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ORIGINAL ARTICLE

Attentional blink magnitude is predicted by the ability to keep irrelevant material out of working memory

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Abstract Participants have difficulty in reporting the second of two masked targets if the second target is presented within 500 ms of the first target—an attentional blink (AB). Individual participants differ in the magnitude of their AB. The present study employed an individual differences design and two visual working memory tasks to examine whether visual working memory capacity and/or the ability to exclude irrelevant information from visual working memory (working memory filtering efficiency) could predict individual differences in the AB. Visual working memory capacity was positively related to filtering efficiency, but did not predict AB magnitude. However, the degree to which irrelevant stimuli were admitted into visual working memory (i.e., poor filtering efficiency) was positively correlated with AB magnitude over and above visual working memory capacity. Good filtering efficiency may benefit the AB by not allowing irrelevant RSVP distractors to gain access to working memory.

Introduction

When two targets must be reported from a rapid serial visual presentation (RSVP) stream, report of the second target (T2) is impaired if it is presented within approximately 500 ms of the first target (T1), however, T2 performance is unimpaired at longer target separations or when T1 is presented but can be ignored (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). This pattern of performance is known as the attentional blink (AB; Raymond et al., 1992). Several theoretical models of the AB suggest that limitations on working memory (WM) underlie the AB (e.g., Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998; Shapiro, Raymond, & Arnell, 1994; Wyble, Bowman, & Nieuwenstein, 2009). For example, Shapiro et al. (1994) posited a WM interference model where the AB was thought to result from interference in an overcrowded WM that held not only T1 and T2, but also distractors that were salient and/or closely trailed the targets. T2 was thought to be lost in the overcrowded WM during T1 processing. Chun and Potter (1995) and Jolicoeur and Dell'Acqua (1998) posit that the AB results from a bottleneck on consolidating items into WM. Chun and Potter (1995) posit a first stage of processing where relevant stimulus features are analyzed, high-level visual representations are created, and meaning is activated, all without processing limitations. In contrast, the second stage where items are consciously identified and encoded into WM requires time and attentional resources. Chun and Potter (1995) suggested that the AB was due to a bottleneck on stage 2 processing where T2's stage 1 representation must wait if it arrives while T1 is still undergoing stage 2 processing. While waiting, T2's stage 1 representation decays or is overwritten by trailing stimuli such that it cannot be processed in stage 2 and brought into awareness.

Does WM influence the AB?

If some models of the AB implicate WM limitations, is there evidence that WM performance can influence the AB? Executive control of WM has been shown to modulate the AB, while simple WM capacity does not appear to be influential. For example, Akyürek and Hommel (2005, 2006) showed that when participants were asked to

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maintain a memory load while performing a standard AB task, neither the number of items maintained in WM nor their similarity to targets or distractors in the RSVP stream influenced the magnitude of the AB. However, Akyürek, Hommel, and Jolicoeur (2007) showed that the contents of WM did influence the AB if those contents were actively examined during the AB task (asking participants to report whether T1 was or was not a member of the memory set). Under these conditions, the magnitude of the AB increased as the size of the memory set increased. Together these results provide evidence that simply maintaining a working memory load does not modulate the AB, but active search of the memory set does modulate the AB.

The above results fit nicely with those from individual differences studies of the AB and WM. Colzato, Spape, Pannebakker, and Hommel (2007) measured individual differences in WM (assessed using the Operation Span or OSPAN task, Turner & Engle, 1989), and in fluid intelligence (as assessed using Ravens Standard Progressive Matrices; Raven, Raven, & Court, 2003). Colzato et al. (2007) observed that individuals with higher WM scores tended to have smaller ABs, even after controlling for fluid intelligence scores (but see Martens & Johnson, 2009). Individual scores on the Ravens SPM positively correlated with overall T2 accuracy, but did not predict AB magnitude. Colzato et al. proposed that a higher operation span may reflect more control over WM executive functions, resulting in smaller AB magnitudes.

WM is comprised of a storage capacity component and an executive control component, with the latter acting to direct attentional and memory processes (Baddeley, 1996). Colzato et al. (2007) observed that individual differences in WM ability predicted individual differences in AB magnitude, but it was unclear whether storage capacity, executive control, or both, accounted for these differences. Arnell, Stokes, MacLean, and Gicante (2010) found that forward digit span, backward digit span, and the variability shared between the two digit span tasks and the OSPAN were unrelated to AB magnitude. However, the variability that the OSPAN did not share with the two digit span tasks was significantly related to the magnitude of an individual's AB, where higher OSPAN scores were associated with smaller AB magnitudes. Given that, the digit span tasks largely measure WM capacity, the results suggest that individual differences in the executive control component of WM, but not individual differences in WM capacity contribute to individual variation in AB magnitude. Although it was unclear exactly what executive control aspect of WM was related to the AB, Arnell et al. (2010) suggested that individual differences in WM may predict AB magnitude because individuals with good executive control of WM may select only the relevant target stimuli during RSVP, better ignoring irrelevant RSVP distractors, and allowing them to be less effective competitors for WM resources.

Several newer models of the AB have emphasized the importance of executive cognitive control and highlighted the role of distractor processing (e.g., Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Olivers and Meeter, 2008; Taatgen, Juvina, Schipper, Borst, & Martens, 2009). For example, with the temporary loss of control (TLC) model, Di Lollo et al. suggest that search for targets is controlled by a top-down input filter set to the target defining feature(s). Once attention is deployed to T1 for its report, less attention is available to control the input settings of the filter and the filter adopts settings based on bottom-up, exogenous control, using information from the T1 + 1 item. The filter will not be reset until T1 processing has been completed. If T2 is presented at short lags, unless it matches the new exogenous filter settings, it will be bypassed by the filter, and will not be attended. Thus, this model suggests that the attentional limits imposed by T1 lead to a loss of cognitive control over the filter.

