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Executive control processes of working memory predict attentional blink magnitude over and above storage capacity

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Abstract When two masked, to-be-attended targets are presented within approximately half a second of each other, performance on the second target (T2) suffers, relative to when the targets are presented further apart in time or when the first target (T1) can be ignored. This phenomenon is known as the attentional blink (AB). Colzato et al. (Psychon Bull Rev 14:1051–1057, 2007) used an individual differences approach to examine whether individual AB magnitude was predicted by individual differences in working memory (WM), using the operation span paradigm (OSPAN). They found that OSPAN score was inversely related to AB magnitude even when a fluid intelligence measure (Raven's SPM) was partialled out. However, it is not clear from this study whether it was the executive control aspect of working memory, the capacity aspect of short-term memory, (or both), that related to AB magnitude. In the present study we used a variety of WM measures that required varying degrees of executive control. OSPAN was negatively related to AB magnitude with Raven's SPM, reading comprehension, reading rate, and digit forward and backward partialled out. Backward and forward digit span did not predict AB magnitude. These results support the conclusion that a "working" executive component of WM predicts temporal limitations of selective attention beyond static STM capacity and general cognitive ability.

Introduction

When two masked targets must be attended, report of the second target (T2) is impaired if it is presented within approximately half a second of the first target (T1), relative to longer target separations (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). This pattern of performance is known as the attentional blink (AB; Raymond et al., 1992). A prominent class of models explains the AB in terms of a bottleneck on conscious stimulus identification or consolidation (Chun & Potter, 1995; Jolicoeur, 1998, 1999). For example, according to Chun and Potter's (1995) two-stage model, T2 is processed through a first stage where high level visual representations are created and semantic meaning is activated. Unless T2 comes within half a second of T1, T2 then proceeds to the second stage of processing where T2 is consciously identified and encoded into working memory (WM), making it available for report. Stage 2 processing requires time and attentional resources. If T2 is presented within 500 ms of T1 and T1 is still undergoing stage 2 processing, then T2's fragile stage 1 representation must wait to gain access to stage 2. While waiting, T2's representation can decay or be overwritten by trailing stimuli, causing stage 2 consolidation to fail. Under these conditions there is no conscious knowledge of T2 in WM to support accurate report, and an AB will be observed. Similarly, Jolicoeur (e.g., Jolicoeur, 1998; Jolicoeur & Dell'Acqua, 1998, 1999) has proposed a bottleneck on stimulus consolidation into WM where T1 consolidation in WM must be completed before T2 consolidation can proceed.

Given that a bottleneck on WM encoding has been proposed by some to underlie the AB, it makes sense to ask: (1) whether WM contents (load) can influence the magnitude of the AB, and (2) whether the processing efficiency

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(executive control) of an individual's WM can influence the magnitude of the AB. The first of these two issues has been addressed by Akyürek and Hommel (2005, 2006) who asked participants to perform an otherwise standard AB task while retaining a variable number of items in WM. On each trial participants were presented with a new memory set immediately before viewing a rapid serial visual presentation (RSVP) stream. At the end of the stream participants were asked to report T1 and T2 and report whether a probe item presented after the RSVP stream was or was not a member of the memory set. The number of items in the memory set, and the relationship of the memory set items to T1, T2 and the RSVP distractors varied within and across their experiments. Akyürek and Hommel showed that memory set size and relevance of the memory set items had modest effects on overall T1 and T2 accuracy (with lower target accuracy for larger set sizes and for memory sets with items relevant to the RSVP task). However, neither memory set size nor task relevance influenced the slope of the function across T1–T2 lags, thereby showing no modulation of AB magnitude as a function of the number or nature of items held in the memory set. Akyürek and Hommel (2006) concluded that the mechanisms underlying the AB are independent of maintenance of items in WM.

