a viewing distance of 60 cm (Visser, personal communication, January 24, 2013). Targets and masks were chosen randomly, with the constraint in the dual-target condition that two different target identities were presented.

Each item in the RSVP was displayed for 41.67 ms with a blank inter-stimulus interval of 58.33 ms (i.e., stimulus onset asynchrony of 100 ms). As illustrated in Fig. 1, in the dual-target trials commenced with a fixation point (self-initiated trials), five to eight distractors followed by T1 then either (a) T2; (b) a mask, then T2; or (c) or a mask, distractor(s), then T2, always followed by a mask. There were five ITIs: 100, 200, 300, 500, or 700 ms. For the single-target task, T1 and, where applicable, the T1 mask, were replaced by random dot distractors. Pseudo-ITIs of 100, 200, 300, 500, and 700 ms were measured from where T1 would have appeared in the RSVP sequence.

Participants were instruction to identify the target(s), with an emphasis on T1 in the dual-target task. Each trial commenced with a white fixation cross and participants initiated each trial by pressing the space bar. After each RSVP, all possible targets were displayed horizontally on the screen with a numbers 1–5 underneath. Participants were prompted to identify the target(s) by pressing the number on the keyboard that corresponded to the target(s) presented in the trial. For the dual-target task, 'T1' was displayed for the first response and 'T2' was displayed for the second response. Although participants were required to identify T1 and T2 separately, responses were scored as correct irrespective of report order (i.e., if T1 = triangle and T2 = square, the response was square then triangle, both T1 and T2 would be scored as correct; if the response was circle then triangle, T1 would be scored as correct). This scoring is in keeping with La Rocque and Visser, and is based on evidence that order information may be lost when identity is correctly processed. There were five practice trials and 125 test trials for each task (25 trials per ITI). Overall T1 accuracy was presented for the participants at the end of the practice trials. No feedback was presented during the test trials.

2.3. Apparatus and procedure

Testing was conducted as part of a larger experiment as part of a one-and-a-half hour session. Tests were administered in a small room, with natural light for the computerised tests and fluorescent light for the non-computerised tests. The computer tasks were run on Dell Optiplex 9010 machines with an Intel core i5-3470 processor running at 3.60 GHz with a Samsung S27ASA950 LED monitor running at 120 Hz. The RSVP tasks were written in MATLAB 8.0.0.783 (MathWorks, release 2012b) using Psychtoolbox 3.0.10, Revision 3187 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997).

Each testing session included two blocks: (1) TOWRE, non-verbal intelligence, and RAN; (2) RSVP tasks. Block order and task order within blocks, was counter-balanced between participants. The exception to this was that the colour RAN was always administered after the paper and pen behavioural tests, and the non-verbal intelligence test was always the second behavioural test administered.

2.4. Method of analysis

AB performance was calculated as T2 identification accuracy at each ITI, for trials on which T1 was correctly identified (i.e., denoted as T2|T1 throughout this paper). As overall T1 accuracy was high (Mean = 0.94, *SD* = 0.05, Min = 0.74, Max = 1), the majority of trials were included in the analysis.

AB depth and width were estimated using Cousineau, Charbonneau, and Jolicoeur's (2006) parameter estimation procedure. The depth measure is the difference between maximum and minimum T2|T1 accuracy. Greater depth values indicate a larger discrepancy between minimum T2|T1 accuracy and T2|T1 accuracy at later ITIs, that is, a deeper AB effect. The width measure reflects the degree of modulation of the U-shape of the AB curve to best fit the data. Greater width values indicate a longer AB recovery time. The Cousineau et al. procedure was used as it provides more sensitive estimates of depth and width than those used by La Rocque and Visser (2009). For reference, La Rocque and Visser estimated depth as minimum T2, and width as the ITI at which T2|T1 accuracy met or exceeded T1 accuracy.

The sensitivity of the current analysis was further increased by using sequential multiple regression rather than Analysis of Covariance (ANCOVA) which was employed by La Rocque and Visser (2009). Dichotomising continuous variables can result in both false positives (e.g., Vargha, Rudas, Delaney, & Maxwell, 1996) and false negatives (through reduction of the power of the test e.g., Cohen, 1978). Therefore, in accordance with the recommendations of Vargha et al. (1996), the analysis was conducted via regression. In addition to this justification, the small number of poor readers ($n = 14$) in the current sample meant that an ANCOVA was not a suitable analysis tool.