Following from Raymond et al. (1992), the Boost and Bounce model of Olivers and Meeter (2008) also emphasizes the role of the distractor immediately trialing T1. According to this model, once detected, T1 is assumed to generate a transient boost of attention to facilitate its encoding. However, the appearance of the T1 + 1 item, which also benefits from this boost, initiates a temporary suppression (the bounce) that restricts subsequent items from being encoded, leading to poor T2 accuracy at short lags. The role of cognitive control and distractor processing is also highlighted in the threaded cognition model of Taatgen et al. (2009). These authors propose that the AB results from "an overexertion of cognitive control" when distractors are presented during T1 consolidation into WM. Notice that the TLC model, the Boost and Bounce model, and the threaded cognition model suggest that the distractors trailing T1 play a key role in initiating the AB and that appropriately modulating cognitive control to minimize distractor impact while still allowing target processing is important for reducing the AB. Individuals may differ in the degree to which these distractors can be effectively ignored or inhibited. If this is the case, then individual differences in the ability to keep irrelevant distractors out of WM may predict individual differences in AB magnitude.

Indeed, there is some evidence that individuals who show reduced processing of RSVP distractors have smaller ABs. Martens, Munneke, Smid, and Johnson (2006) observed electrophysiological brain recordings for 'blinkers' (individuals who show an expected AB pattern) and 'non-blinkers' (individuals who fail to show an AB) while they completed an RSVP task. They found that non-blinkers displayed a large, discrete, earlier P3 component to T1. They also found that non-blinkers had less activation to distractors and greater differences in the frontal selection positivity, such that non-blinkers showed larger differences in neural activation between targets and distractors. Non-blinkers appeared to be more selective in their processing of RSVP stimuli, illustrating an increased ability to extract only target information from the stream of letters. This heightened selectivity of target stimuli would result in reduced competition and interference from distracters, leaving more attentional resources available for T2 processing. Dux and Marois (2008) also concluded that greater processing of RSVP distractors was associated with larger ABs. They recently reported that individuals who showed greater identity priming of T2 by a distractor earlier in the RSVP stream (suggesting less inhibition of the distractor), had greater ABs and lower T1 accuracy than individuals who showed less identity priming (presumably due to greater inhibition of distractors). Martens and Valchev (2009) have also provided evidence that those prone to larger ABs engage in greater processing of irrelevant distractors. They observed that blinkers produced a larger AB when visual distractors were presented in irrelevant locations on the computer screen relative to when the distractors were absent, while the presence/absence of distractors had no influence on the AB magnitude of non-blinkers.

Visual WM filtering efficiency

If individuals vary in how selective they are about admitting items into WM, then we should be able to: (1) measure an individual's ability to select only relevant items for entrance into WM during a visual WM task, (2) quantify the efficiency of their filtering, and (3) relate it to their AB magnitude. The first two of these goals have been accomplished by Vogel, McCollough, and Machizawa (2005) using event-related brain potentials (ERPs) and a visual WM task. The capacity of visual WM (WM for visual material that is being held as a visual representation as opposed to recoded as a verbal representation) is highly limited, with the ability to hold only three to four visual items at a given time (e.g., Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). Vogel, Luck, and their colleagues (e.g., Vogel et al., 2001, 2005) have investigated the capacity of visual WM by presenting a brief array of variously colored boxes. Following a retention interval of about 1-s, participants are then shown a test array that is either the same as the original array, or where one of the boxes has changed color. Results with this task consistently show that typical visual WM capacity (known as K) ranges from three to four items (Vogel et al., 2001).

In the above studies, all of the display items were potentially relevant. Vogel et al. (2005) showed that individuals vary in the extent to which items that are known to be irrelevant can be kept out of WM (i.e., in the efficiency of their visual WM filtering), and that the efficiency of this filtering can be estimated by a filtering efficiency ratio. Vogel et al. (2005) measured an ERP component that represents the encoding and maintenance of stimuli in visual WM. This contralateral delay activity (CDA) component is present contralateral to the visual hemifield in which the to-be-attended stimulus appears, and its amplitude increases as a function of the number of stimuli represented in WM, with an asymptotic limit reached at each individual's WM capacity. Vogel et al. (2005) used the CDA component to study individual differences in controlling access to visual WM. They cued participants to either hemifield and presented a memory array of: (1) two red, (2) four red, or (3) two red and two blue randomly oriented rectangles. Participants were instructed to focus only on the red rectangles. After a brief retention interval, participants were shown a test array and were required to make a judgment as to whether or not there was a change in orientation in one of the red rectangles. An increase in CDA amplitude was observed for the arrays of four red rectangles compared to the arrays of two red rectangles. The filtering efficiency, or how well individuals were able to prevent distracters from entering WM and taking up valuable space, was measured by observing the relative amplitude of the 2 red + 2 blue condition. Perfect filterers displayed a CDA amplitude in the 2 red + 2 blue condition similar to that of the 2 red condition, whereas poor filterers showed an amplitude characteristic of the 4 red condition. Vogel, et al. (2005) quantified filtering efficiency using the CDA amplitudes (the CDA benefit for the extra two items being irrelevant versus relevant, over the cost for the extra two items being relevant versus absent) and found that the filtering efficiency was positively correlated with an individual's WM capacity. The 2 red + 2 blue CDA amplitude was significantly smaller in the high-capacity individuals than in the low-capacity individuals. This suggests that the high-capacity individuals are more efficient at selecting only the relevant stimuli from the visual field, thereby reducing the likelihood of problems related to capacity limitations.