While maintenance of items in WM has been shown to have no influence on AB magnitude (Akyürek & Hommel, 2005, 2006), active use of those same items does modulate the AB. Akyürek, Hommel, and Jolicoeur (2007) used a task similar to those used by Akyürek and Hommel (2005, 2006), but with a critical difference where the T1 task required participants to determine whether T1 was or was not a member of the memory set. On each trial participants viewed a memory set of 1–4 letters immediately before viewing an RSVP stream. Participants were asked to report whether T1 was or was not a member of the memory set, and then to report the T2 digit. Akyürek et al. (2007) showed clear evidence that the magnitude of the AB (effect of target separation) increased with the size of the memory set. There was no effect of memory set size on T2 accuracy at the long T1-T2 separation (T2 presented 8 items, or lags, after T1), but T2 accuracy was lower for larger set sizes at lag 3. The contrasting results between Akyürek and Hommel (2005, 2006) and Akyürek et al. (2007) appear to result from the need to actively search the memory set in the task employed by Akyürek et al. (2007), compared to simply maintaining the memory set in the Akyürek and Hommel (2005, 2006) tasks. Indeed, Akyürek et al. (2007) posited that passive memory processes such as maintenance of items in WM may be fundamentally different from active use, manipulation, or consolidation of items into WM, and suggest that these processes may have very different effects on attention. The argument of Akyürek et al. (2007) is also consistent with the results and conclusions of Han and Kim (2004) which showed that the number of letters or digits maintained in WM had no effect on the efficiency of search in a visual search paradigm. However, when this same information needed to be manipulated during visual search (for example ordering letters alphabetically), then search efficiency decreased as more items were added to the memory set. Thus, the results of both Han and Kim (2004) and Akyürek and colleagues suggest that maintenance of items in WM does not influence limited-capacity attentional processing, but that active use or manipulation of the same information in WM does modulate attentional processing.

So, in answer to the question posed above, it appears that the contents of WM can influence the magnitude of the AB, but only provided that the contents require active manipulation or use. The other question that was posed in relation to WM and the AB was whether the efficiency of an individual's WM can influence the magnitude of the AB. It is well known that individuals differ in WM ability and that WM capacity is positively related to fluid intelligence (e.g., Kane & Engle, 2002). McLaughlin, Shore, & Klein, 2001) also demonstrated that the AB was a reliable individual difference variable, showing a correlation of .66 for individuals' AB magnitude with two different AB tasks administered 4 weeks apart in time. Colzato, Spape, Pannebakker, and Hommel (2007) used the operation span task (OSPAN; Turner & Engle, 1989) as a measure of WM and found that WM capacity was negatively related to AB magnitude, where larger WM capacity was associated with smaller AB magnitudes, even after controlling for fluid intelligence. In contrast, fluid intelligence [as measured by Ravens Standard Progressive Matrices (SPM), Raven, Raven, & Court, 2003] was not significantly related to AB magnitude (the slope of the T2 accuracy function across lag), but higher fluid intelligence scores predicted higher overall T1 and T2 accuracy (the average height of the T2 accuracy function across lag). The finding that WM scores predicted AB magnitude over and above fluid intelligence is important, as it allowed Colzato et al. (2007) to argue for the importance of WM processes per se, as opposed to more general intellectual functioning.

When interpreting the relationship between WM performance and AB magnitude, Colzato and colleagues emphasized individual differences in executive control of information in WM and posited several different means by which individual differences in executive control could relate to the AB. The proposed emphasis on the role of executive control in the AB is consistent with fMRI and MEG studies (e.g., Gross, Schmitz, Schnitzler, Kessler, Shapiro, Hommel, & Schnitzler, 2004; Marcantoni, Lepage, Beaudoin, Bourgouin, & Richer, 2003; Marois, Chun & Gore, 2000) of the AB which have shown that the AB is associated with activation in areas such as lateral frontal sites and the anterior cingulate—areas thought to be involved in working memory and executive control of attention (Miller & Cohen, 2001; Posner & Dehaene, 1994). However, as mentioned by Colzato et al. (2007), Baddeley (1996) argued that there are two separate components to WM: (1) a storage component that reflects older "seven plus or minus two" capacity conceptualizations of short term memory, and (2) a more dynamic executive control component that reflects the efficiency of handling information in WM. Indeed several studies have provided neurophysiological evidence for this dissociation between storage and executive control and have suggested that the prefrontal cortex (PFC) has a relatively pure supervisory/executive role in WM while the information itself may be held in more posterior mnemonic buffers (e.g., Curtis & D'Esposito, 2003; D'Esposito, Cooney, Gazzaley, Gibbs & Postle, 2006; Postle, Berger, & D'Esposito, 1999; Postle, 2006). Therefore, finding that WM performance on the OSPAN negatively predicts AB size does not allow one to conclude whether this relationship relies on the executive control component of WM, the maintenance/storage capacity of WM, or both.

