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The visual attentional blink reflects constraints on temporal visual processing, not just a lapse of visual memory

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Background: Most theories related to the attentional blink (AB), defined as the refractory period of 300 to 500 msecs following a conscious visual identification, during which a second detection task is impaired, argue that limitations of 'visual working memory' (VWM) underlie the phenomenon rather than suppression of attention. The current study examined the relationship between performance on an AB task and classical measures of visual and auditory memory and executive function (EF).

Methods: Fifty-one adult volunteers completed the AB task but only 27 of these also completed an extensive battery of traditional measures of short-term and working memory, processing speed and EF. Correlation and regression methods were used to analyse the data.

Results: Bivariate correlation showed a significant relationship between AB duration and non-verbal intelligence and processing speed. Multiple regression analysis demonstrated that four factors (non-verbal intelligence, letter-number sequencing, visual search and visuo-spatial recognition memory) explained 40 per cent of the variance, with better reasoning skills and letter-number sequencing associated with a shorter AB, and better visuo-spatial recognition memory associated with a longer AB.

Conclusion: The positive beta weight in the model for visuo-spatial recognition memory may reflect that the ability to later recall a target depends on its depth of encoding. On the other hand, the negative betas in the regression model for verbal intelligence and processing speed indicate that AB duration may be a potentially useful measure of temporal rate of visual processing. Finally, the lack of any relationship between the AB and executive function performance measures used suggests that the mechanism of the AB is primarily confined to early sensory processing and lower level working memory.

The term attentional blink (AB) was coined by Raymond, Shapiro and Arnell1 and describes the refractory period following the identification of a visual target (T1) within a rapid serial visual presentation (RSVP) stream of letter items.2 During this refractory period, ability to detect a second target (T2) is impaired for approximately 300 to 500 msecs.1,3 Predominant theories suggest that the AB occurs when the second target T2 appears before the processing of the first target T1 is complete. Thus, the AB is thought to be the result of temporal limitations on the conscious processing of visual information at the level of visual working memory (VWM).4–9 Later evidence has questioned whether the limitations resulting in the AB are the result of a modality-specific limitation, such as VWM, or whether they are the result of central limitations to the processing and storage of all information.10–15 A recent paper16 suggests that during the AB, there is a delay in the selection of targets for consolidation in short-term memory. Even though current modality-specific and amodal theories of the AB imply the involvement of visual and auditory working memory (WM), it remains to be shown whether traditionally-defined WM functions bear a relationship to the AB. Working memory has been defined as a combination of the moment-to-moment awareness and instant retrieval of information from a long-term store.17 From a more traditional cognitive perspective, Baddeley18,19 has further suggested that WM involves three main components: 1. a visuo-spatial sketchpad 2. a phonological loop 3. the central executive. The visuo-spatial sketchpad is thought to be a system for the brief storage, manipulation and retrieval of visual information, while the phonological loop is argued to have a greater involvement in verbal working memory tasks. Thus, if considered in terms of Baddeley's model, the most likely mechanism of the visual attentional blink involves the visual spatial sketchpad and possibly the central executive, which acts as a central desktop meditating and recalling information from either the visuospatial sketchpad or the phonological loop.18,19 A more dynamic theory of working memory has been suggested by Koch and Crick,20 who conceive of WM as a gate on information processing allowing an item or a small sequence of items into conscious awareness. They also argue that attention is critical to the creation of an object representation that can be held in working memory for some duration of time. They argue that if attention is not paid to a specific aspect of the visual scene, only a transient representation is formed of the information thereby increasing the likelihood of interference from following stimuli.20 It is this conceptualisation that bears the greatest resemblance to the suggested operation of WM in the AB. Specifically, the models of Chun and Potter4 and Vogel, Luck and Shapiro8 both suggest that a representation of the second target (T2) is created in the first stage of VWM but decays before stage two processing of the T1 item has been completed. Vogel, Luck and Shapiro8 go further than Chun and Potter4 in their definition to suggest that attention mechanisms are responsible for the transfer of information between stage 1 and 2 of VWM. What is not understood now is the degree of relationship between the AB and more traditional measures of working memory and visual processing. Within the neuropsychological literature, the most basic conceptualisation of WM has been operationally defined in terms of the auditory digit span and other more demanding tasks that measure the ability to store and manipulate streams of either auditory or visual information, as in the most commonly used intelligence test, the Weschler Adult Intelligence Scales (WAIS). Thus, in order to better understand the mechanisms involved in the AB task, it is essential to examine how it relates to existing conceptualisations of working memory functions, especially in view of a recent case report. The patient with a known short term memory difficulty as estimated by traditional tests such as the auditory digit span, showed lower overall target identifications but continued to display the AB refractory period, suggesting that the reliance on traditional conceptualisations of short-term memory/working memory21 in explaining the AB may be inadequate. Furthermore, given the utilisation of the AB task to examine visual attentional processing within clinical populations such as those with dyslexia22–25 and stroke-induced visual neglect,26–28 an examination of the relationship between the AB and more traditional neuropsychological functions is warranted. Thus, the aim of the current experiment was to examine the construct validity of the AB as a measure of the limitations on complex visual processing, by comparing performance on the AB task with commonly used measures of WM function. We also compared the performance on the AB task with performance on a number of commonly used measures of executive function (EF). In this case, executive functioning has been operationally defined as a process measured by tasks, which require a sequence of higher order behaviours (such as the co-ordination of information, planning and acquisition of skills) rather than the simple retention and manipulation of information involved in the backwards digit span task. These measures provide a discriminant measure, with which to compare the AB. That is, while it is theoretically predicted that the AB may relate to working memory and other visual-spatial processes, it is unlikely that relationship would be observed with such general functions as executive processes, as the AB paradigm can be considered more in terms of its requirements for sustained visual attention rather than complex memory encoding. The AB paradigm requires sustained visual attention during the rapid, very transient presentation of a stream of objects but requires selection of the two targets only for identification and encoding of only the first target with all the others being vetoed.