The present study

The present study includes a typical AB task, a conventional visual WM capacity task allowing us to measure WM capacity (K), and a visual WM filtering efficiency task modeled on that of Vogel et al. (2005). The goal is to examine whether visual WM filtering efficiency can predict individual differences in AB magnitude. We predict that filtering efficiency scores will be negatively related to AB magnitude, where greater control over access to WM will be associated with smaller AB magnitudes due to a greater ability to ignore irrelevant RSVP distractors. Furthermore, we predict that this will be true even when (or perhaps especially when) variability due to WM capacity is removed. Furthermore, we predict that WM capacity will not be predictive of their AB magnitude once selection efficiency is co-varied out.

Methods

Participants

Sixty Brock University undergraduate students (47 female) participated individually in a single-session experiment lasting 1.5 h. Participants were between the ages of 18 and 26 ($M = 19.6$, SD = 1.95). All participants spoke English as their first language and reported normal or corrected-to-normal vision and no color blindness. Participants were granted course credit or received a small monetary payment for their participation in the experiment. All participants performed the experimental tasks in the same order: (1) filtering efficiency task, (2) attentional blink task, (3) WM capacity task.

Apparatus

All stimuli were presented with the use of E-Prime software (Schneider, Eschman, & Zuccolatto, 2002). All tasks were performed on a desktop Dell PC with a Duo Core processor and a 17 inch color CRT monitor running at 60 Hz. Manual responses were made using a keyboard.

Materials and procedure

Filtering efficiency task

The visual WM filtering efficiency task was a behavioural task (no ERPs were collected) modeled on that of Vogel et al. (2005). Participants completed 144 trials in which two brief sequential arrays of colored rectangles were presented, and participants were instructed to make a judgment as to whether or not the spatial orientation of one of the red rectangles changed across the two arrays. Each array consisted of either three or six rectangles on a gray background. Each rectangle was 0.9 cm by 0.4 cm, subtending 0.7 by 0.3 degrees of visual angle at a viewing distance of approximately 70 cm. Rectangles were randomly selected to appear vertically, horizontally, oblique 45 degrees to the left, or oblique 45 degrees to the right. Each rectangle was randomly presented at one of 16 non-overlapping locations within a 6.2 cm by 6.6 cm invisible square subtending 5.1 by 5.4 degrees of visual angle. There were three different experimental conditions: (1) 3 red rectangles, (2) 6 red rectangles, and (3) 3 red + 3 blue rectangles.[1] In each of the three experimental conditions half of the trials involved an orientation change of one of the red rectangles (see Fig. 1a). The six conditions (3 display conditions × change/no change) were presented randomly within the block of trials with the constraint that each condition was presented twice every 12 trials.

Each trial began with the presentation of a fixation cross for 2,000 ms, followed by a blank screen for 900 ms. The memory array was then presented for 100 ms, followed by a display of only the gray background for 900 ms, and then the test array (presented for 2,000 ms). Participants were instructed to report whether the orientation of one of the red rectangles changed or not after each test array. A change in orientation involved one of the red rectangles rotating along its midpoint, randomly resulting in one of the other three possible orientations. Participants were instructed to ignore the blue rectangles (and were never queried about them) and were told to focus only on the red rectangles. Participants made unspeeded key press responses indicating the presence or absence of an orientation change across the arrays. The next trial began 1,000 ms after the participant's key press response. False alarm rates (saying "yes" when there was no orientation change) were subtracted from hit rates (saying "yes" when there was an orientation change) to provide sensitivity scores for each participant in each of the three display conditions.

Performance on the three display conditions was used to calculate a filtering efficiency score for each individual following Vogel et al. (2005). In the efficiency formula by Vogel et al. (2005), the numerator contained the difference in the CDA amplitude between the 4 red and 2 red + 2 blue condition. Because a low CDA reflects good filtering in their task, the numerator essentially reflects the CDA benefit of efficiently filtering the irrelevant blue rectangles, with a greater numerator indicating more benefit from filtering. In the denominator, they used the difference between 4 red and 2 red, which essentially reflects the range of CDA for each participant. Thus, their filtering efficiency score was essentially the benefit from filtering the irrelevant distractors over the total cost when the extra two items were relevant. We used the same logic where an individual's filtering efficiency score was determined by the following calculation: Filtering Efficiency = (3 each–6 red)/(3 red–6 red). As in Vogel et al., efficiency of filtering was therefore a function of an individual's performance benefit based on their ability to ignore the three irrelevant items over the

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[1] In order to avoid ceiling effects on behavioural accuracy set sizes of three and six were used here instead of the set sizes two and four used by Vogel et al. (2005). Ceiling effects were not a concern in Vogel et al. where the dependent variable was CDA amplitude.