A series of sequential multiple regressions were conducted with AB depth and width entered as dependent variables. Using the Bonferroni procedure, alpha was set to .025 to control for multiple comparisons. Standardised RAN letter scores, and raw RAN-colour scores (averaged across conditions), were entered in the first regression block of each regression. The predictor variables of interest (i.e., phonemic decoding, sight-word efficiency, or single-target RSVP performance) were entered in the second regression block of the applicable analyses. Age and non-verbal IQ were not included in the regression equations as correlations indicated that they did not share variance with the other variables.

To ensure participants' reading abilities were in the normal range (as in La Rocque & Visser, 2009), participants with a standard score under 90 on the phonemic decoding test ($n = 6$) or on the sight-word efficiency test ($n = 7$) were excluded from analyses involving those variables. Due to the overlap in these two criteria, 11 individuals were excluded based on reading scores outside of the normal range. A further 10 individuals were excluded based on a floor effect for the fitting of the AB width parameter, though inclusion of these individuals did not change the pattern of the results.

3. Results

3.1. Performance on RSVP tasks

Overall T1 accuracy was high and negatively skewed, indicative of a ceiling effect: Mean = 0.94, *SD* = 0.05, Min = 0.74, Max = 1. As T2 accuracy was based on only those trials in which T1 was correctly reported, the majority of trials were included. To test for order effects and the presence of an AB effect, a mixed 2 (RSVP task order: single-target first, dual-target first) by 5 (ITI: 100, 200, 300, 500, 700 ms) Analysis of Variance (ANOVA) was conducted. As the assumption of sphericity was violated, degrees of freedom were adjusted using the Greenhouse–Geisser procedure (also used for the single-target one-way ANOVA). A significant main effect of ITI was present, $F(3.4,133.6) = 40.24$, $p < .01$, $\eta_p{}^2 = 0.51$, which is displayed in Fig. 2, indicating an AB effect. The main effect of RSVP task order, $F(1,39) = 1.9$, $p = 0.18$, $\eta_p{}^2 = 0.05$, = .04, and the RSVP task order by ITI interactions were not significant, $F(3.4,133.6) = 0.82$, $p = 0.5$, $\eta_p{}^2 = 0.02$. Thus, completion of the single-target task did not unduly influence dual-target performance.

Single target accuracy is also presented as a function of pseudo-ITI in Fig. 2. Overall accuracy was high and relatively higher at longer pseudo-ITIs. A one-way ANOVA indicated that single-target task accuracy was significantly affected by pseudo-ITI, $F(4,156) = 5.99$, $p < .01$, $\eta_p{}^2 = 0.13$. This will be considered further in the discussion.

3.2. AB and reading

All the following analyses were based on 41 participants with phonemic decoding and sight word efficiency scores of 90 or more (i.e., within the normal range) and a valid AB width parameter. Pearson product moment correlations were used to examine the relationships between variables prior to regression analyses. These are presented in Table 1. There are strong relationships between: phonemic decoding and RAN colours, better reading associated with faster naming; sight word efficiency and RAN letters, better reading associated with more accurate naming. There are medium relationships between: phonemic decoding and AB Width, negative relationship, i.e., better reading associated with shorter AB effects; the two RAN measures, negative relationship; sight word reading and RAN colours, negative relationship; and sight word reading and phonemic decoding, positive relationship. Higher single target accuracy is related to reduced AB depth (strong). As Age and IQ were weakly and not significantly related to all variables, these were not included in subsequent analyses.

The relationship between the AB (width and depth) and reading was tested by two sequential regressions. The overall models for the regression containing the control variables were not significant for either AB width: AB width: $F(2,38) = 0.8$, $p = 0.46$, adjusted $R^2 = -0.01$; or AB depth: $F(2,38) = 1.98$, $p = 0.15$, adjusted $R^2 = 0.05$ (see Table 2 for full regression statistics). Including the reading measures resulted in a significant improvement in the fit of the model for AB width: AB width: $F(2,36) = 3.00$, $p = 0.03$ (single-tail), change $\Delta R^2 = 0.14$; but not AB depth: $F(2,36) = 0.43$, $p = 0.66$, $\Delta R^2 = 0.02$. Phonemic decoding was the only significant predictor for width. As depicted in Fig. 3, the longer the duration of the AB, the poorer the phonemic decoding scores.