To test whether the executive control component of WM, the storage capacity component of WM, or both underlie the relationship between WM performance and AB magnitude the present study used three different working memory tasks that each required the maintenance of information in memory, but varied in the degree of executive demands. A forward digit span task (from the Wechsler Adult Intelligence Scale, WAIS-III) was employed where strings of two to nine digits were presented aurally, and participants were asked to repeat back the digits in the correct order immediately afterward. The task required no manipulation of the information, and was taken as a simple capacity measure of working memory. The backward digit span task from the WAIS-III was also included. This was the same as the forward digit span task, but required participants to verbally report the digit series (of 2–8 digits) in the reverse order where the last digit in the set was to be reported first, and so on. Although this task does require active manipulation of the information, there is no additional competing information, verbal rehearsal can still be employed, and report is immediate. Thus, backward digit span was assumed to measure capacity and require relatively modest executive control demands (Kaufman & Lichtenberger, 1999). The OSPAN task (Turner & Engle, 1989), used by Colzato et al. (2007), was the third and final measure of working memory. In the OSPAN task participants are given visually presented mathematical operations [e.g., (3+5)/2 = 4] and five-letter words (e.g., CLOCK). Participants are asked to read the operation aloud, state whether the provided solution is true or false, and then say the word aloud at which point the stimuli disappear. On each trial there are between two and six operation/word pairs in the set. When the set is completed participants are asked to report all of the words in the correct order. The OSPAN task is considered by many to be the gold-standard measure of WM due to its high executive control demands. High executive demands result from the attentional control needed to maintain words with minimal verbal rehearsal in the face of information competing for WM resources (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Bleckley, Conway, & Engle, 2001). Each participant performed all three WM tasks, the AB task, Ravens SPM, and a reading rate and reading comprehension task (Brown, Nelson & Denny, 1973).

Consistent with the interpretation of Colzato et al. (2007), we predicted that the executive control aspect of WM, but not WM capacity, would predict AB magnitude. This prediction was based on the findings that WM load can modulate the AB when WM contents must be actively searched (Akyürek et al., 2007), but not when the WM load must simply be maintained throughout the RSVP stream (Akyürek & Hommel, 2005, 2006). The predicted pattern would also be consistent with activations of lateral-frontal cortex (associated with executive control) observed with MEG and fMRI data during the AB task (e.g., Gross et al., 2004; Marois et al., 2000). If the executive control aspect of working memory is responsible for the relationship between OSPAN scores and AB magnitude, then individuals' OSPAN scores should not only predict AB magnitude over and above Raven's fluid intelligence scores (as in Colzato et al., 2007), but also uniquely predict AB magnitude over and above the combined influence of fluid intelligence and forward/backward digit span scores. Indeed, if the executive control aspect is solely responsible for the relationship between OSPAN scores and AB magnitude, then the relationship between these measures should actually increase when the variability OSPAN shares with digit span tasks (presumably variability that is due to WM capacity) is partialled out. However, if forward and backward digit span negatively predict AB magnitude to the same degree as OSPAN scores, and none of the WM tasks predict unique variability, then this will provide evidence that WM capacity is responsible for the relationship between OSPAN scores and AB magnitude, and that executive control plays no role in the relationship. If both capacity and executive control aspects of WM underlie the relationship between OSPAN scores and AB magnitude, then all three WM measures should predict AB magnitude separately, but only OSPAN scores should still explain unique variability in AB magnitude over and above Ravens fluid intelligence scores and digit spans.

Methods

Participants

Fifty Brock University undergraduate students (age 18–29) participated individually in a single session lasting 3 h. Each participant reported learning English before the age of 5 and normal or corrected-to-normal visual acuity. Participants received course credit or a small monetary payment. All of the participants performed the tasks in the following order: (1) the Nelson–Denny reading test, (2) the three AB tasks, (3) forward digit span, (4) backward digit span, (5) the OSPAN, (6) Ravens SPM.

Apparatus

For the AB and OSPAN tasks, all stimuli were presented, and all computer responses collected, using E-Prime software (Schneider, Eschman, & Zuccolotto, 2002) running on a desktop PC with 17 in. colour CRT monitor. Participants made all manual responses using the computer keyboard. Ravens SPM and the Nelson–Denny reading test were administered in paper and pencil format. The digit span tasks were administered orally.