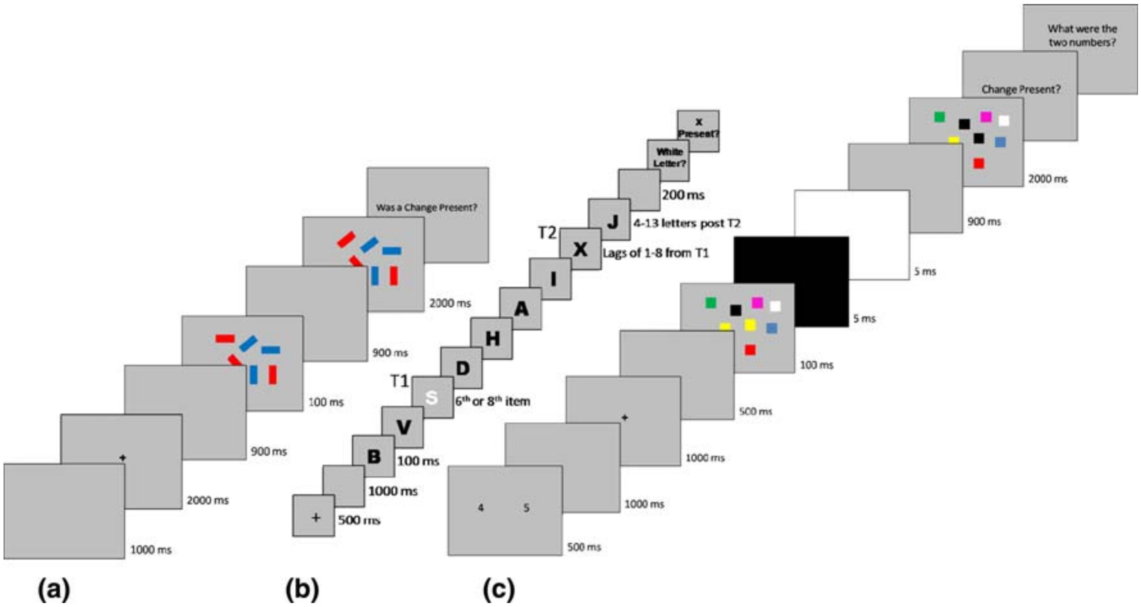

Fig. 1 A visual depiction of the cognitive tasks used here. **a** Shows the 3 red + 3 blue condition of the WM filtering efficiency task with an orientation change present. Participants reported whether the orientation of one of the red rectangles changed across the two displays. **b** Shows a sample RSVP stream with T2 present at lag 5. Participants reported the identity of the white (T1) letter, and reported the presence/absence of the black (T2) X. **c** Shows the WM capacity task with a change present. Participants reported whether or not any square changed color across the two displays

performance cost of needing to attend to an extra three relevant items. The filtering efficiency measure should theoretically yield scores that range from 0 to 1, with scores outside this range representing error. Participants whose selection efficiency score was greater than 1.0 were removed from the analysis.[2]

AB task

During the AB task, 120 RSVP letter streams were presented. Each stream was shown at a rate of 10 letters/s (100 ms per item with no blank interstimulus interval). Each stream contained 20 letters (19 black, and 1 white) presented in 18-point Courier New font on a gray background. Participants were asked to identify the lone white letter (T1) within each stream and to report the presence/absence of the letter 'X' (T2) somewhere within the stream after the white letter (see Fig. 1b). T1 was present in all trials as either the sixth or the eighth item in the stream. T2 was present on two-thirds of the trials. When present, T2 was presented equally often at lags 1–8 following T1 (i.e., 100–800 ms target separation). Following the completion of the stream, participants were prompted on the screen to identify T1 (simply by pressing the corresponding letter on the keyboard), and then to make a judgment regarding the presence or absence of T2 (press '1' for 'present' and '0' for 'absent'). All responses were unspeeded, with accuracy being stressed.

T1 accuracy, T2 sensitivity, and AB magnitude were calculated for each participant. T1 accuracy was computed by averaging each individual's percentage correct T1 accuracy across all trials. To control for individual differences in bias to report the presence of T2, overall T2 sensitivity was measured by averaging T2 hits (saying present when the X was present) across all lags and then subtracting each individual's overall T2 false alarm rate (saying present when the X was absent). AB magnitude was calculated by averaging T2 sensitivity at the longest lags (lags 7 and 8) where T2 performance should not be impaired by T1 processing, and subtracting average T2 sensitivity at the shortest lags (lags 1–4) where T2 performance was reduced due to the

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[2] Nineteen of the 60 participants had filtering efficiency scores larger than 1.0 with the vast majority of these 19 having scores just slightly above 1, suggestive of slight measurement error. To be conservative, these participants were excluded from the analyses, leaving $N = 41$. In each case, a filtering score of greater than 1.0 was the result of the participant having slightly higher accuracy in the 3 red + 3 blue condition than in the 3 red condition. This pattern suggests that that these participants were fully able to filter out the irrelevant blue distractors, but that their scores in the 3 red condition were slightly underestimated and/or the scores in the 3 red + 3 blue condition were slightly overestimated. Following the assumption that scores in the 3 red condition should be just as high as scores in the 3 each condition, when we corrected the 3 red scores so that they were equal to the 3 each scores, the pattern of results observed when using all 60 participants was the same as the patterns reported here with $N = 41$. Namely, a significant correlation was observed between filtering efficiency and AB magnitude ($r = -0.29$, $p = 0.025$), and filtering efficiency predicted AB magnitude over and above WM capacity and T2 sensitivity (semi-partial $r = -0.32$, $p = 0.012$).

AB. Overall T2 sensitivity was then co-varied out of AB magnitude given that we wanted to examine the impact of the WM measures on the AB slope independently from the height of the line.