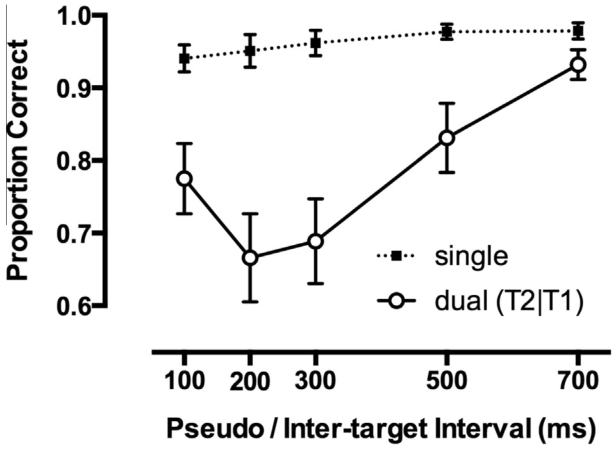

Fig. 2. Proportion correct single- and dual-target (T2|T1) rapid serial visual presentation task accuracy as a function of inter-target interval (pseudo-ITI in the case of the single-target task). Error bars represent the 95% confidence intervals.

3.3. Single-target accuracy, reading, and the AB

To test whether single-target accuracy mediated the relationship between AB width and phonemic decoding, a sequential regression was conducted in which overall accuracy on the single-target task was entered with phonemic decoding. The overall model for the control variables is as reported in Table 2. The fit of the model was similar to that reported above; $F(2,36) = 3.6$, $p = 0.04$, $\Delta R^2 = 0.11$; phonemic decoding was a significant predictor and single-target accuracy was not (see Table 3 for full regression statistics). Therefore, the evidence does not indicate that single-target accuracy mediates the relationship between the AB width and phonemic decoding.

To elaborate on the significant correlation between single-target accuracy and the AB width (see Table 1), regression fitting was employed. A non-linear (second-order polynomial: $Y = B_0 = B_1 * X + B_2 * X^2$) fit best characterised the relationship between single-target accuracy and AB depth ($\beta_1 = 0.13$ [95% Confidence Intervals: 0.001, 0.26], $\beta_2 = -0.34$ [-0.51, -0.17], $R^2 = .50$, see Fig. 4). Please note, this was conducted for the full sample ($n = 65$) as reading was not a factor of concern: fit was better for $n = 41$ ($\beta_1 = 0.21$ [0.04, 0.37], $\beta_2 = -0.44$ [-0.65, -0.23], $R^2 = .63$).

4. Discussion

The present study had three aims. (1) To build upon the work of La Rocque and Visser (2009), which indicated that the AB is related to phonological reading in typical adults with poorer readers exhibiting a deeper AB than skilled readers. (2) To explore whether this relationship holds true for sight-word as well as phonological reading. (3) To determine if the relationship between the AB and reading is mediated by single-target accuracy. The results indicated that there is a relationship between the AB and reading in typical adults. However, whereas La Roque and Visser demonstrated a relationship between AB depth and phonemic decoding, the present results demonstrated a relationship between AB width and phonemic decoding. AB width and depth were not related to sight-word reading, and single-target accuracy did not mediate the relationship between the AB and phonemic decoding. Single-target accuracy was however related to AB depth. These findings are discussed below.

4.1. The AB is related to phonological reading in typical adults

The findings of the current study indicated that AB width is related to nonword reading in typically reading adults. This is in contrast to La Rocque and Visser (2009) who reported a relationship with AB depth. There are three key differences between the present study and that of La Rocque and Visser: the inclusion of a single-target task, the manner in which the AB parameters were estimated, and the method of analysis.

The current study included a single-target task the completion of which was counterbalanced with completion of the dual-target task. There was no evidence that order affected the results therefore inclusion of the single-target task cannot account for the discrepant findings.

La Rocque and Visser (2009) calculated width as the ITI at which T2|T1 accuracy equalled or exceeded T1 accuracy. The present

Table 1
Pearson product moment correlations coefficients for the relationships between single-target accuracy, the AB, age, non-verbal intelligence, rapid automatised naming, and reading.

	Single T Acc.	AB width	AB depth	Age	IQ	RAN letters	RAN colours	PD
AB width	−0.17							
AB depth	−0.63**,^	−0.25						
Age	−0.06	0.00	0.11					
IQ	0.14	0.07	−0.16	0.12				
RAN letter	0.04	−0.19	0.29	0.13	−0.15			
RAN colour	−0.14	0.14	−0.04	−0.12	0.02	−0.44**		
PD	0.07	−0.39*	0.13	0.16	0.03	0.27	−0.55**,^	
SWE	0.00	−0.22	0.18	0.00	−0.15	0.79**,^	−0.42**	0.32*

Note: standardised scores were used for the phonemic decoding (PD) test, sight-word efficiency test (SWE), non-verbal intelligence (IQ) and RAN letter tests. Single T Acc. = Single-target accuracy. $N = 41$.

