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1. Title Page

Title: Temporal variability predicts the magnitude of between-group attentional blink differences in developmental dyslexia: a meta-analysis

Authors: Nicholas A. Badcock & Joanna C. Kidd

ARC Centre of Excellence in Cognition and its Disorders, Department of Cognitive Science, Macquarie University

North Ryde, New South Wales, Australia

Corresponding Author: Nicholas A. Badcock

Australian Hearing Hub, 16 University Drive

North Ryde, New South Wales, Australia, 2109

Phone number: + 61 2 9850 4067

e-mail: nicholas.badcock@mq.edu.au

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2. Abstract

Background. Here we report on a meta-analysis of the attentional blink (AB) research focussed on specific reading impairment, commonly referred to as developmental dyslexia. The AB effect relates to a limitation in the allocation of attention over time and examined in a dual-target rapid serial visual presentation paradigm. When the second target appears in close temporal proximity to the first target, the second target is reported less accurately.

Method. A Web of Science search with terms 'dyslexia attentional blink' returned 13 AB experiments (11 papers) conducted with developmental dyslexia (9 were included in this meta-analysis). The main pattern of performance was lower overall accuracy in groups of individuals with dyslexia relative to typically reading peers. That is, a between-group main effect. This meta-analysis examined the size of the between-group effect in relation to physical presentation characteristics, which differed between and within experiments.

Results. Four noteworthy variables were related to the between group effect-size; fixation duration (positive relationship, $R^2 = .89$, $p <.01$, $n = 6$), maximum temporal position of T2 (negative relationship, $R^2 = .46$, $p <.05$, $n = 9$), the difference between the minimum and maximum temporal position of T2 (negative relationship, $R^2 = .53$, $p <.05$, $n = 9$), and the stimulus onset asynchrony (negative relationship, $R^2 = .46$, $p <.05$, $n = 9$).

Discussion. These are discussed with respect to the preparation of task-set, temporal orienting, and speed of processing, recommending these as considerations for future research.

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3. Introduction

Aside from a specific difficulty with the typical acquisition of reading, developmental dyslexia has been associated with a number of cognitive weaknesses. One of these weaknesses is the ability to rapidly deploy attention across time (e.g. Hari & Renvall 2001; Tallal 1976). Here we focus on a single paradigm used to assess the rapid allocation of visual attention across time: a dual-target Rapid Serial Visual Presentation (RSVP) paradigm. Performance in this paradigm has been described as an ‘Attentional Blink’ (AB) effect. The AB is an attentional phenomenon whereby the processing of the first target (T1) is considered to disrupt the processing of a second target (T2) when the two targets appear in close temporal proximity (i.e. within 500 ms; Broadbent & Broadbent 1987; Raymond, Shapiro & Arnell 1992). The standard AB pattern is illustrated by the solid line in Figure 3.1 . The main point to note is that at short inter-target intervals (e.g. 200 to 300 ms) T2 accuracy is lower than at long (e.g. 500 to 700 ms) intervals.

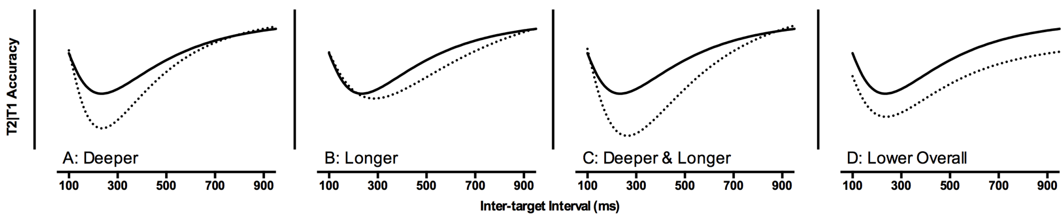

Figure 3.1 Four patterns of attentional blink (AB) performance: second target performance, given that the first target was correctly reported, as a function of the inter-target interval. The solid line depicts a standard AB performance. The dashed lines depict atypical AB performance related to deeper (panel A), longer (B), and deeper and longer AB effects (C), as well as lower overall accuracy (D).

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In a review of the AB literature on developmental dyslexia, McLean, Castles, Coltheart, and Stuart (2010) demonstrated that the most common difference between dyslexic and typically reading groups was a main effect; that is, overall, the performance of the dyslexic readers was lower than that of typical readers. Therefore, rather than a difficulty in rapidly deploying attention across time (or “sluggish attentional shifting”, see Hari & Renvall 2001), dyslexic readers had a general difficulty with the AB paradigm. To illustrate this point, four different patterns of AB performance are presented in Figure 3.1 . Specific difficulties with the AB may relate to deeper, longer, or deeper and longer effects (illustrated in Figure 3.1 , panels A to C). However, what is noted in the dyslexia literature is the fourth option, lower overall accuracy (see Figure 3.1 , panel D), reflecting a general difficulty with the dual-target paradigm. The current paper reports on a meta-analysis of the AB and dyslexia literature to explore this general difficulty.