Stimuli and procedures

AB Task

Stimulus type (letters, words, and object pictures) was blocked, with all participants performing the letter block first and the object block last. Different types of stimuli were used in each block to reduce any stimulus specific effects that may relate to other cognitive performance measures. All participants performed the blocks in the same order to reduce any variability in individuals' AB scores that may result from order effects. This was appropriate given that AB performance was never compared across stimulus conditions. Each block contained 80 trials, with eight trials for each factorial combination of T1–T2 lag (2, 3, 4, 5, or 7 items) and T2 presence/absence. In each block, each trial began with a fixation cross that was presented for 500 ms followed by a 500 ms blank screen; then a rapid serial visual presentation (RSVP) stream of 16 items was presented one at a time in the center of the computer screen. Each individual letter stimulus was approximately 1.2 cm high and wide for a visual angle of approximately 1.4° at an unfixed viewing distance of about 50 cm. Each object picture was approximately 3.0 cm high and wide (approximately 3.4°). Word stimuli always approximated 1.0 cm in height (approximately 1.2°) but varied in width from 3.5 cm (approximately 4.0°) to 5.0 cm (approximately 5.7°). Each item was presented for 100 ms, with no blank ISI. In each block the first target (T1) was colored red, whereas all the other RSVP items were black. The participants were instructed to identify the red item for the T1 task (the red item could be *fish, speak*, or *kite* for words; *g*, *k*, or *m* for letters; and a dog, hand, or chair for object pictures). T1 was present on all trials as the sixth or eighth item in the RSVP stream. A second target (T2) was presented on half of all trials, equally often 2, 3, 4, 5 or 7 items after T1. T2 was the word report for word trials, *r* for letter trials, and a book for object picture trials. Participants were instructed to report whether the T2 item was present or absent in the stream. Six items were used as RSVP distractors for each stimulus category, but the same distractor was never presented in two successive positions within a stream. All the distractors had the same size, color, shading, and/or font as the targets from the same category. For word trials, distractors were the words towel, paper, fact, clock, cable and patrol. For letters, the distractors were *b*, *c*, *h*, *p*, *x*, and *y*; for objects, the distractor pictures were a teddy bear, a hat, a table, a wheelbarrow, a cup, and a fan. After each RSVP stream, a sentence on the screen prompted participants to enter the identity of T1. Participants identified T1 with an unspeeded button press, using labeled keys, and were told to guess if unsure. After making their T1 response, the participants were prompted by another sentence to report whether the T2 item was present (press "1") or absent (press "0"), using an unspeeded response. Once the first and the second responses had both been entered, the next trial began after a 1 s blank inter-trial interval.

OSPAN

Participants completed the operation span task (OSPAN; Turner & Engle, 1989) modified for use on a computer. Participants were told to try to remember the words for serial recall. They viewed pairs of centrally presented mathematical operations and unrelated words on screen [e.g., $(2 \times 4) + 1 = 7$? CLOCK]. Participants were required to read the operation aloud, make a key press indicating whether the provided solution was "true" or "false" and then read the word aloud. The operation and word remained on the screen until the manual true/false response for the operation was made. Immediately after their response, the next operation/word pair was presented. Immediately after the last operation/word pair, participants were prompted by the computer screen to serially recall all the words by writing them in the correct order on a sheet of paper. The set size varied randomly between two and six operations and words. Three sets of each size were presented, for a total of 15 sets. The span score was calculated as the total number of words that were recalled correctly in the proper order when all of the mathematical operations in a given set were correctly identified as "true" or "false".

Digit span

Participants performed the digit forward and digit backward tasks from the WAIS-III. The experimenter read digit lists from the WAIS-III aloud at a rate of one per second with consistent tone and emphasis. Immediately after the set of digits had been read, participants were instructed to report back the digits verbally in the same order as they were read (digit forward) or the reverse order (digit backward). In the digit forward condition participants received two trials at each set size starting at set size 2 and working up to set size 9. In the digit backward condition participants received two trials at each set size starting at set size 2 and working up to set size 8. If participants were incorrect on both trials of a given set size then no further set sizes were given. The digit forward score was the number of digit forward trials where all digits were reported accurately in the correct order (maximum score of 16). The digit backward score was the number of digit backward trials where all digits were reported accurately in the correct reverse order (maximum score of 14).

Ravens SPM

Participants completed the Raven's standard progressive matrices (SPM) which is a popular non-verbal test of fluid intelligence or Spearman's g (Raven et al., 2003). Participants were given 60 multiple choice non-verbal abstract reasoning questions. For each question participants were asked to pick the pattern option that completed the larger pattern. The test contained five sets, each with twelve questions, with questions within a set becoming increasingly difficult. Participants received one point for each correctly answered question for a maximum score of 60.