* $p < .05$.

** $p < .01$.

^ $p < .001$ (Bonferroni correction).

Table 2
Regression descriptive and inferential statistics for AB width and depth, and phonemic decoding.

Dependent		Predictor	*B*	Std. error	Beta	*t*
AB width	Block 1	RAN letters	−0.04	0.05	−0.16	−0.89
		RAN colours	0.01	0.03	0.07	0.41
	Block 2	RAN letters	−0.02	0.07	−0.07	−0.28
		RAN colours	−0.03	0.03	−0.17	−0.85
		PD	−0.05	0.02	−0.43	−2.35*
		SWE	−0.01	0.02	−0.1	−0.37
AB depth	Block 1	RAN letters	0.03	0.01	0.34	1.98
		RAN colours	0.01	0.01	0.12	0.67
	Block 2	RAN letters	0.04	0.02	0.44	1.67
		RAN colours	0.01	0.01	0.19	0.93
		PD	0.01	0.01	0.16	0.82
		SWE	0	0.01	−0.14	−0.53

Note: PD = phonemic decoding, SWE = sight word efficiency, IQ = KBIT, non-verbal intelligence.

* $p < .05$.

study used the Cousineau et al. (2006) curve fitting procedure to extract a width parameter. It is possible that curve fitting allowed for the detection of width effects that were undetected by La Rocque and Visser. Further, the present study also used the curve fitting procedure to estimate a depth (amplitude) parameter whereas La Rocque and Visser used minimum T2|T1 accuracy. While it is possible this difference contributed to the lack of a relationship between depth and reading, amplitude and minimum T2|T1 accuracy were very highly correlated in the present study (i.e., $r = -.98$) as well as other research (Cousineau et al., 2006). It is, therefore, unlikely that the different methods of calculating the depth of the AB can account for the discrepant findings.

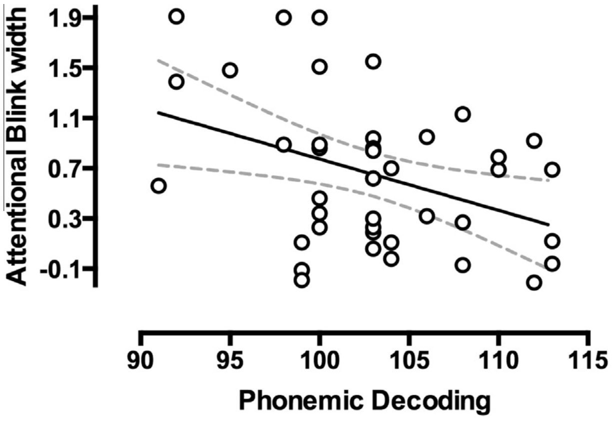

Fig. 3. Scatter plot and regression line for the relationship between AB width and Phonemic decoding. *Note:* Higher values on the *y*-axis reflect longer AB effects.

The third area of difference between this and the original study is the method of analysis. La Rocque and Visser (2009) used ANCOVAs, however due to the small number of participants in the low-normal reading group in the present study ($n = 11$, La Rocque & Visser $n = 23$), the ANCOVA (which, incidentally, indicated no effect of group for the present study) was not suitable. For this, and the other reasons provided in Section 2.4, the present study utilised regression. However as regression should have increased the statistical power of the analysis, the alternate method of analysis does not offer a satisfactory account for the failure to replicate a relationship between AB depth and reading.

It does not appear that methodological differences account for the discrepant findings between the two studies. Considered together, La Rocque and Visser's (2009) and the current study indicate that the AB and reading are related in typical adults, but the precise nature of this relationship is unclear. As mentioned, AB width and depth are known to be correlated (Cousineau et al., 2006) and it is possible that they represent different aspects of the same attentional mechanism (Li, Lin, Chang, & Hung, 2004). However, little is known about what individual differences in AB parameters represent, and how they relate to one another or reading proficiency. We do know that instructions prioritizing T1 or T2 affects the width but not the depth of the AB: emphasis on T1 leads to a longer but not deeper AB (Cousineau et al., 2006). This appears most consistent with a capacity limitation account of the AB: when greater resources are allocated to T1 consolidation there is a longer delay in resource allocation to T2 (e.g., Chun & Potter, 1995; Jolicoeur, 1998). As the target-distractor selection demands are constant between conditions, selection accounts do not provide a clear account of these findings. More relevant to reading, Olson, Chun, and Anderson (2001) manipulated the length of target words in an AB, including phonological length. Longer words elicited greater AB effects and, although not analysed by parameters, this manipulation affected AB depth. These two studies suggest that

Table 3
Regression descriptive and inferential statistics for phonemic decoding and AB width including single-target accuracy.