METHODS

The protocol for the research project conforms to the provisions of the Declaration of Helsinki (as revised in Edinburgh 2000). Ethical approval for the collection of data was obtained through the La Trobe University Human Ethics Committee and informed consent was obtained from all participants. Fifty-one adult volunteers aged between 19 and 39 years (mean: 21.2 years) were verbally screened for existing learning or neuropsychological difficulties prior to participation in the experiment. All participants had normal or corrected to normal visual acuity. As testing took several hours to complete, full data are available for only 27 participants, although all completed the attentional blink test and a number of other tests from the battery.

Attentional blink Sequences of 50 black lower-case letters (randomly selected from the letters A to W without the letter I) were presented on a grey background at a single spatial location on iMac computer monitors. Letters subtended approximately 1.5 × 2.0 degrees (height × width) at the viewing distance of 57 cm and were presented at a rate of 11.7 items per second. In each sequence a red letter, the first target item (T1), was presented randomly between positions 6 and 10 in the RSVP stream. In 75 per cent of trials the second target (T2—a black letter X), was presented within the stream of letters following the target letter (Figure 1).

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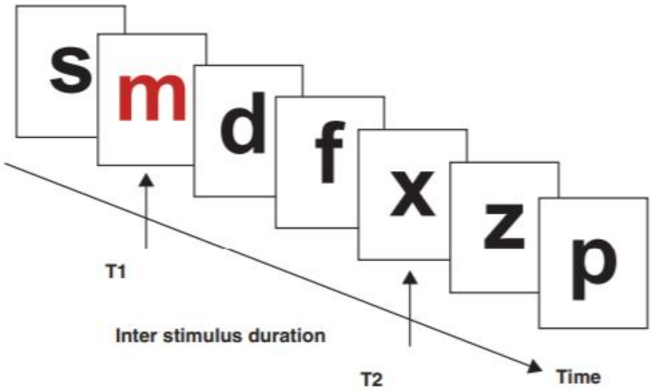

Figure 1. Cartoon illustrating the sequence of black lower case letters presented as a rapid series of visual presentations (RSVP) with a presentation rate of 11.7 letters per second used for the single detection and AB tests. The RSVP used a red letter as the first target T1 and a letter X as the second target T2. The duration of the attentional blink (AB) was calculated as the time taken to recover to the 80 per cent correct T2 detection performance (a level attained in training trials for all individuals).

In the remaining 25 per cent of trials (randomly interleaved) no T2 was presented (T2 absent trials). To calculate a score for this test, data for each participant were examined individually and the AB duration was estimated as the inter-stimulus duration at which T2 detection for a given participant recovered to 80 per cent accuracy.