Reading rate and comprehension

Participants completed the reading rate and reading comprehension portions of form D of the Nelson–Denny reading test (Brown et al., 1973). Participants were told that they would need to answer multiple-choice questions after reading paragraphs in the test booklet. They were warned that they would have a limited amount of time (the 15 min cut-time administration was used) and that they should work quickly to try to correctly answer as many questions as possible. The number of correct multiple-choice responses was used to calculate the reading comprehension score. Because the cut-time version of the test was used, scores were multiplied by 1.33 × 2 to produce the reading comprehension score used in subsequent analysis (Brown et al., 1973). The first minute of the reading test was used to provide a measure of reading rate. Participants were instructed to read the first text passage as quickly as possible with good comprehension. Participants began reading when the experimenter said "go" and read silently for 1 min until the experimenter said "stop". Participants then pointed to the word that they were reading when told to stop. The word count for that line of text was used to estimate their reading rate where a higher word count indicated a faster reading rate. Each participant completed the reading rate and reading comprehension test once.

Results

For each participant, mean T1 accuracy was computed for each of the three stimulus types and overall across stimulus type. To control for individual differences in bias to report the presence of T2, a T2 sensitivity score (T2 hits across all lags minus T2 false alarms across all lags) was computed for each participant for each stimulus type as was an overall mean sensitivity across stimulus type. To calculate the AB magnitude for each participant, the T2 sensitivity score at each lag (T2 hits at that lag minus the false alarm rate across lags, given that absent T2's did not have a lag) was computed for each individual for each combination of stimulus type and lag, and then T2 sensitivity at short lags (lags 2 and 3) was subtracted from the average T2 sensitivity score at long lags (lags 5 and 7). AB magnitudes were then averaged across stimulus type for each participant. All the trials were used for calculations of T2 sensitivity and AB magnitude (not just T1 correct trials), so that the relationships between T1 accuracy and T2 sensitivity and between T1 accuracy and the AB magnitude could also be examined. However, all of the relationships between AB magnitude and other variables were also observed when only T1 correct trials were included.

One-way repeated measures ANOVAs showed significant effects of lag on T2 sensitivity for each of the three stimulus types [$F(4,196) = 5.78$, $P < 0.001$, MSE = 0.026; $F(4,196) = 39.07$, $P < 0.001$, MSE = 0.026; $F(4,196) = 64.37$, $P < 0.001$, MSE = 0.023, for letters, words, and objects respectively]. These reflected typical and robust ABs where T2 sensitivity increased as lag increased (see Fig. 1). For the subsequent analyses, scores on all the AB measures (AB magnitude, T2 sensitivity, T1 accuracy) were averaged across the three stimulus blocks (word, letter, object picture) to create a composite score for that measure.[1] This was justified by the results of principal components analyses which showed consistent individual differences in T1 accuracy, T2 sensitivity, and AB magnitude across the stimulus types. For AB magnitude, a single component

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[1] The same pattern of results was obtained when a latent AB magnitude factor was created that represented the common variance in the AB scores amongst the three stimulus types.

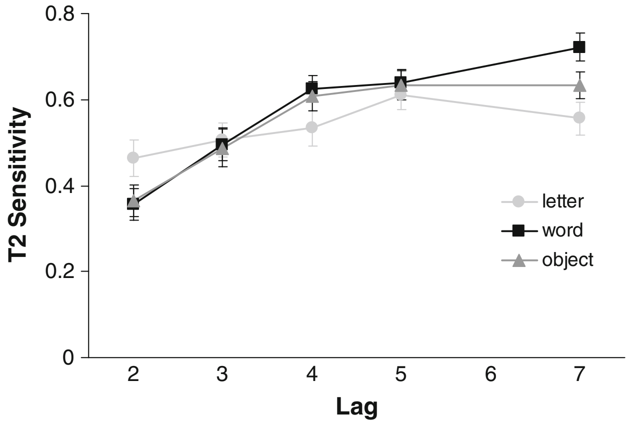

Fig. 1 Mean T2 sensitivity as a function of T1–T2 lag and stimulus type (letter, word, object picture). *Error bars* represent the standard error of the mean

accounted for 55.4% of the variance among the three AB estimates (one for each stimulus type), and each AB measure loaded strongly onto that component (loadings were 0.59–0.84). For T2 sensitivity, a single component accounted for 72% of the variance in T2 sensitivity, with strong loadings on that component for each stimulus type (0.82–0.88). For T1 accuracy, a single component accounted for 60% of the variance in T1 accuracy, and loadings on that component ranged from 0.66 to 0.83.