The AB is considered to reflect a temporal limitation of attention. Most generally it is thought that a finite set of resources is required to consolidate a short-term representation of a target item for conscious report. While these resources are performing the consolidation of T1, the representation of T2 may decay and will not be available for conscious report (for reviews see Dux & Marois 2009; Martens & Wyble 2010). If this consolidation lasts longer, short-term representations waiting to be processed may decay; in order to update these representations for consolidation, regressive eye-movements made during reading may increase. This pattern of eye-movements has been noted in developmental dyslexia (Schneps et al. 2013). However, of the thirteen experiments published in this area, only three identify AB performance consistent with the notion of longer consolidation (or more rapid memory decay). These three experiments (Hari, Valta & Uutela 1999; Laasonen et al.

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2012; Lallier et al. 2010) report that the accuracy of T2 report in dyslexia reaches the same level of accuracy as that of typical readers at long inter-target intervals; however, the time required to reach this accuracy is longer for dyslexic than typical readers. The majority of the experiments do not demonstrate this interaction, with accuracy remaining lower in dyslexic readers across all inter-target intervals (Badcock, Hogben & Fletcher 2008; Buchholz & Aimola Davies 2007; Facoetti et al. 2008; Lallier, Donnadieu & Valdois 2010; McLean et al. 2010; Visser, Boden & Giaschi 2004). One anomalous experiment reports higher accuracy across all inter-target intervals in a group of dyslexic readers (Lacroix et al. 2005): this will be considered in the discussion. If the majority of the evidence points to a general deficit in the AB paradigm for dyslexic readers, what underpins the general deficit?

When McLean et al. (2010) added single-target RSVP accuracy as a covariate in their analyses, twenty per cent of the dual-target RSVP performance difference between dyslexic and typical readers was accounted for. When controlling for single-target accuracy, in combination with a continuous-performance measure (accounting for nine per cent of the between-group variation), the between-group effect was no longer significant. Simulating this sort of inattention factor produces patterns of data that mimic dyslexic group performance (Roach, Edwards & Hogben 2004; Stuart, McAnally & Castles 2001). A general factor common to single- and dual-target RSVP paradigms may account for the between group differences noted in the AB and also have much broader implications beyond RSVP paradigms.

In RSVP paradigms, the target serial position varies in time relative to the onset of the RSVP. Single-target RSVP performance has been shown to be sensitive to this temporal variation. In a series of experiments, Ariga and Yokosawa (2008)

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demonstrated that single-target RSVP accuracy increased as a function of foreperiod: that is, at longer intervals from the onset of the RSVP, accuracy was higher. There is a body of literature on the effects of temporal orienting, particularly with respect to reaction time (Niemi & Näätänen 1981; Nobre, Correa & Coull 2007), but temporal predictability and cueing have also been demonstrated to increase accuracy in the AB (predictability Badcock et al. 2013; cueing Martens & Johnson 2005). Recently, Tang, Badcock, and Visser (2013) demonstrated that some of the increases in dual-target RSVP performance that occur with accuracy are attributable to learning the temporal locations of targets. Given that temporal orienting has a role in both single- and dual-target RSVPs, it presents as a candidate explanation for differences between dyslexic and typical readers in RSVP performance.

Another element common to single- and dual-target RSVP paradigms is the engagement of ‘task-set’. Monsell proposed the concept of task-set with respect to task-switching paradigms (Monsell 1996; Rogers & Monsell 1995) whereby, even during a simple paradigm when the task was well known to the participants, a cognitive model of the task-requirements must be engaged to complete the task. In an RSVP paradigm the cognitive model would include searching for letters while ignoring numbers and reporting the identity of letters. Therefore, this concept is similar to the proposal that endogenous control of a ‘visual-filter’ is set up at the outset of the RSVP task (Di Lollo et al. 2005). Di Lollo et al. suggest that the AB is caused by a ‘temporal loss of control’ of the visual filter (but see Dell’Acqua et al. 2009; and also Olivers et al. 2011). It may be that the engagement of task-set accounts for some of the time-related increases in single-target accuracy noted previously (i.e. Ariga & Yokosawa 2008). Nevertheless, it is an additional candidate for the differences between dyslexic and typical readers noted in RSVP performance.

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The current investigation aimed to explore the basis of the significantly lower dual-target RSVP accuracy that has been reported in dyslexic versus typical reading groups. Based on evidence that single-target RSVP performance can account for the dual-target RSVP between-group difference, we examined variability in temporal and task-set related features via a meta-analysis of the AB literature on developmental dyslexia. Temporal variations as well as the task-set requirements were selected as common to both single- and dual-target RSVP tasks.

4. Method

Experiment Selection

Searching the Web of Science with the terms 'dyslexia attentional blink' returns 26 entries (4th of March 2014). When exclusions were made based on the comparison of dyslexic readers with respect to age-matched typical readers on a dual-target task requiring the identification and/or detection of two targets, 11 papers were relevant, two of which include two experiments (Buchholz & Aimola Davies 2007; Visser, Boden & Giaschi 2004). Badcock et al. (2011) report a reanalysis of their 2008 data. This was not included in the present meta-analysis because it is not an independent experiment. We excluded a further three experiments from the meta-analysis: 1) that of Lacroix et al. (2005), who report a group difference with a direction different to all other findings in the area (i.e. the dyslexic group had better performance than controls, this is discussed in section 7.1); 2) experiment 1 from Buchholz and Aimola Davies (2007), due to an anomalous effect-size (greater than 5 standard deviations from the mean of the included experiments: the condition/experiment in which the targets and distractors were numbers was excluded); 3) and the case study reported by

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Lallier, Donnadieu, Berger, and Valdois (2010), for which a between-group effect-size could not be computed.