Working memory: digit span subtest from the Weschler Adult Intelligence Scale

The auditory digit span subtest of the most commonly used adult intelligence scale, the Weschler Adult Intelligence Scale (WAIS-III), was administered in accordance with the standardised procedure.29 This requires verbal recall of increasing sequences of digits verbally presented by the experimenter at a rate of one digit per second. Both the forwards and backwards (where the order of recall is the reverse of administration) methods were used to establish the overall score and individual subscale scores. The test was terminated following two consecutive errors at a particular trial length. The forwards method of the digit span has traditionally been used to measure the capacity of verbal short-term memory. The backwards method of administration is thought to involve more extensive mechanisms of working memory, given the need to manipulate information to reverse the verbal sequence.

Working memory: letter number sequencing subtest from the WAIS III

Similar to the digit span, the letter number sequencing task29 involved verbally presented sequences of mixed letters and numbers read out by the experimenter at a rate of one per second to a participant who was then asked to report first the letters in alphabetical order followed by the numbers in numerical order. Following successful performance, trial length increased until two consecutive errors occurred. Like the digit span backwards, the letter number sequencing task has been assumed to require the functions of working memory, however, it is likely to place a greater load on WM than the digit span task due to the need to separately encode, categorise and store both the letter and number sequences.

Executive function: Wisconsin Card Sort Test (WCST)

A computer-based version of the WCST, the most common test of intellectual flexibility, was used. Participants are required to sort cards into piles on the basis of changing criteria. The sorting required may be on the basis of the colour, shape or number of elements on the card. The only feedback given to the participant is an indication 'correct' or 'incorrect' following each sorting decision. Thus, participants are required to adapt their sorting behaviour to changes in the sorting rule on the basis of trial-by-trial feedback. Total errors were recorded automatically by the computer program. Traditionally, the WCST has been used in the assessment of cognitive flexibility in brain-damaged participants. Importantly, the WCST has been shown to suffer ceiling effects in its use in neurologically intact participants.30

Executive function: Austin Maze (AM)

Austin Maze performance has traditionally been considered to reflect executive function performance and has also been shown to relate to some measures of visual spatial memory ability such as the VisuoSpatial Memory Task described below.30 Participants are required to push buttons arranged in a 15 × 15 array and to determine a correct path beginning at the start point and leading to the opposing corner via a process of trial and error. A red or green light indicates errors or success following each button press. Participants repeated the entire path 10 times and the total errors across all 10 trials were recorded.

Visuo-spatial: recognition and placement memory

This task31 was employed in the current study to measure the ability both to encode and recall abstract visual shapes, and to provide a measure of memory for spatial organisation. Participants viewed the arrangement of seven abstract shapes arranged on a 6 × 4 matrix for 10 seconds. The shapes were removed and the participant was asked to select the same seven shapes when presented randomly among eight other distracter items. The participant was then asked to arrange the abstract shapes on the display matrix in the same lay-out as originally presented. Five trials of the same spatial arrangement were conducted initially and a delayed recall trial was conducted after 30 minutes. Measures of the total recognition memory (VSM—recognition) and the correct placement of items (VSM—placement) across all trials were recorded.31

Visuo-spatial: symbol search (SS)

Taken from the WAIS-III, the symbol search task is a pen and paper test requiring the participant to visually search for either of two target items, presented at the left of the page, among a short sequence of spatially arrayed distracters and is broadly considered to measure general processing speed. Participants are required to circle either 'yes' or 'no', depending on whether one of the targets is present. Participants are told to complete as many as possible within two minutes and to work as quickly as possible without making errors. The total number of correct responses within the two minutes is recorded.

Non-verbal intelligence: Raven's Progressive Matrices (RPM)

The RPM is a test of non-verbal problemsolving ability. Participants are presented with an incomplete visual pattern and a number of options for the completion of the pattern. Participants were asked to complete all matrices within 20 minutes. This test has often been used in the existing literature and has been shown to relate highly to other measures of intelligence.32

Procedure

All tests were administered to participants in a random order at various times of day to control both order and time of day effects. For the attentional blink task administration, participants were initially trained to recognise the T1 and T2 items at a performance level of at least 80 per cent correct. Following this, participants were advised that for the AB task, not all trials would contain a T2 item. The single task control and dual task (AB) tests were administered in random order. At the completion of testing and scoring of performance, data were entered into a central spreadsheet for analysis.