Dependent		Predictor	*B*	Std. error	Beta	*t*
AB width	Block 2	RAN letters	−0.04	0.04	−0.15	−0.89
		RAN colours	−0.03	0.03	−0.19	−0.97
		PD	−0.05	0.02	−0.44	−2.47*
		Single T Acc.	−0.71	0.65	−0.16	−1.09

Note: PD = phonemic decoding, Single T Acc. = single-target accuracy, IQ = KBIT, non-verbal IQ. Block 1 is as reported in Table 2.

* $p < .05$.

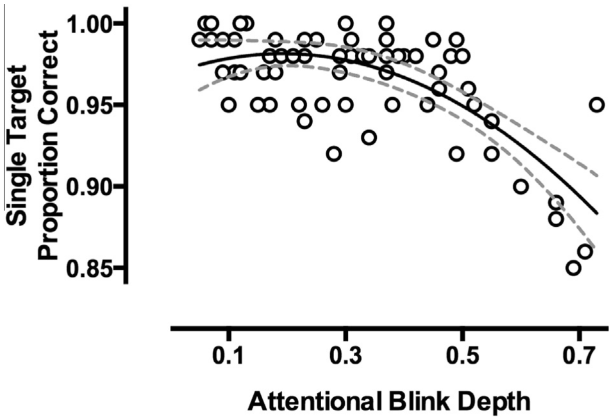

Fig. 4. Scatter plot and regression fit for the relationship between single target proportion correct and AB depth. Note: Higher values on the *x*-axes reflect deeper AB effects and the grey dotted lines represent the 95% confidence intervals for the fit.

explicit allocation of resources to T1 affects AB width whereas implicit allocation of resources to T1 affects AB depth. It should be noted that the dual-target instructions in the current study emphasised T1. The instructions to participants are not noted in La Rocque and Visser (2009), therefore it may be this emphasis that differentiates the two results. Manipulation of target emphasis in the procedures employed by Olsen et al. would be a useful next step.

Interestingly, the presence of a relationship between the AB and reading in typical readers appears to be limited to adults, with the relationship not being evident in developing readers (McLean et al., 2009). McLean et al. found that dual-target performance was related to word identification, phonemic decoding, and irregular word reading, with poorer readers on all measures exhibiting poorer T2 accuracy regardless of ITI. This is in contrast to the findings in adults, where the width (current study) or depth (La Rocque & Visser, 2009) relate to reading.

The differing results between developing and experienced readers may arise from the use of speeded verse unspeeded reading measures. Reading ability in the present study, and that of La Rocque and Visser (2009), was measured using a speeded reading task, susceptible to a speed-accuracy trade-off (Schweizer, 1996). Whereas McLean et al.'s (2009) reading ability measure was based on accuracy alone. Individual differences in mental processing speed are highly correlated with T2 accuracy, with individuals with faster mental processing speeds exhibiting reduced ABs (Klein, Arend, Beauducel, & Shapiro, 2011; study 1). It is possible that the relationship between the AB and reading in typical adults is a by-product of mental processing speed; however, the rapid automatised naming measures (letters and colours) were included to factor out variance due to processing speed. Future research would benefit from disentangling whether the relationship arises from reading speed and/or accuracy.

4.2. The AB is related to phonological but not sight-word reading

Phonological reading but not sight-word reading was related to the AB in the current study. Generally this relationship has been demonstrated previously (La Rocque & Visser, 2009; McLean et al., 2009) and the majority of dyslexia and the AB research has focussed on phonological reading difficulties (for a review see Badcock & Kidd, 2015). In typical readers, the AB paradigms have required the identification of target shapes. Although verbal labelling of these shapes in not required, target identity being indicated with a symbol-labelled button-press, it is likely that word retrieval is required. Whilst longer words are associated with longer AB effects (Olson, Chun, & Anderson, 2001), shapes have been selected as stimuli as they are considered to have relatively automatic retrieval. However, automatic retrieval is also associated with sight-word reading as stipulated by the dual-route cascaded model of reading (Coltheart et al., 2001) as well as rapid automatised naming, and neither was related to the AB in the current study. Therefore, some different mechanism or further processing of the shape targets likely underpins the relationship.