The final number of experiments included was 9 (Badcock, Hogben & Fletcher 2008; Experiment 2, Buchholz & Aimola Davies 2007; Facoetti et al. 2008; Hari, Valta & Uutela 1999; Laasonen et al. 2012; Lallier, Donnadieu & Valdois 2010; McLean et al. 2010; Experiments 1 and 2, Visser, Boden & Giaschi 2004).

As is any field, a bias for the publication of significant results may mean that this meta-analysis overestimates the true between-group difference. The main objective of this analysis is to examine variables related to this between-group difference. Noteworthy relationships will need to be directly manipulated in dyslexia investigations prior to theoretical incorporation. This meta-analysis takes a further step than is typical, exploring the meta-analytic variable with respect to task-parameters. Whilst not all of the regular PRISMA checklist (Moher et al. 2009) are applicable, this can be found in the supplementary materials of this article.

4.1 Variable selection and calculation

Eighteen variables were selected in 6 categories: stimulus onset asynchrony, fixation duration, identity, RSVP position, temporal position and variability, and between-group effect-size.

4.1.1 Stimulus onset asynchrony (SOA)

SOA represents the time period between the onset of one stimulus and the next. This was determined from the method sections of the respective papers.

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4.1.2 *Fixation duration*

The presentation duration (in ms) of the RSVP fixation symbol varied between experiments. In three experiments (Laasonen et al. 2012; Visser, Boden & Giaschi 2004), the fixation remained on screen until a key press. These experiments were excluded on the basis that the presentation duration of the fixation could not be determined. Therefore, 6 experiments involving fixation duration were included in the analyses.

4.1.3 *Identity*

By ‘identity’ we refer to the number of possible identities of T1, T2, and distractors. For example, if T2 is a letter of the alphabet (e.g. letter X), and T1 as well as the distractors are any letter other than that used for T2, there is 1 possible identity for T2, 25 possible identities for T1, and 25 for the distractors. Note: T1 and the distractor identities both have 25 possibilities because there are randomly selected on each trial and the T1 identity for one trial will be the distractor identity on another trial. This example is for illustrative purposes, many studies omit ‘I’, ‘O’, and ‘Q’ due to the limited masking properties.

The Visser et al. (2004) and McLean et al. (2010) experiments included random-dot distractors with different ‘identities’ for each presentation. The precise number of identities is difficult to determine and would regardless be a clear outlier. Therefore these studies were excluded, leaving 6 experiments in the analyses involving distractor identity.

4.1.4 RSVP Positions

This refers to the number of possible positions within the RSVP of T1 and T2 relative to fixation, and the number of T2 positions relative to T1. For example, if T1 were presented at positions 6, 7, and 8 in the RSVP, the total number of positions would be 3. The number of T2 positions is calculated from the minimum T1 position plus the minimum inter-target intervals (ITIs or lag) through to the maximum T1 position plus the maximum ITI. For the current example, if T2 was presented at 12 ITIs immediately following T1, the minimum RSVP position would be 7 (6 + 1) and the maximum RSVP position would be 20 (8 + 12). Therefore there would be 14 possible RSVP positions for T2 relative to fixation. The number of T2 positions relative to T1 would simply be the number of ITIs: 12 in the current example.

In the case of Facoetti et al. (2008) where only two targets and accompanying masks were presented, possible RSVP positions corresponds to the number of temporal positions relative to fixation. It is worth noting that this 'skeletal' RSVP paradigm may produce more variable results at the electrophysiological level (see Craston, Wyble & Bowman 2006).

4.1.5 Temporal position and variability

Temporal position is defined as the presentation time (in ms) of T1 relative to fixation offset, T2 relative to fixation offset, and T2 relative to T1 onset. For example, if T1 is presented at in RSVP position 6, 7, and 8, and the stimulus onset asynchrony is 100 ms, this would correspond to 600 (minimum), 700, and 800 (maximum) ms. If T2 is presented at positions 1 to 12 following T1, this would correspond to 700 (min T1 + min T2 = 600 + 100) through to 2000 (max T1 + max T2 = 800 + 1200). These timings also include the period of time between fixation offset and the onset of the RSVP.

Temporal position variability was calculated by taking the difference between the minimum and maximum temporal positions. To follow the example, for T1, 800 – 600 = 200 ms; for T2, 2000 – 700 = 1300 ms. T2 temporal position variability relative to T1 was the difference between the minimum and maximum ITIs: 1200 – 100 = 1100 ms.

4.1.6 Between-group effect-size

The between-group effect-size was calculated in standard deviation units, Cohen’s d. In all but one case, Cohen’s d was derived from the ANOVA between-group effect statistics (F and degrees of freedom see http://www.lyonsmorris.com/ma1/index.cfm), depending on the availability of data in the published reports. Where the required data were not reported (i.e. Hari, Valta & Uutela 1999), an overall Cohen’s d was based upon the between-group differences, averaged across all inter-target intervals, determined using Data Thief (http://www.datathief.org/).

This method of Cohen's d calculation does not allow for an estimate of variance therefore we have not included a Forest plot as part of this meta-analysis. All data points for each study are included in the Supplementary Materials.