Table 1 shows the means and standard deviations for each of the measures, as well as the Pearson zero-order correlations between all measures. AB magnitude was not related significantly to any performance measure except T2 sensitivity (all other r's < 0.20, all P's > 0.18. The negative relationship between AB size and T2 sensitivity is not surprising given that those with a larger AB would be expected to have lower overall T2 accuracy, if all else were equal. Indeed, there was no significant relationship between AB magnitude and T2 sensitivity at the longest lag, $r(49) = 0.22$, $P > 0.12$. In contrast, T2 sensitivity and T1 accuracy were each related to OSPAN and Ravens scores, where higher scores were associated with greater overall T1 and T2 RSVP performance (see Table 1). Digit span scores and reading scores did not predict any RSVP measures, but both forward and backward digit span scores were positively related to OSPAN performance, and many of the relationships between the reading tasks, WM tasks, and Ravens were significant (see Table 1).

Predicting AB magnitude

Given that several of the predictor measures were intercorrelated, simultaneous multiple regressions were performed to examine whether any predictor could explain unique variability in any of the RSVP performance measures. For the first regression, AB magnitude was the criterion measure, and OSPAN, digits forward, digits backward, Ravens, reading comprehension and reading rate scores were entered as simultaneous predictors. As shown in Table 2, the combined predictors explained a non-significant 21% of the variability in AB magnitude ($R = 0.47$, $F(6,42) = 1.84$, $P = 0.11$), and OSPAN score was the only significant predictor of unique variability ($\beta = -0.44$, semipartial $r = -0.35$, $P < 0.05$). The finding that OSPAN predicted AB magnitude over and above the other performance measures was not a spurious result of OSPANs relationship with T1 and T2 performance, as OSPAN scores were still a significant unique predictor of AB magnitude ($\beta = -0.38$, semipartial $r = -0.30$, $P < 0.05$) when variability due to T1 and T2 performance was partialled out by adding them into the regression as additional simultaneous predictors (see

Table 1 Means (with standard deviations in parentheses) for each of the cognitive performance measures with Pearson zero-order correlations between all pairs of measures using an alpha of 0.05 for significance

	Mean (SD)	AB magnitude	T1 accuracy	T2 sensitivity	OSPAN	Digits forward	Digits backward	Ravens	Reading comp.
AB magnitude	0.19 (0.16)								
T1 accuracy	0.96 (0.03)	−0.08							
T2 sensitivity	0.55 (0.18)	−0.29*	0.66**						
OSPAN	35.57 (9.68)	−0.15	0.28*	0.31*					
Digits forward	11.20 (0.25)	0.01	0.09	0.11	0.31*				
Digits backward	8.40 (0.36)	0.19	0.18	0.25	0.57**	0.47**			
Ravens	48.60 (7.38)	0.17	0.28*	0.35*	0.37*	0.25	0.45**		
Reading comp.	42.88 (15.21)	0.04	0.07	0.01	0.19	0.38*	0.15	0.14	
Reading rate	258.92 (83.33)	0.17	−0.04	0.02	0.31*	0.26	0.31*	0.18	0.52**

$N = 50$. T1 accuracy is expressed in percent correct. T2 sensitivity is expressed in hits minus false alarms. AB magnitude is the difference between T2 sensitivity at long lags (5 and 7) and short lags (2 and 3). OSPAN and Raven's scores are out of a maximum of 60 points. Forward digit span is the number of correct trials out of 16, and backward digit span is the number of correct trials out of 14. Reading rate is the number of words read per minute and reading comprehension is scored out of 96. * $P < 0.05$, ** $P < 0.01$

Table 2 Results from simultaneous regression predicting AB magnitude with non-RSVP performance measures

Predictors	Standardized regression coefficients (β)	Semipartial correlations	*t* values
OSPAN	−0.44	−0.35	−2.55*
Digits forward	−0.08	−0.06	−0.47
Digits backward	0.35	0.25	1.83
Ravens	0.17	0.15	1.12
Reading comprehension	−0.12	−0.09	−0.68
Reading rate	0.24	0.19	1.38