The initial impetus for investigating the relationship between reading and the AB concerned the general allocation of attention over time (Hari et al., 1999). Difficulties in the AB were noted as evidence of slower disengagement of attention, which has been implicated for discriminating speech sounds, however controversially, thought to be important for the acquisition of language (Tallal, Stark, & Mellits, 1985). This may fit with an association between AB width and reading in general. However, it does not account for the lack of relationship between the AB and sight-word reading. The peculiar aspect of phonological reading is that novel words, as used in the phonemic decoding task of the current study, are processed sublexically as they cannot be retrieved from a store of known words (i.e., the mental lexical or through lexical access; Coltheart et al., 2001). Reading via the sublexical route is a resource dependent process and is known to modulate AB performance: more decoding, leading to a deeper AB effect (Olson et al., 2001). If the resources required for sublexical processing in reading and AB target consolidation are common, this could account for the observed relationship. Phonemic decoding efficiency and AB target consolidation may be constrained by this resource. The findings could be accounted for by a smaller capacity or slower processing in poor readers. Consistent with this, children with dyslexia require a longer target-to-mask interval to identify visually presented numbers at the same level of accuracy to typically reading peers (see Di Lollo, Hanson, & McIntyre, 1983). The single-target task in the current study may not have been sensitive enough to detect a relationship with reading in the current sample.

It may be the case that this common resource relates to cognitive control. Badcock and Kidd (2015) report on a meta-analysis of the AB and dyslexia. The major finding in this literature is lower overall performance in groups of individuals with dyslexia; that is to say, there are no group differences related to the shape (i.e., width or depth) of the AB. Using a meta-regression to examine the physical presentation factors that differed between studies to predict the between group difference, the inter-trial interval or pre-RSVP time predicted the group difference. The pattern of the relationship indicated that the longer the time before the onset of the RSVP, the greater the difference between groups. Badcock and Kidd suggested that the endogenous engagement of task-set (particularly temporal variability of the targets), may be disrupted or slower in groups of people with dyslexia. These conclusions relate to dyslexia and overall performance in a dual-target task, whilst the current study focused on the normal range of reading and the shape of the AB effect (i.e., an interaction rather than a main effect). Nevertheless, implicating cognitive control in AB performance (see also Arnell, Stokes, MacLean, & Gicante, 2010), especially with respect to reading, provides a useful mechanism to underpin future research in this area.

As a limitation, it is also possible that the failure to find a relationship between the AB and sight-word reading in typical adults may be related to the reading measure. The sight-word efficiency subtest of the TOWRE (Torgesen et al., 2012) consists of a mixture of regular and irregular words. As the pronunciation of regular words can be obtained via the lexical or sublexical reading routes (Coltheart et al., 2001), the sight-word efficiency test does not provide a pure measure of lexical reading ability. However, whilst acknowledging this limitation, Wagner et al. (1999) claim that it is necessary to be able to read the test stimuli via the lexical route in order to obtain an average or above average test score. As participants who scored below the normal range were excluded, it is unlikely that participants utilised a phonological strategy in the sight-word efficiency test. Further, the sight-word efficiency test may have been too easy for participants in the present study, as scores were differentiated by speed not error. It is possible that these factors may have masked a relationship between the AB and sight-word reading. The conclusion that the AB is related to the phonological but not sight-word reading route in typical adults should therefore be considered preliminary.

4.3. Single-target accuracy does not mediate the relationship between the AB and reading

Single-target accuracy did not mediate the relationship between the AB and reading. This is at odds with McLean et al.'s (2010) finding in the AB and dyslexia: the between-group difference was no longer significant when single-target accuracy was controlled in the analysis. However, in contrast to the current findings, McLean et al. reported that reading was related to overall T2 accuracy, irrespective of ITI, whereas in the current study, the width of the AB was related to reading. Therefore, single-target processing played a role when inter-target interference did not in children, in contrast, single-target processing did not play a role when inter-target interference did in adults. It would be useful to follow up this finding with children and adults in the same study, ensuring the ceiling effects were avoided, which was not the case in the current study.

The lack of a mediating relationship between single-target accuracy and reading in the present study may be attributable to the ceiling effect present in the single-target task. As observed by Badcock, Hogben, and Fletcher (2008), the use of single-target tasks that are too easy may mask group or individual differences. The finding that single-target performance does not mediate the relationship between the AB and reading typical readers should be interpreted with caution and considered preliminary.