4.2 Not correcting for multiple comparisons

Pearson's product-moment or Spearman's *rho* (non-parametric comparisons) correlation were calculated to examine the relationships between the dependent measures in this paper. Most critical are 17 correlations examining whether the between-group effect-size is related to any of the other factors. There has been no correction for multiple comparisons in this instance. This decision has been made to reduce the risk of Type 2 errors and on the basis that relationships of note in the meta-analysis will need to be demonstrated empirically before they should be applied theoretically (see Cabin & Mitchell 2000, for a discussion on considering correcting for multiple comparisons).

5. Results

Descriptive statistics for the 18 parameters are presented in Table 5.1 (see Supplementary Materials for all data points from each experiment). Of importance are the normality tests: the SOA, T1 and T2 identity, number of T2 positions relative to T1, and the minimum temporal position of T2 relative to T1 parameters, were not normally distributed. Therefore, the relationship between each variable and effect-size (Cohen's d) was assessed using Spearman non-parametric correlations, as opposed to Pearson product-moment tests.

The correlation coefficients between the 18 parameters are presented in Table 5.2. Most critical is the bottom row in which correlations for the relationship of between-group effect-size to all other parameters are reported. There are four relationships worth drawing attention to. The first is between Fixation Duration and effect-size ($r = .95$, $p<0.01$), indicating that the longer the fixation symbol is on the screen, the greater the between-group difference. The second two are the negative correlations between T2 max time and effect-size ($r = -.68$, $p<0.05$) and T2 temporal variability within the RSVP and effect-size ($r = -.73$, $p<0.05$). These relationships indicate that the greater the temporal variability of T1 and T2 within the RSVP, the smaller the between-group difference. It is important to note that these variables are highly correlated themselves ($r = .99$, $p<0.01$). The fourth relationship of note is between

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SOA and effect-size (r = -.68, p>0.05). These are also negatively correlated indicating that the longer the SOA, the smaller the between-group difference. This relationship fails to reach significance but carries a large effect-size, and has a significant linear fit (see below) and has therefore been included. These relationships are presented in scatter plots, fitted with linear regression lines, in Figure 5.1; Fixation Duration, R^2 = .89, p <.01; T2 time max, R^2 = .46, p <.05; T2 time difference, R^2 = .53, p < .05; Stimulus Onset Asynchrony, R^2 = .46, p < .05.

Table 5.1

Parameter descriptive statistics and normality test statistics for the attentional blink experiments on developmental dyslexia (n = 9).

Section	Parameter	M (SD)	Median (IQR)	min	max	Shapiro-Wilk
2.1.1	SOA	106.9 (11)	100 (7)	100	133.3	0.70**
2.1.2	Fixation duration^	467 (258)	500 (0)	0	800	0.79
2.1.3	T1 id	11 (9)	8 (14)	2	24	0.81*
	T2 id	4 (3)	5 (5)	1	8	0.81*
	Distracter id^	14 (10)	14 (16)	1	24	0.89
2.14	T1 pos	6 (3)	5 (5)	2	11	0.89
	T2 pos	16 (10)	15 (13)	6	36	0.91
	T2 pos rel T1	7 (3)	6 (4)	4	12	0.80*
2.1.5	T1 time min in RVSP	661 (279)	600 (412)	225	958.5	0.88
	T1 time max in RSVP	1261 (622)	900 (940)	350	1999.5	0.85
	T1 time difference in RSVP	600 (357)	424 (628)	125	1066.4	0.87
	T2 time min in RVSP	802 (244)	700 (328)	425	1066.4	0.87
	T2 time max in RSVP	2420 (710)	2300 (1300)	1575	3465.8	0.92
	T2 time difference in RSVP	1619 (491)	1600 (850)	1000	2399.4	0.93
	T2 time min rel T1	141 (49)	116 (100)	100	213.2	0.77*
	T2 time max rel T1	1146 (267)	1200 (547)	800	1466.3	0.88
	T2 time difference rel T1	1005 (301)	1100 (604)	600	1333	0.87
2.1.6	Group Effect size (Cohen's d)	0.92 (0.23)	0.98 (0.19)	0.5454	1.295	0.92

Section = method description reference; ^ n = 6; SOA = Stimulus Onset Asynchrony; T1/T2 = first/second target; id = identity; pos = number of positions in RSVP; rel T1 = relative to T1 position or time; ** p < .01, * p < .05

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Table 5.2

Correlations coefficients between variables of the attentional blink experiments on developmental dyslexia (n = 9).