Working memory capacity task

The WM capacity task was modeled on an experiment from Vogel et al. (2001). The task contained 50 trials in which participants were shown two sequential arrays of eight variously colored squares and were instructed to make a judgment as to whether or not the color of one of the squares changed across the two arrays (see Fig. 1c). Each square was 0.8 cm by 0.8 cm, subtending 0.7 by 0.7 degrees of visual angle at a viewing distance of 70 cm. Each square was randomly presented at one of 20 non-overlapping locations within an 11.6 cm by 8.9 cm invisible square subtending 9.4 by 7.3 degrees of visual angle, with the constraint that no squares could occupy the same location. The background color of the display was always gray and the color of each square was randomly drawn with replacement from a list of 7 possible colors (red, blue, yellow, black, white, green, and purple). On trials where a color change was present, one of the squares was chosen at random to change to one of the six remaining colors during the blank retention interval between the two arrays. To ensure that participants were not recoding the colors verbally and performing phonological rehearsal of color names, two random numbers (between 1 and 9) were presented for 500 ms at the start of each trial. Participants were prompted for the identity of these two numbers at the end of each trial.

Each trial began with the presentation of the two digits for 500 ms, and this was followed by a 1,000 ms blank interval, a 1,000 ms fixation cross, and then by a 500 ms blank interval. The memory array of colored squares was then presented for 100 ms. To mask any local transients across the displays, the first display was followed by a black screen for 5 ms, a white screen for 5 ms, and then a 900 ms retention interval where only the gray background was visible. Following the retention interval, the test array appeared for 2,000 ms. Following the test array, participants made an unspeeded key press response indicating the presence or absence of a color change. Participants were then prompted for the two numbers that had been presented at the beginning of the trial. The WM capacity of each participant was calculated by using a formula that assumes that if an individual can hold K items in their memory from an array of S items, then their capacity should be reflected in their successful performance in K/S trials (Cowan, 2001). To account for random guessing, false alarm rates specific to each individual were taken into account. The formula is therefore $K = S(H - F)$, where H is the hit rate and F is the false alarm rate (Vogel et al., 2005). Only trials where the two digits were reported correctly were included in the calculation.

Results

The AB

As in most previous studies of the AB, T2 performance was calculated only for trials where T1 was identified correctly. Figure 2 displays the conditionalized T2 sensitivity (i.e., T2 hits–false alarms for T1 correct trials) as a function of T1–T2 lag. A repeated-measures one-way ANOVA on T2 sensitivity indicated a significant effect of lag [$F(7, 280) = 51.97$, $p < 0.001$]. Subsequent paired-samples *t*-tests with the Bonferroni correction compared T2 sensitivity at each of the shorter lags (1–7) to T2 sensitivity at the longest lag (8). These showed significant differences between lags 1 [$t(40) = 8.12$, $p < 0.001$], 2 [$t(40) = 11.23$, $p < 0.001$], 3 [$t(40) = 9.45$, $p < 0.001$], and 4 [$t(40) = 5.84$, $p < 0.001$] when compared to a lag of 8. T1 accuracy averaged 93.7% (SD = 6.95) and did not vary as a function of T2 lag ($F < 1$).

Filtering efficiency

Mean sensitivity (hits–false alarms) equaled 0.80 (SD = 0.18) in the 3 red condition, 0.68 (SD = 0.17) in the 3 red + 3 blue condition, and 0.41 (SD = 0.17) in the 6 red condition of the filtering efficiency task. A repeated-measures one-way ANOVA indicated significant differences in performance across the three conditions ($F(2, 80) = 187.93$, $p < 0.001$). Paired-samples *t*-tests, with a Bonferroni correction showed significant differences between all three

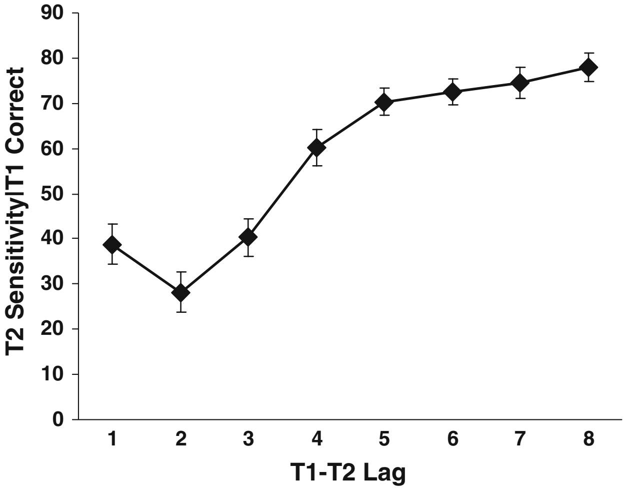

Fig. 2 Mean T2 sensitivity (hits–false alarms) for T1 correct trials as a function of T1–T2 lag. Error bars represent the standard error for that mean

Table 1 Means (*M*), standard deviations (SD) and Pearson correlations for working memory and RSVP measures

	M	SD	AB magnitude	T2 sensitivity	T1 accuracy	WM efficiency
AB magnitude	34.29	19.91				
T2 sensitivity	57.95	17.90	0.00			
T1 accuracy	93.70	6.95	0.25	0.42**		
WM selection efficiency	0.68	0.25	$-0.29^{\dagger}$	−0.16	−0.05	
WM capacity (*K*)	4.11	1.24	0.06	0.13	0.19	0.32*

** $p < 0.01$, *$p < 0.05$, †$p < 0.10$

experimental conditions (3 red–6 red: $t(40) = 16.66$, $p < 0.001$; 3 red–3 each: $t(40) = 7.71$, $p < 0.001$; 6 red–3 each: $t(40) = 12.16$, $p < 0.001$). As expected, mean accuracy was highest in the 3 red condition, lowest in the 6 red condition, and intermediate in the 3 each condition.