RESULTS

Data from all tests were collated prior to the analysis of correlations between the different tests. The results obtained for the AB task were compiled first in order to calculate individual parameters prior to further analysis.

Data screening

Results from the AB test were examined to ensure that the overall refractory period obtained from the task was consistent with previous knowledge of the AB function. Figure 2 shows the average proportion of correct T2 detections plotted as a function of post-T1 target presentation time for single task controls and dual task trials in all cases where T1 was correctly identified.

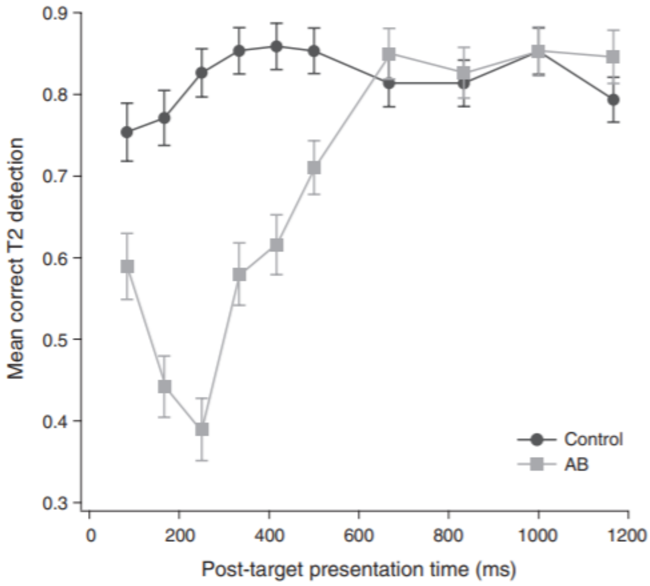

Figure 2. Graph of mean correct target T2 detection as a function of post-target T1 presentation time showing the attentional blink (AB) for dual task trials compared with single task control trials (n = 27).

The collated results presented in Figure 2 show a distinctive attentional blink effect for this sample group. There was a significant deficit in mean correct T2 detection in AB trials in the first 200 msecs. Performance then proceeded to recover to the single task performance level at approximately 600 msecs posttarget presentation time. Similar curves were created for each participant and specific summary statistics were derived from each. The post-target presentation times at which the performance returned to 80 per cent accuracy were calculated for each individual.

Correlation between neuropsychological tests

Visual inspection of bivariate scatter plots supported the assumption of linearity for all situations. Thus, data transformations were not required prior to the analysis of correlations. Table 1 presents the correlations for the same data set following the removal of outliers on both of the two AB recovery variables. Data outside two standard deviations from the mean on either AB recovery to single detection performance (AB-Single) or to 80 per cent T2 detection (AB—80 per cent) were excluded from this analysis. This resulted in the exclusion of three participants from the sample resulting in a final sample size of 24. Table 1 shows the Pearson correlation coefficient values for the relationship between performance on the neuropsychological tests employed in the current study. In the interests of parsimony, only the significant correlation coefficients will be presented. Interestingly, the Wisconsin Card Sort Test did not show a significant correlation with any of the other measures. Table 1 indicates that the AB duration shows a significant relationship with the time-limited Symbol Search task.

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	Variables	Correlation coefficient (r)
SHORT-TERM MEMORY		
Digit span(F)	Digit span (B)	0.618**
Digit span (F)	Letter number sequencing	0.544**
Digit span (B)	Letter number sequencing	0.423**
Digit span (B)	Symbol search	0.406*
DS total	Letter number sequencing	0.543**
DS total	Symbol search	0.415*
EXECUTIVE FUNCTION		
Austin maze (T)	Visual spatial memory—placement	-0.474*
Austin maze (T)	Letter number sequencing	-0.460*
Austin maze (T)	Symbol search	-0.549*
Austin maze (T)	Ravens total	-0.566*
NON-VERBAL INTELLIGENCE		
Ravens total	Visual spatial memory—recognition	0.545**
Ravens total	Visual spatial memory—placement	0.506**
ATTENTIONAL BLINK		
AB: single	Ravens total	0.410*
AB: single	Symbol search	0.433*