Experiment Parameter	1°	2^	3°	4°	5^	6	7	8°	9	10	11	12	13	14	15°	16	17
1. SOA°																	
2. Fixation Duration^	-.36																
3. T1 id°	-.01	-.43															
4. T2 id°	-.52	.64	-.29														
5. Distractor id^	.65	-.68	.81	-.84*													
6. T1 pos	.14	-.50	.80*	-.39	.72												
7. T2 pos	-.07	-.25	.64	-.27	-.06	.62											
8. T2 pos rel T1°	.34	-.70	.64	-.76*	.81	.85**	.78*										
9. T1 time min	.51	-.48	.44	-.93**	.84*	.50	.01	.71*									
10. T1 time max	.58	-.50	.48	-.88**	.85*	.58	.07	.69*	.97**								
11. T1 time difference	.79*	-.52	.40	-.79*	.86*	.61	.11	.69*	.91**	.98**							
12. T2 time min	.58	-.46	.48	-.88**	.84*	.54	.03	.69*	.99**	.99**	.95**						
13. T2 time max	.48	-.65	.54	-.93**	.93**	.59	.14	.73*	.94**	.93**	.88**	.93**					
14. T2 time difference	.48	-.73	.54	-.93**	.92**	.59	.19	.82**	.87**	.85**	.80*	.85**	.98**				
15. T2 time min rel T1°	.35	.43	-.11	.54	-.65	.08	-.06	-.24	-.48	-.36	.01	-.36	-.50	-.50			
16. T2 time max rel T1	.07	-.72	.43	-.42	.73	.22	.10	.19	.34	.22	.12	.26	.57	.69*	-.63		
17. T2 time difference rel T1	.09	-.75	.42	-.50	.80	.23	.07	.26	.42	.30	.18	.34	.63	.74*	-.73*	.99**	
18. Group effect-size (Cohen's d)	-.66	.95**	-.38	.58	-.78	-.45	-.17	-.48	-.49	-.58	-.63	-.51	-.68*	-.73*	.25	-.47	-.46

° non-normally distributed variable, Spearman tests were conducted for all comparisons; ^ n = 6; SOA = Stimulus Onset Asynchrony; T1/T2 = first/second target; id = identity; n pos = number of positions in RSVP; rel T1 = relative to T1 position or time; ** p < .01, * p < .05

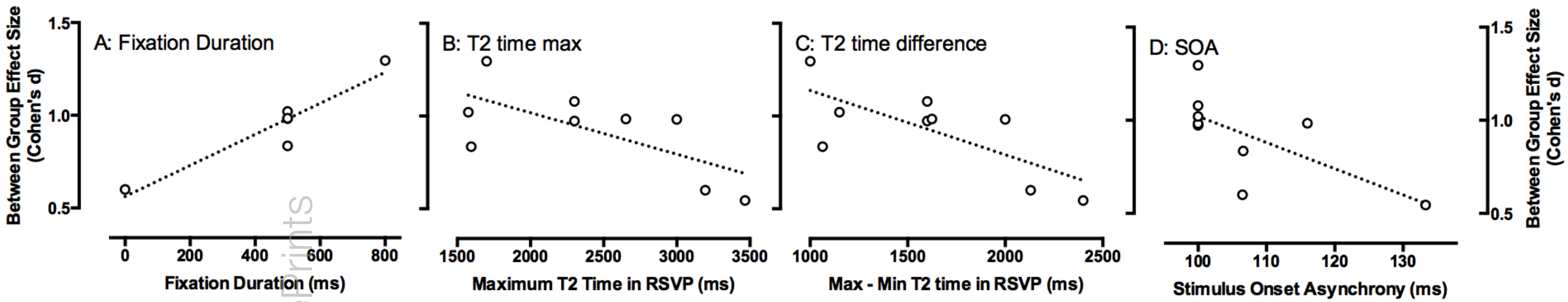

Figure 5.1 Scatter plots and linear regression fitted curves for the relationship between the between-group effect-size (Cohen's d, y-axis) and, from left, Fixation Duration (panel A; R^2 = .89, p <.01), T2 time max (B; R^2 = .46, p <.05), T2 time difference (C; R^2 = .53, p <.05), and Stimulus Onset Asynchrony (D; R^2 = .46, p <.05).

Please note, although the relationship between distracter identity and effect-size was large (r = -.78, p = .07), it was non-significant as was the linear fit (R^2 = .61, p = .07); therefore this was not flagged as part of the major discussion as the other four variables. In conjunction with this, distractor identity is heavily confounded with the maximum temporal position and temporal variability of the second target (r = .93 and r = .92, both p <.01). This is the case for a number of the variables and is mentioned in section 7.2.

6. Discussion

In a meta-analysis of attentional blink (AB) experiments focussed on developmental dyslexia, we examined whether the between-group effect-size was related to the variability of a series of presentation-related parameters. As noted by McLean et al. (2010), the clearest pattern in this literature is that performance of groups of individuals with dyslexia is poorer overall (see Figure 3.1 panel D); that is, statistically, there is a main effect, indicative of a general difficulty with the dual-target rapid serial visual presentation (RSVP) paradigm in dyslexia, rather than a specific AB effect. The results of the meta-analysis indicate four presentation-related variables were related to the between-group effect-size: fixation duration, maximum temporal position of T2 in the RSVP, variability of T2 temporal position in the RSVP, and the stimulus onset asynchrony (SOA). These have important implications for applications of the AB in specific populations and visual temporal attention in developmental dyslexia.

6.1 Fixation Duration

The longer the exposure duration of the fixation symbol, the greater the difference between-groups (r = .95, p<0.01). To be clear (as mentioned), three of the nine AB

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and dyslexia experiments included in the meta-analysis were excluded from the analysis of fixation duration because the fixation symbol remained onscreen until a key was pressed. Therefore, the finding is limited as it is based on six experiments, with fixation durations of 0, 500, and 800 ms. Nevertheless, given the strength of the relationship, it is worth further consideration[1].