Working memory capacity (*K*)

In the current study, the average memory capacity (*K*) was 4.1, with a standard deviation of 1.24. This *K* estimate is similar, but slightly higher, than estimates obtained in previous visual WM capacity studies[3] where individual memory capacities have been found to range from 1.5 to about 5 items with a typical sample mean between 3 and 4 items (e.g., Vogel et al., 2001).

WM relationships with the AB

Table 1 displays the means and standard deviations for each individual difference variable along with correlations among the measures. WM capacity (*K*) was significantly positively related to filtering efficiency, replicating the pattern observed by Vogel et al. (2005). *K* was not significantly related to AB magnitude, but the relationship between filtering efficiency and AB magnitude approached significance ($p = 0.065$), where individuals scoring higher on the filtering efficiency measure tended to have smaller AB magnitudes. Given that filtering efficiency was significantly related to *K*, and we wanted to investigate WM filtering efficiency independently of WM capacity, a simultaneous linear regression analysis was conducted to determine the ability of filtering efficiency scores to predict AB magnitude while controlling for *K*. Filtering efficiency was a significant predictor of AB magnitude ($\beta = -0.35$, semipartial $r = -0.33$, $p < 0.05$), over and above *K* (see Fig. 3), but *K* was a non-significant predictor over and above filtering efficiency ($\beta = 0.17$, semipartial $r = 0.16$, $p > 0.30$), providing evidence that the portion of filtering efficiency that is unrelated to WM capacity is negatively related to AB magnitude.

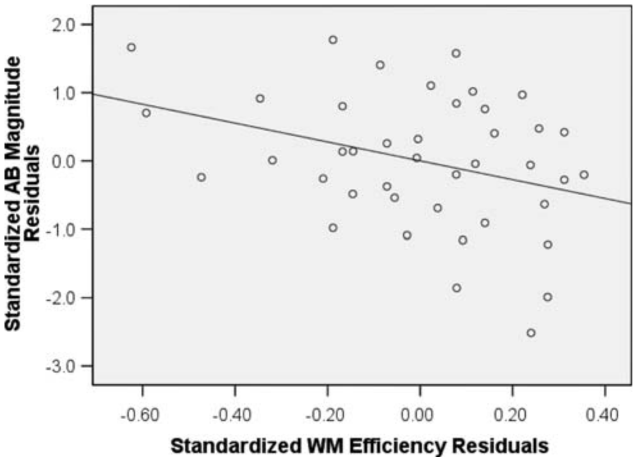

Fig. 3 Scatterplot showing the negative relationship between standardized AB magnitude scores residualized on T2 sensitivity and standardized selection efficiency scores residualized on WM capacity (*K*)

When a median split was used to divide participants into those with low (*M* efficiency = 0.47) and high (*M* efficiency = 0.89) filtering efficiency scores, a significant difference in AB magnitude was obtained, $t(39) = 2.34$, $p < 0.05$), and this was also true when *K* was included as a covariate, $F(1,38) = 7.47$, $p < 0.01$). To examine the effect of WM filtering efficiency on T2 sensitivity at various lags, WM filtering efficiency group (low/high) from the median split was included as a between participant factor in a mixed-model ANOVA with lag (1 to 8) as a within participant factor and *K* and overall T2 sensitivity as covariates. The results showed a significant main effect of lag, $F(7,259) = 3.22$, $p < 0.01$, and a significant lag by filtering efficiency group interaction, $F(7,259) = 2.31$, $p < 0.05$, where the lag effect was larger for those with low filtering efficiency. As one can see Fig. 4, individuals with relatively

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[3] It is possible that the slightly higher estimate of *K* obtained here resulted from the fact that the displays in the present study allowed for triplets of the same colour in a single display, whereas previous studies have often allowed only singles and doubles (see Awh, Barton, & Vogel, 2007). The use of triplets may have encouraged participants to group the items on some trials, and therefore increased their estimates of *K*. Note below that *K* shows no relationship with any AB variables, so if grouping was present, this strategy does not appear to be related to AB magnitude.

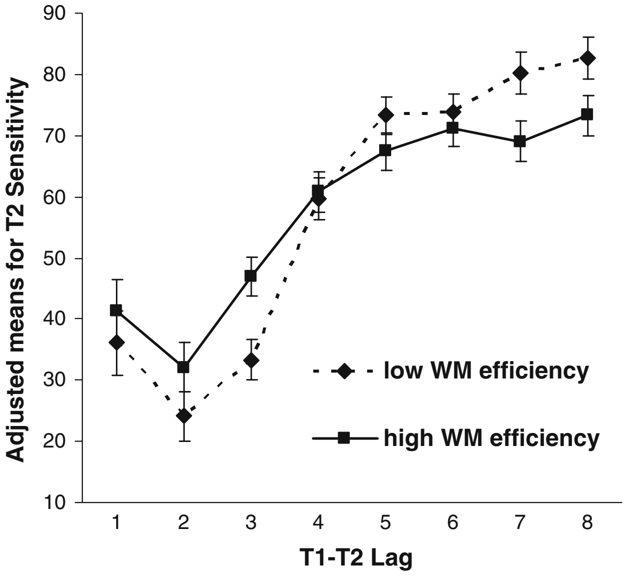

Fig. 4 T2 performance as a function of T1–T2 lag and low/high filtering efficiency group with *K* and overall T2 sensitivity covaried out. *Error bars* represent the standard error for that mean

low WM filtering efficiency had a greater lag-dependent change in T2 performance across lags than did individuals with relatively high WM filtering efficiency.