* $p < 0.05$, ** $p < 0.01$

Table 1. Pearson correlation coefficients showing the degree and direction of significant relationships between variables (following removal of outliers)

This relationship resembles that with the Raven's Progressive Matrices, as better performance on the symbol search task seems to be associated with a longer AB. Again, the Austin Maze test significantly related to performance on a number of visual spatial and short-term memory functions. Interestingly, the Wisconsin Card Sort Test again showed no significant relationship with any of the other tests, however, visual inspection of the WCST data indicated that a ceiling effect was involved in the testing, as very few participants made many errors. To further examine the covariation between different variables, backward multiple regression analysis was conducted. While we recognise the low power of this technique when applied to small sample sizes, we argue that due to the exploratory nature of the current study, a higher type 1 error rate ($\alpha = 0.1$) is acceptable statistical practice to increase the overall power of the analysis. Based on a sample of 24 participants and eight predictors, the overall power of the analysis was 0.2495 based on a small effect size. When calculated using the obtained multiple correlation coefficient of 0.402, the calculated power of the analysis was 0.74. The results of the multiple regression analysis are presented in Table 2.

Variables in model	Beta	Adjusted R^2	DF	F value	P value
RPM raw score	-0.609	0.408	4,22	5.485	0.003
Letter number seq.	-0.336				
Symbol search	0.284				
VSM recognition	0.685				

Table 2. Backwards multiple regression for the prediction of AB duration

Table 2 shows that following the removal of variables that did not contribute to the prediction equation, only four variables remained in the model. Overall, the combination of the four variables explains approximately 40 per cent of the variance in AB duration ($R2 = 0.408$). Interestingly the regression analysis showed greater relationships between the AB and other variables than was observed based on bivariate correlations, suggesting that reliance on only bivariate correlations may be misleading. Importantly, examination of the standardised regression coefficients, indicating the direction of relationship, showed a negative association between AB duration and scores for RPM and Letter Number sequencing (LNS). That is, higher scores are associated with a shorter AB duration. Conversely, higher scores on both the Symbol Search and VSM Recognition tasks were associated with longer AB duration. Not surprisingly, the Placement component of the Visual Spatial Memory Task did not show any relationship with the AB in any analyses.