The clearest explanation for a greater effect-size with longer fixation durations is group differences in cognitive preparation during fixation presentation. If dyslexia were associated with poor preparation, typical readers would be advantaged by greater preparation before the offset of the fixation symbol. Therefore, with no fixation symbol, typical readers would have a limited advantage due to preparation, and the difference between the groups would be small. Such a scenario would account for the data we observe here (see Figure 5.1). This could occur due to limited or slow preparation. But preparation of what?

One possibility with respect to preparation is *task-set*. Task-set is a cognitive model of the task requirements (Monsell 1996; Rogers & Monsell 1995). This is a similar concept to the visual filter which is implicated in selection theories of the AB (e.g. Di Lollo et al. 2005). For a task including two number targets in a series of black letter distractors, the task-set would involve ignoring letters and attending to two numbers. The task-set may also be influenced by goals. Ferlazzo et al. demonstrated that the AB could be mediated by varying the instructions to participants (Ferlazzo et al. 2007). With standard instructions, e.g., report the identity of two numbers, an AB effect was observed. However, with modified instructions consisting of a single goal,

[1] Please note, we have conducted two pilot studies with adults, unselected for reading ability, in which we manipulated fixation duration and find that this influences overall performance: shorter fixation corresponds with lower overall performance.

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e.g., report the sum of the numbers, the AB effect was not observed. Therefore it is likely that the task-set preparation time may be reduced for a single goal.

With respect to dyslexia, it may be that the preparation of task-set is slow, with dyslexic readers (as a group) taking more than the maximum fixation duration of 800 ms. It might be that the preparation of task-set is not initiated until the onset of the RSVP sequence in dyslexic reader (again, as a group). Although not manipulated in dyslexia, foreperiod – the time period before the presentation of T1 – has been shown to influence the AB in non-selected samples of adults, with reduced effects at longer, predictable, or cued foreperiods (longer and predictable, Badcock et al. 2013; cued, Martens & Johnson 2005). Therefore there seems to be an influence of the temporal orienting of attention (for a review see Nobre, Correa & Coull 2007) in the AB which may also be a component of task-set.

In summary, it may be slow or incomplete development of task-set during the fixation period that influences overall dual-target accuracy in developmental dyslexia. Further empirical data is needed to test this suggestion.

6.2 T2 temporal position and variability

The temporal position of T2 was related to between-group effect-size for the dyslexic and typical readers. The maximum temporal position of T2 ($r = -.68$, $p<0.05$) and the variability between the minimum and maximum temporal positions of T2 ($r = -.72$, $p<0.05$) were negatively related to effect-size. This indicates that the longer the temporal distance between fixation and the presentation of T2, as well as the greater the variability in temporal position of T2, the less the difference between-groups. These two variables are heavily confounded with each other ($r = .99$, $p<0.01$). One explanation for the pattern is temporal orienting.

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When attention can be directed to a particular point in time, decisions regarding a target are more accurate (again see Nobre, Correa & Coull 2007, for a revew). This has also been demonstrated in the AB. When Martens and Johnson (2005) cued the temporal location of targets within an RSVP sequence, the AB was reduced. Similar reductions were found when Badcock et al. (2013) individually tailored foreperiod and made it predictable between trials: relative to when the temporal location of T1 was randomly selected between 250 and 750 ms, the AB was reduced. Further to this, Tang, Badcock, and Visser (2013) demonstrated that practice in the AB actually increased expectations about the temporal locations of the targets. This suggests that with exposure to RSVP tasks, observers are learning about the temporal locations of the targets. Therefore, if time periods were longer and more variable, the predictability of temporal locations would be more difficult. Under these circumstances, it might be that the task is more challenging for both dyslexic and typical readers, reducing the difference between-groups. In this sense, to maximise the difference between-groups, short and easily predicted (i.e. minimal variability) time periods should be selected. In a re-analysis of earlier data, Badcock et al. (2011) demonstrated that practice effects in the AB differentiated between the dyslexic and typically reading groups: where differences were apparent in the first half the experiment, the dyslexic readers had poorer performance, but not in the second half of the experiment.

In summary, there is evidence in support of slower learning in the AB in dyslexic readers (Badcock, Hogben & Fletcher 2011). Additional evidence suggests the temporal locations are learned during the AB (Tang, Badcock & Visser 2013). In combination, this evidence offers an explanation for the reduced between-group effect for dyslexia and typical readers in the AB with longer and more variable T2 temporal

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locations. At longer and more variable T2 temporal locations, both groups have difficulties learning the temporal locations of the targets. At shorter and less variable T2 temporal locations, the dyslexic reading group has relatively more difficulty learning the temporal locations of the targets; therefore, the between group difference is due to enhanced performance in typical readers.

6.3 Stimulus Onset Asynchrony (SOA)

Longer SOAs were associated with smaller differences between the dyslexic and typical readers ($r = -.66$, $p>0.05$). Although large in magnitude, this effect failed to reach significance. One of the reasons for this is that the distribution was positively skewed and predominantly driven by a single experiment in which the SOA was 133 ms. Therefore, we do not wish to place too much emphasis on this result but we do want to raise it for future consideration.