Neither *K* nor WM filtering efficiency were related to overall T1 accuracy or T2 sensitivity. When both filtering efficiency and *K* were added as simultaneous predictors of T1 accuracy, as above, neither were significant unique predictors (p's > 0.20), and this was also true when T2 sensitivity was the criterion (p's > 0.17).

Discussion

WM and the AB

The current study provides support for the relationship between individual differences in AB magnitude and visual WM filtering efficiency. While WM capacity was unrelated to AB magnitude, filtering efficiency scores were predictive of AB magnitude when variability due to WM capacity was removed. Higher scores on the filtering efficiency task were associated with smaller AB magnitudes. Thus, the current results suggest that control over access to WM, but not the capacity component of WM, underlies the AB deficit, at least in part.

This dissociation of WM predictors is in line with proposed divisions of WM. Baddeley (1996) posited that there were two separate components to WM; (1) a storage capacity component, and (2) a more dynamic executive control component that reflects the efficiency of handling information in WM. Several researchers have suggested that the prefrontal cortex is involved in the executive control aspect of WM, while capacity may be limited by more posterior mnemonic buffers (e.g., Curtis & D'Espisito, 2003; Postle, Berger, & D'Esposito, 1999). The present link between executive control of WM and the AB is also consistent with fMRI, MEG, and ERP studies (e.g., Gross et al., 2006; Marcantoni, Lepage, Beaudoin, Bourgouin, & Richer, 2003; Marois, Chun, & Gore, 2000; Martens et al., 2006) showing that the AB is associated with activation in sites, such as prefrontal cortex and lateral frontal cortex—areas associated with executive control of attention and WM (e.g., Miller & Cohen, 2001; Posner & Dehaene, 1994).

The present results also support those of Colzato et al. (2007) and Arnell et al. (2010) who observed a negative relationship between OSPAN performance and AB magnitude. Recall that Arnell et al. (2010), showed that performance on forward and backward digit span tests (primarily reflecting WM capacity) did not predict AB magnitude, but that performance on the OSPAN WM test (which requires good executive control of WM) predicted AB magnitude over and above forward and backward digit span tasks, suggesting that it was the executive control aspect of WM, and not the capacity component, that underlies individual differences in AB magnitude. The OSPAN task used by Arnell et al. (2010) and Colzato et al. (2007) is a relatively complex task requiring a number of WM executive control abilities that are likely related. This makes it difficult to determine what subset of WM executive control abilities might underlie the relationship between OSPAN scores and AB magnitude. Indeed, Colzato et al. (2007) suggested several different means by which the executive aspect of WM could relate to the AB (e.g., more efficient parallel processing, more efficient attention allocation, longer attentional windows, or greater ability to ignore irrelevant information) and pointed out that it was difficult to know which of these may be involved. In contrast to the OSPAN task, the present WM filtering efficiency task is much less complex and the filtering efficiency score more precisely measures the degree to which irrelevant information is allowed to enter visual WM. Filtering efficiency may be one of many WM executive control abilities tapped by the OSPAN task. Indeed, Conway, Cowan, and Bunting (2001) showed that individuals with low OSPAN scores were over three times more likely to hear their to-be-ignored own name, demonstrating the classic cocktail party effect (Moray, 1959; Wood and Cowan, 1995), than were those individuals with high scores on the OSPAN, suggesting that OSPAN scores do reflect, in part, the ability to filter out irrelevant information from WM. Thus, the present results suggest that individual differences in the selection of relevant information, and the exclusion of irrelevant information, into visual WM is the WM executive control ability (but perhaps not the only one) that can explain the relationship between WM and AB magnitude. Individuals who are worse gatekeepers of WM, failing to keep out irrelevant information, would likely be at a disadvantage in the AB task, as they would invest more attention in irrelevant RSVP distractors which may then increase competition between targets and distractors, thereby exacerbating the AB.

Distractor filtering and the AB

The supposition that WM filtering efficiency predicts AB magnitude because it predicts the amount of competition that RSVP distractors will provide is consistent with the electrophysiological findings of Martens et al. (2006). They found that non-blinkers showed larger differences in neural activation between RSVP streams containing targets and RSVP streams containing only distractors, and less activation on the distractor-only trials when compared to blinkers. Their results suggest that non-blinkers are more selective in their processing of rapidly presented information and may invest less attention in task-irrelevant RSVP distractors. Recently, Martens and Valchev (2009) have provided support for this idea, showing that the magnitude of the AB increased for blinkers when visual distractors were presented in irrelevant locations on the computer screen relative to when the distractors were absent. In contrast, the presence/absence of distractors had no influence on the AB magnitude of non-blinkers. Similarly, Dux and Marois (2008) reported that individuals who showed less priming of T2 by a distractor presented earlier in the RSVP stream displayed smaller AB magnitudes, and they interpreted these results as suggesting that individuals with smaller ABs inhibit distractors more thoroughly than individuals with larger ABs. The results of these studies suggest that distractors may receive less attentional processing by some individuals, and that less processing of irrelevant distractors during the AB task is associated with reduced ABs. Here, we extend these findings to show that less processing of irrelevant distractors on an unrelated visual WM task can also predict AB magnitude. Together the results suggest that it is not how much you can hold in your WM, but how selective you are over what you let into WM that predicts your AB magnitude.

It is worth noting however, that the present AB experiment required a task switch from T1 (identify white letter) to T2 (detect black X), thus a portion of the variability in AB magnitude estimated here may be due to task switch costs. An alternate possibility to the distractor processing hypothesis posited above, is that WM selection efficiency is related to executive task switch control in addition to, or opposed to, the AB per se. This alternative suggests the need for a future study examining the relationship between WM selection efficiency and AB magnitude using an AB experiment where the T1 and T2 tasks are the same (e.g., report the two digit targets that were presented among the letter distractors).