4.4. Preparation and the AB

Whilst this is the first study to identify a relationship between single-target accuracy and AB depth, there is a growing body of work pointing to the role of cognitive preparation in performance on RSVP tasks. The linear increase in single-target accuracy as a function of time is suggested to be a result of cognitive preparation (Ariga & Yokosawa, 2008; McLean et al., 2010; Visser, Boden, & Giaschi, 2004). There is also evidence that temporal orienting, thought to enhance the preparation of attention, influences the AB. When the temporal position of T2 is cued (Martens & Johnson, 2005; Experiments 2 and 3), learned (Tang, Badcock, & Visser, 2013), or predictable (Badcock, Badcock, Fletcher, & Hogben, 2013) the depth of the AB is significantly reduced. Badcock et al. (2013) also demonstrated that an individually tailored foreperiod to T1 reduced the AB depth and width. Therefore it is clear that the capacity to prepare for the arrival of the targets influences the AB, and it may be this preparation that underpins the relationship between single-target processing and the AB depth in the current results. Further research is required to determine the precise nature of the role of cognitive preparation/control in the AB.

5. Conclusion

The AB is related to single item phonological reading in typical adults. We suggest that the same cognitive resource is required for phonemic decoding and target consolidation in the AB, potentially related to endogenous cognitive control. Single-target accuracy did not mediate the relationship between the AB and reading, indicating that the relationship arises from the cost of T1 processing on T2. Single-target accuracy was found to be a predictor of AB depth, implicating cognitive preparation as a factor in AB performance.

Acknowledgments

Thank you to Associate Professor Troy Visser for his prompt and helpful responses to all queries regarding the original study; to Kathryn Preece for assistance during the data collection phase; and to Ian Parry for the IT support. This research was funded by the Macquarie University Psychology Department and the Australian Research Council Centre of Excellence in Cognition and its Disorders (CE110001021) http://www.ccd.edu.au.

References

Ariga, A., & Yokosawa, K. (2008). Attentional awakening: Gradual modulation of temporal attention in rapid serial visual presentation. *Psychological Research, 72*(2), 192–202. http://dx.doi.org/10.1007/s00426-006-0100-4.

Arnell, K. M., Stokes, K. A., MacLean, M. H., & Gicante, C. (2010). Executive control processes of working memory predict attentional blink magnitude over and above storage capacity. *Psychological Research PRPF, 74*(1), 1–11. http://dx.doi.org/10.1007/s00426-008-0200-4.

Badcock, N. A., Badcock, D. R., Fletcher, J., & Hogben, J. (2013). The role of preparation time in the attentional blink. *Vision Research, 76*, 68–76. http://dx.doi.org/10.1016/j.visres.2012.10.010.

Badcock, N. A., Hogben, J. H., & Fletcher, J. F. (2008). No differential attentional blink in dyslexia after controlling for baseline sensitivity. *Vision Research, 48*(13), 1497–1502. http://dx.doi.org/10.1016/j.visres.2008.03.008.

Badcock, N. A., & Kidd, J. C. (2015). Temporal variability predicts the magnitude of between-group attentional blink differences in developmental dyslexia: A meta-analysis. *PeerJ, 3*, e746. http://dx.doi.org/10.7717/peerj.746.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*(4), 433–436. http://dx.doi.org/10.1163/156856897X00357.

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 21*(1), 109–127. http://dx.doi.org/10.1037/0096-1523.21.1.109.

Cohen, J. (1978). Partialed products are interactions; partialed powers are curve components. *Psychological Bulletin, 85*(4), 858–866. http://dx.doi.org/10.1037/0033-2909.85.4.858.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108*(1), 204–256.

Cousineau, D., Charbonneau, D., & Jolicoeur, P. (2006). Parameterizing the attentional blink effect. *Canadian Journal of Experimental Psychology = Revue Canadienne de Psychologie Expérimentale, 60*(3), 175–189. http://dx.doi.org/10.1037/cjep2006017.

Di Lollo, V., Hanson, D., & McIntyre, J. S. (1983). Initial stages of visual information processing in dyslexia. *Journal of Experimental Psychology. Human Perception and Performance, 9*(6), 923–935.

Di Lollo, V., Kawahara, J., Ghorashi, S. M. S., & Enns, J. T. (2005). The attentional blink: Resource depletion or temporary loss of control? *Psychological Research, 69*(3), 191–200. http://dx.doi.org/10.1007/s00426-004-0173-x.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Bulletin & Review, 2*(4), 460–493. http://dx.doi.org/10.3758/BF03210983.