Di Lollo, Hanson, and McIntyre (1983) observed that children with dyslexia showed evidence of slower processing rates under conditions of backward masking. Backward masking certainly plays a role in AB processing, although it may serve the function of bringing performance off ceiling (Jannati et al. 2012; Jannati, Spalek & Di Lollo 2011). The work of Di Lollo et al. (1983) has been considered in the dyslexia and AB research but it has been dealt with via comparisons in a single-target task, rather than adaptive method as Di Lollo et al. used. That is, if the groups do not differ on a single-target task, then the sensitivity is matched. With respect to single-target tasks, the statistics usually indicate that there is no difference between dyslexic and typical readers (Badcock, Hogben & Fletcher 2008; Buchholz & Aimola Davies 2007; Laasonen et al. 2012; Visser, Boden & Giaschi 2004), and therefore sensitivity differences can be dismissed as an explanation for dual-target task group differences.

Accuracy rates in these single-target tasks are at ceiling, most likely hiding any group differences. In fact, there is one study in which single-target performance was not at ceiling and the dyslexic readers were statistically poorer in the single-target task (McLean et al. 2010). Furthermore, when used as a covariate in the dual-target analysis, the group difference was no longer significant. In light of this evidence, future investigations should control for individual sensitivity to targets within the dual-target paradigms, if for no other reason than to ensure that ceiling effects do not influence results.

7. Further considerations

7.1 The Lacroix et al. anomalous result

There is one anomalous result in the AB and dyslexia literature. Lacroix et al. (2005) reported better overall performance in their group of children (15-years of age) with developmental dyslexia, relatively to typically reading peers. The above parameters (fixation duration, temporal locations of T2, and SOA) do not offer any insight into this finding, in fact, the fixation duration (800 ms) would predict the opposite effect in light of the above discussion. Two pieces of information may be relevant. The sample included children, and the stimuli (targets and distractors) were numbers. Buchholz and Aimola Davies (2007) presented a similar design in adults. As well as their results being in the typical direction (i.e. poorer performance in dyslexic readers), the effect-size was five standard deviations from the mean of all effect-sizes examined in this meta-analysis; recall that these results were excluded from the meta-analysis. Lallier et al. (2010) found the typical pattern of results when number targets were presented in number distractors in children (approximately 10-years of age), however, the task required identification of T1 and detection of T2 which was always the number zero. The other experiments involving children included random dot distractors (McLean et al. 2010; Visser, Boden & Giaschi 2004) or no distractors (Facoetti et al. 2008). Therefore, it seems that some combination of the sample age group, the target-distractor relationship, and task-set may have some bearing on this relationship.

As suggested by Lacroix et al. (2005), superior dual-target accuracy in the dyslexic group may be explained by development differences in the depth of target processing. Suppose the group with dyslexia have less detailed representations for numbers and the group with typical reading have more detailed representations for numbers. If greater resources were required to access the more detailed representations, the typical readers would exhibit poorer performance. This may change with development. As the retrieval of these representations becomes more automatic, the effect may revers, potentially as observed by Buchholz and Aimola Davies (2007) in an adult sample. Furthermore, if the adults with dyslexia were slower to access these representations they may also show greater interference from distractors from the same category. However, this does not fit with the other adult research with letters as targets and distractors (Badcock, Hogben & Fletcher 2008; Hari, Valta & Uutela 1999; Laasonen et al. 2012) or Lallier et al.'s (2010) findings.

One characteristic of these experiments is task-set: two involve the identification of two targets (Buchholz & Aimola Davies 2007; Lacroix et al. 2005), whereas the others involve the identification of T1 and the detection of an always known T2. This constitutes a 'task-switch' and has been associated with a cost which is independent of the AB effect (Potter et al. 1998). However, we are not aware that the difficultly of identification-identification (id-id) versus identification-detection (id-det) conditions have been assessed. It is the case that guessing T2 in an id-det paradigm would result in 50% accuracy, whereas it would be lower in an id-id paradigm[2]. Furthermore, practice effects in the AB suggest that repeated targets become easier to process due to acquired distinctiveness (Maki & Padmanabhan 1994); therefore, the id-det paradigm may be less difficult, especially over time. If this were the case, id-det paradigms may constitute easier task-sets, relative to id-id paradigms. Following these assumptions, results from id-det paradigms (specifically Lallier, Donnadieu & Valdois 2010) are difficult to compare with id-id paradigm (i.e. Buchholz & Aimola Davies 2007; Lacroix et al. 2005).

We are left with questions concerning the comparability of id-id and id-det paradigms as well as evidence from children and adults. Based on the current evidence we are unable to settle on a conclusion. It is likely that task-set has an important role and generalisation across samples at different developmental stages should be made cautiously. As mentioned with respect to SOA, individually tailoring SOA would overcome one of these difficulties. In the case of the Lacroix et al. (2005) evidence, it may have been that individuals in this particular dyslexic group required shorter SOAs on average relative to their age-matched peers to achieve equivalent levels of accuracy. Tailoring SOA would overcome difference in the speed of access to the target information, allowing for a comparison of the duration of this processing cost on T2. Some strategies for adjusting SOA have been reported (Badcock et al. 2006; Badcock et al. 2013).

[2] We thank Veronika Coltheart for this suggestion.