Theoretical implications for the AB

The present results highlight the importance of using executive control to admit relevant targets, but not relevant distractors, into WM. These results are consistent with the Shapiro et al. (1994) interference theory of the AB in that the ability to keep irrelevant distractors out of WM would predict less interference in the WM store and less resultant AB. The present data are also consistent with newer models of the AB emphasizing cognitive control over influence from irrelevant distractors—for example, the TLC model (Di Lollo et al., 2005), the Boost and Bounce model of Olivers and Meeter (2008), and the threaded cognition model of Taatgen et al. (2009).

The present results are also consistent with the overinvestment hypothesis of Olivers and Nieuwenhuis (2005, 2006) who posit that the AB results from an unnecessary overinvestment of attention to T1 and distractors in the RSVP stream. Recent results with both induced (Olivers & Nieuwenhuis, 2006) and naturally occurring affect (MacLean, Arnell, & Busseri, 2009; Rokke, Arnell, Koch, & Andrews, 2002) have shown larger ABs for individuals with negative affect and smaller ABs for individuals with positive affect. Positive affect has been linked to a relaxed and flexible processing style and diffuse attention (e.g., Fredrickson, 2001), while negative affect has been linked to heighten focusing of attention (e.g., Kramer, Buckhout, & Eugenio, 1990). When overinvestment is reduced because of positive affect or an additional task (Olivers & Nieuwenhuis, 2005, 2006), then distractors are thought to be less effective competitors for entrance into WM, thereby reducing the AB.

Poor WM filtering efficiency could potentially be associated with over-focusing of attention. Individuals who are generally more “focused”, and process even irrelevant items, may tend to over-invest their attention in each RSVP item. When they overinvest in T1 this leaves very little attention for T2 at short lags. However, at long lags they can over-focus their attention on T2 and show a benefit in performance for their extra efforts. This would result in low T2 accuracy at short lags and high T2 accuracy at long lags, creating a larger AB. There is some suggestion that this was the case in the present data. Note that in Fig. 4 that low WM filtering efficiency participants actually showed better relative T2 performance at longer lags compared to high filtering efficiency participants, despite showing lower accuracy at shorter lags. This pattern was also observed in the present study when overall T2 sensitivity was not covaried out, and was also found in MacLean et al. (2009) where participants with high negative affect had lower T2 accuracy at short lags, but better T2 accuracy at long lags relative to individuals with high positive affect. In contrast, participants who are generally more "diffused" (having a positive, relaxed cognitive style) may be more efficient in their selection of only relevant material, may invest as little as needed in each item in the RSVP stream, and as such may have lower T2 costs at short lags due to reduced interference from T1. However, because they may invest less in all items, including T2, diffusers may show reduced T2 accuracy at long lags relative to individuals who are more focused. This would result in a flattened slope and less AB.[4] Thus, the present T2 accuracy pattern observed here, supports the idea that individuals with low WM efficiency may be admitting irrelevant information into WM by over-focusing their attention, while those with high WM scores may have more diffused attention that admits only relevant items into WM. Intriguingly, thus far, the only measures found to predict AB magnitude in individual differences studies of the AB are trait/state affect (MacLean et al., 2009; Rokke et al., 2002) and executive control of WM (the present results, Arnell et al., 2010; Colzato et al., 2007; Dux & Marois, 2008). It is possible WM control is a mediator between affect and AB magnitude where affect controls the degree of attentional diffusion/focus which modulates WM gate keeping and the resultant AB, and this is an interesting avenue for further investigation.

Predicting RSVP target accuracy

The finding that WM selection efficiency predicts AB magnitude but not overall target accuracy (T1 or T2) is consistent with previous studies showing that AB magnitude (the slope of the line across lag) and overall T2 accuracy (the average height of the line across lag) are predicted by different sets of cognitive and affective predictors (Arnell, Howe, Joanisse, & Klein, 2006; Arnell et al., 2010; Colzato et al., 2007; MacLean et al., 2009). While AB magnitude appears to be related to affective trait/state (MacLean et al., 2009; Rokke et al., 2002) and executive control of WM (the present results, Arnell et al., 2010; Colzato et al., 2007; Dux & Marois, 2008; Martens & Valchev, 2009), overall target accuracy seems to be more sensitive to measures of information processing speed and general intelligence (Arnell et al., 2006; Arnell et al., 2010; Colzato et al., 2007). The consistent finding that overall T2 accuracy and AB magnitude are dissociable measures in individual differences studies of the AB, calls us to remind AB researchers that the magnitude of the AB can only be estimated accurately when the slope of the T2 accuracy function across lag is isolated.

Conclusion

In conclusion, the present results show that individual differences in WM filtering efficiency in a visual WM task predict individual differences in AB magnitude over and above WM capacity, which was not related to AB magnitude. Better WM filtering ability was associated with smaller ABs. We posit that this is because good WM filtering efficiency allows RSVP distractors to be less viable competitors with T2 for limited WM resources.

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[4] It is possible that poorer filtering may not only predict better long lag T2 performance (as we found here), but also higher T1 accuracy (which we did not find here).Greater overinvestment may not always lead to greater target accuracy, as the greater overinvestment to targets would also be accompanied by a greater overinvestment to adjacent distractors, and therefore it is difficult to know when one should expect greater overinvestment to lead to greater target performance. Our speculation is that this may depend on the nature of the target task, the target, and the distractor.

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