DISCUSSION

The results of the current experiment showed clear evidence of the attentional blink effect as expected on the basis of previous literature.1,4,33,34 Analysis of the bivariate correlation coefficients showed relationships between the AB duration, the RPM and SS as a measure of general processing performance but no significant relationship with traditionally accepted measures of working memory. In both RPM and SS, a positive correlation was observed, indicating that the constraints on visual target selection and visual processing speed were associated with longer AB duration. Thus, these results are counter intuitive to the suggestion that a shorter AB duration would be related to better performance on other measures of visual problem solving and processing speed. Analysis of the full data set using the technique of multiple regression showed that both the RPM and SS tasks along with LNS and VSM Recognition remained significant predictors of AB duration. While both the RPM and LNS tasks, which both require storage and manipulation of visual or auditory information, showed a negative relationship with AB, the SS and VSM recognition tasks, which both require accurate local attention to spatial details prior to embedding in memory, showed a positive relationship. The finding of an association between length of the AB and tasks requiring the encoding of salient information is not entirely surprising, as it is highly likely that in-depth encoding plays some role in the duration of the AB, particularly in naive observers. The difficulty of interpretation comes from the fact that the positive beta value suggests that better performance on the VSM recognition task is actually predictive of a longer AB duration, suggesting that the more accurately one encodes individual distinct visual items, the more likely they are to require a longer duration to encode T1 and hence a longer AB. That is, the more detailed the visual spatial memory encoding, the greater the likelihood of the participant taking a longer time to consciously encode single individual letters. Similarly, the relationship observed between the AB and the Symbol Search task, where actual performance was inversely related, could also be considered as counter intuitive, if both tasks are viewed in terms of the need for visual search. Two major differences in the tasks may lead to the involvement of different mechanisms. First, while the AB is a rapid temporal processing task, the SS search task involves attention and the slower processing of a small spatial array and little need to encode individual items into memory, as they remain present throughout the trial. Second, while the AB task involves attending to rapidly presented, well-known stimuli and the rejection of distracting information, the SS tasks involve the encoding and identification of novel/abstract forms. Thus, the current results may be indicative of a trade-off between the ability to rapidly screen well known information and the ability to adequately encode and recall complicated novel visual patterns. It is possible that participants, who take longer to encode new information, actually form more lasting permanent representations of the information and thus, are better able to recall the items at a later time. Those participants who show a short duration for the AB task may rely more on a screening procedure, whereby the global perception of the familiar nature of the letter forms, rather than encoding each letter, and are therefore able to focus more on the dual screening aspect of the task involved. While such a hypothesis is speculative at best, it is consistent with the finding of an extended AB in situations where the complexity of items in the RSVP stream and thus, the number of salient details to be encoded is increased.2,7,12,34–36 A greater number of salient details would also argue for a longer AB as it is well-established that conscious attention is serial in nature. One finding that was unexpected in the analysis of multiple regression was the change in relationship with the Raven's Progressive matrices. When examined using bi-variate correlations, the RPM showed a positive relationship with the AB, suggesting an association between higher RPM score and a longer AB, however, once the pattern of relationship was examined in conjunction with the other measures via multiple regression, the RPM remained as a significant predictor of AB duration and showed a negative Beta value, suggesting that higher RPM scores relate to a shorter AB duration. The basis of this relationship may be due to a general factor of non-verbal processing ability, as measured by the RPM task, being involved in the AB. Furthermore, the rapid and demanding nature of the AB task may be easier for participants with a higher non-verbal problem solving ability than for other participants. A speculative suggestion is that the ability to perform the pattern completion involved in the RPM task may relate to the ability to hold visual information in working memory and to manipulate that information to test alternative solutions. Thus, a similar role for working memory may be implicated in both tasks. Perhaps, one of the more important findings is that the auditory LN Sequencing task remained as a significant predictor of the AB duration, despite the fact that performance on the auditory digit span tasks did not. This seems to implicate all general temporal limitations on attention, as an important constraint on the processing of information. More specifically, our results would support the suggestion that the AB is related to the processing of complex information in a time critical context rather than the simple recall of stored information. In particular, as the LN sequencing task was presented auditorally, the current results lend support to the suggestion that the AB may involve central limitations to conscious awareness10,11,13,37–39 rather than as the result of the limitations of a modality specific STM as has often been proposed previously.1,4,5,7,34,40,41 Not unexpectedly, the AB did not show any significant relationship with any traditional measures of executive function. It is likely that the high level planning and co-ordination involved in tasks, such as the Austin Maze (AM) and WCST, occur at cognitive levels above those related to viewing and vetoing rapidly presented information as occurs in the AB. Furthermore, the untimed nature of the attention shifting involved in the WCST task probably relies on mechanisms different from those involved in the rapid, temporally limited shifts of attention in the AB. These results could be considered to support the hypothesis that the visual AB relates to the visual loop of the WM, in tasks that merely require attention to, but not manipulation of, a large amount of rapidly presented information and which do not require complex decision-making and planning. Importantly, the correlations observed for the Austin Maze score would support the suggestion that the AM is related more to untimed visuo-spatial and decisionmaking Working Memory processes than to the processing of rapidly presented information.30 Similarly, the moderate correlations observed between the forwards and backwards methods of the auditory digit span and the relationship between the DS tests and the LNS task are also consistent with existing literature.42,43 Overall, the results of the current study support theories of the AB that implicate the involvement of low-level attentional working memory functions and separate them from the more complex executive function tests. Further examination of the relationship between the AB and other tests investigating the rate of visual processing is warranted. The current study has shown that the combination of factors included here (RPM, LN, SS, VSMrecognition) account for approximately 40 per cent of the variance in AB duration. It is also critical to examine whether the AB does, in fact, arise from modality specific or central limitations to visual processing. The evidence provided for the relationship between the AB and the LN Sequencing Task would suggest that central limitations on working memory may be involved in both tasks rather than modality specific processes. Further clarification of the relationship between the AB and other cognitive functions is critical, given the use of the AB task in clinical populations as diverse as children and adults with dyslexia, adolescents with specific language impairments and schizophrenics. The AB provides a novel method for the examination of temporal limitations on attention in visual processing and the rapid operation of low level working memory functioning. Furthermore, given the sensitivity of the AB, if it is also found to be reliable, it will be likely to provide a useful tool in screening of rapid visual processing speed and encoding into visual memory.

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