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7.2 Confounded variables

There were significant inter-correlations between the variables, which are due to the commonalities and differences between experiments. For example, the variables indexing the temporal location of the first and second targets were highly correlated, r-values greater than .8. Similarly, the number of distractor identities was significantly related to the maximum and variability of temporal positions of the second target ($r = .93$ and $r = .94$, both $p < .01$). With respect to the number of distracter identities, this was highly – though not significantly – correlated with the between-group effect-size ($r = -.74$, $p = .09$). This relationship also fits with an advantage for typical readers learning to ignore a small distractor set (see Maki & Padmanabhan 1994 for the role of distracter set in practice with the AB paradigm). However, the variables highlighted in the results and discussion sections are based on the strength and significance of relationships with between-group effect-size. Without direct experimental manipulation of these variables, it cannot be determined whether the highlighted variables are the critical factors. Therefore we have purposefully restricted the considerations of the relationship between the highlighted variables and reading mechanisms until such a relationship is demonstrated.

One suggestion arising from these confounds is that a common paradigm be adopted for AB and dyslexia research. Considering the limited reliance on literacy experience for shape-targets and random-dot distracters used by McLean et al. (2010) and Visser et al. (2004), this seems like a good starting place. Furthermore, this paradigm has also been used to evaluate the relationship between AB performance and typical reading (La Rocque & Visser 2009; McLean et al. 2009), so there is a growing body of evidence common to this target and distracter set related to reading.

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7.3 Subtypes of dyslexia

We have not been able to address the subtypes of dyslexia in this meta-analysis and we want to flag this as an important consideration for future research. McLean et al. (2010) examined their results with respect to non-word and irregular word reading independently but did not find a difference with respect to the between group relationship. La Rocque and Visser (2009) found a relationship between non-wording reading and AB magnitude, suggesting some role of phonological processing. However, this specifically related to a between group interaction rather than an overall main effect, therefore it is not clear what role phonological processing would have for the current set of variables. A critical step in pinning down the relevance of any variable in relationship to dyslexia, is pinning down which particular component of the reading process, and in turn which subtype, the variable is associated with.

7.4 The available evidence

This research is limited by the available evidence. The number of experiments published in the literature is small, and exclusory criteria reduced this to 9 (6 for some variables) in the current meta-analysis. The dataset is limited to published work which may be associated with biases with respect to the publication of significant effects. The results should be interpreted with these limitations in mind.

8. Summary and Conclusion

In this paper we report on a meta-analysis of published AB experiments conducted in developmental dyslexia. We examined the common occurrence of an overall between-group difference where dyslexic readers exhibit lower target reporting accuracy in relation to task parameters which varied between and within experiments. This between-group difference was related to fixation duration, maximum and variability of second target temporal location, and stimulus onset asynchrony. Future investigations should consider the development of task-set, temporal learning, and the influence of backward masking in the AB and dyslexia in order to best determine the relationship between reading and the AB, and whether it may be a potential tool for intervention.

9. Acknowledgements

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11. Supplementary Materials

Table 11.1

Data values for the 18 variables for each experiment on the attentional blink and dyslexia

Authors	Year	Experiment	SOA	Fixation Duration	T1 id	T2 id	Distractor id	T1 pos	T2 pos	T2 pos rel T1	T1 time min	T1 max time	T1 time difference	T2 time min	T2 max time	T2 time difference	T2 time min rel T1	T2 max time rel T1	T2 time difference rel T1	Group effect-size (Cohen's d)
Hari et al.	1999	1	106.5	0	24	1	24	10	21	12	958.5	1917	958.5	106.5	1278	1171.5	1065	3195	2130	0.60
Visser et al.	2004	1	100	key press	5	5	0	2	8	4	600	900	300	100	1400	1300	700	2300	1600	1.08
Visser et al.	2004	2	100	key press	5	5	0	2	8	4	600	900	300	100	1400	1300	700	2300	1600	0.97
Lacroix et al.	2005	1	100	800	10	10	10	5	12	8	500	900	400	100	800	700	600	1700	1100	-0.93
Buchholz & Aimola Davies	2007	1	100	800	8	8	8	5	11	4	500	900	400	200	800	600	700	1700	1000	1.30
Buchholz & Aimola Davies	2007	2	100	800	9	8	8	5	11	4	500	900	400	200	800	600	700	1700	1000	2.07
Badcock et al.	2008	1	100	500	19	1	19	11	23	12	900	1800	900	100	1200	1100	1000	3000	2000	0.98
Facoetti et al.	2008	1	100	500	8	8	1	6	36	6	225	350	125	200	1100	900	425	1575	1150	1.02
Lallier et al.	2010	1	116	500	2	1	9	3	15	7	912	1840	928	116	812	696	1028	2652	1624	0.98
Lallier et al.	2010	case	100	500	2	1	9	3	14	7	800	1840	1040	100	700	600	900	2540	1640	NA
McLean et al.	2010	1	106.6	500	4	6	0	3	6	4	318	742	424	213.2	852.8	639.6	531.2	1594.8	1063.6	0.84
Laasonen et al.	2012	1	133.3	key press	24	1	24	8	19	8	933.1	1999.5	1066.4	133.3	1466.3	1333	1066.4	3465.8	2399.4	0.55

SOA = Stimulus Onset Asynchrony; T1/T2 = first/second target; id = identity; n pos = number of positions in RSVP; rel T1 = relative to T1 position or time; ** $p < .01$, * $p < .05$

PRISMA 2009 Checklist

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	

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Section/topic	#	Checklist item	Reported on page #
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	

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