Hari, R., Valta, M., & Uutela, K. (1999). Prolonged attentional dwell time in dyslexic adults. *Neuroscience Letters, 271*(3), 202–204. http://dx.doi.org/10.1016/S0304-3940(99)00547-9.

Jolicoeur, P. (1998). Modulation of the attentional blink by on-line response selection: Evidence from speeded and unspeeded Task1 decisions. *Memory & Cognition, 26*(5), 1014–1032. http://dx.doi.org/10.3758/BF03201180.

Kaufman, A. S., & Kaufman, N. L. (2005). *Kaufman brief intelligence test* (2nd ed.). Circle Pines, Minnesota: American Guidance Language Service.

Klein, C., Arend, I. C., Beauducel, A., & Shapiro, K. L. (2011). Individuals differ in the attentional blink: Mental speed and intra-subject stability matter. *Intelligence, 39*(1), 27–35. http://dx.doi.org/10.1016/j.intell.2010.11.004.

Kleiner, M., Brainard, D. H., & Pelli, D. G. (2007). What's new in Psychtoolbox-3? *Perception, 36*. http://dx.doi.org/10.1068/v070821 (ECVP Abstract Supplement).

La Rocque, C. L., & Visser, T. A. W. (2009). Sequential object recognition deficits in normal readers. *Vision Research, 49*(1), 96–101. http://dx.doi.org/10.1016/j.visres.2008.09.027.

Li, C. R., Lin, W., Chang, H., & Hung, Y. (2004). A psychophysical measure of attention deficit in children with attention-deficit/hyperactivity disorder. *Journal of Abnormal Psychology, 113*(2), 228–236. http://dx.doi.org/10.1037/0021-843X.113.2.228.

Martens, S., & Johnson, A. (2005). Timing attention: Cuing target onset interval attenuates the attentional blink. *Memory & Cognition, 33*(2), 234–240. http://dx.doi.org/10.3758/BF03195312.

McLean, G. M. T., Castles, A., Coltheart, V., & Stuart, G. W. (2010). No evidence for a prolonged attentional blink in developmental dyslexia. *Cortex, 46*(10), 1317–1329. http://dx.doi.org/10.1016/j.cortex.2010.06.010.

McLean, G. M. T., Stuart, G. W., Visser, T. A. W., & Castles, A. (2009). The attentional blink in developing readers. *Scientific Studies of Reading, 13*(4), 334–357. http://dx.doi.org/10.1080/10888430903001365.

Olson, I. R., Chun, M. M., & Anderson, A. K. (2001). Effects of phonological length on the attentional blink for words. *Journal of Experimental Psychology. Human Perception and Performance, 27*(5), 1116–1123.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*(4), 437–442. http://dx.doi.org/10.1163/156856897X00366.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology, 18*(3), 849–860.

Schweizer, K. (1996). The speed-accuracy transition due to task complexity. *Intelligence, 22*(2), 115–128. http://dx.doi.org/10.1016/S0160-2896(96)90012-4.

Tallal, P., Stark, R. E., & Mellits, D. (1985). The relationship between auditory temporal analysis and receptive language development: Evidence from studies of developmental language disorder. *Neuropsychologia, 23*(4), 527–534.

Tang, M. F., Badcock, D. R., & Visser, T. A. W. (2013). Training and the attentional blink: Limits overcome or expectations raised? *Psychonomic Bulletin & Review, 1–6*. http://dx.doi.org/10.3758/s13423-013-0491-3.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (2012). *Test of word reading efficiency* (2nd ed.). Austin, Texas: Pro-ed.

Valdois, S., Bosse, M.-L., & Tainturier, M.-J. (2004). The cognitive deficits responsible for developmental dyslexia: Review of evidence for a selective visual attentional disorder. *Dyslexia, 10*(4), 339–363. http://dx.doi.org/10.1002/dys.284.

Vargha, A., Rudas, T., Delaney, H. D., & Maxwell, S. E. (1996). Dichotomization, partial correlation, and conditional independence. *Journal of Educational and Behavioral Statistics, 21*(3), 264–282. http://dx.doi.org/10.3102/10769986021003264.

Visser, T. A. W., Boden, C., & Giaschi, D. E. (2004). Children with dyslexia: Evidence for visual attention deficits in perception of rapid sequences of objects. *Vision Research, 44*(21), 2521–2535. http://dx.doi.org/10.1016/j.visres.2004.05.010.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1999). *The comprehensive test of phonological processing*. Austin, Texas: Pro-ed.