* $P < 0.05$

Table 3). In this analysis T2 sensitivity was also a significant unique predictor of AB magnitude, even after all of the cognitive measures were accounted for ($\beta = -0.50$, semipartial $r = -0.35$, $P < 0.01$), and a significant 34% of the variability in AB magnitude was explained by all predictors combined [$R = 0.58$, $F(8,40) = 2.54$, $P < 0.05$]. The finding that OSPAN score was not significantly related to AB magnitude in the zero-order correlations, but was a significant predictor of AB magnitude in the regression analyses provides evidence that one or more of the other predictors shared variability with OSPAN that was unrelated to AB magnitude. When this shared variability was removed by entering them as simultaneous predictors, the OSPAN score was purified and the portion of the OSPAN variability that was specific to the OSPAN score remained and was related to AB magnitude. Backward and forward digit spans were the predictors that accomplished this. Indeed, OSPAN score was significantly related to AB magnitude whenever backward and forward digit span were included as predictors in the model, regardless of which other predictors were included or excluded, and was never a significant predictor of AB magnitude whenever backward and forward digit span were not included as predictors, regardless of what other predictors were included or excluded. For example, when only backward digit span, forward digit span, and OSPAN were entered as simultaneous predictors of AB magnitude, a non-significant 15% of the variability in AB magnitude was explained by the three predictors combined [$R = 0.38$, $F(3,45) = 2.63$, $P > 0.06$), but OSPAN was a significant unique predictor ($\beta = -0.50$, semipartial $r = -0.35$, $P < 0.05$; see Fig. 2 for the relationship between OSPAN and AB magnitude with backward and forward digit span partialled out of the OSPAN score). Thus, the variability shared between the digit spans and OSPAN scores was unrelated to AB magnitude, but the variability OSPAN did not share with the digit spans was related to AB magnitude.

Table 3 Results from simultaneous regression predicting AB magnitude with all performance measures

Predictors	Standardized regression coefficients (β)	Semipartial correlations	*t* values
OSPAN	−0.38	−0.30	−2.33*
Digits forward	−0.08	−0.06	−0.49
Digits backward	0.36	0.26	1.99
Ravens	0.26	0.22	1.69
Reading comprehension	−0.16	−0.13	−1.00
Reading rate	0.25	0.20	1.54
T1 accuracy	0.25	0.18	1.40
T2 sensitivity	−0.50	−0.35	−2.75**

* $P < 0.05$, ** $P < 0.01$

Predicting RSVP target performance

A regression was also performed to predict overall T2 sensitivity scores (collapsed across lag). When OSPAN, digits forward, digits backward, Ravens, reading comprehension and reading rate scores were entered as simultaneous predictors, as above, a non-significant 17% of the variability in T2 sensitivity could be explained [$R = 0.41$, $F(6,42) = 1.39$, $P > 0.24$) with no unique predictors (see Table 4). Both Ravens and OSPAN predicted T2 sensitivity in the zero-order correlations. The lack of unique predictors of T2 sensitivity in the regression results suggests that the cognitive performance measures are largely redundant predictors explaining overlapping variability in T2 sensitivity.

A similar pattern of results suggesting redundant predictors was observed when the same cognitive performance measures were used to predict T1 accuracy. Despite finding significant zero-order correlations between T1 accuracy and Ravens as well as T1 accuracy and OSPAN scores, a non-significant 14% of the variability in T1 accuracy was explained in the multiple regression [$R = 0.38$, $F(6,42) = 1.15$, $P > 0.35$) with no unique predictors (see Table 5).

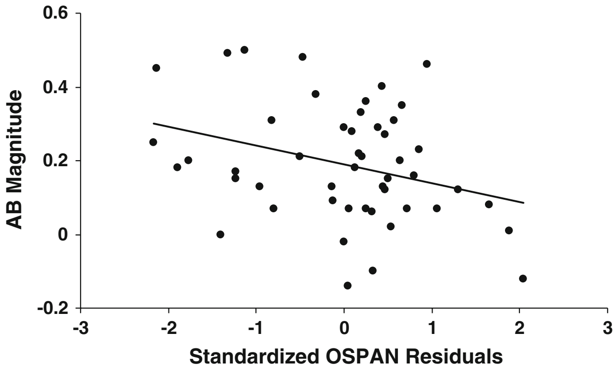

Fig. 2 Scatterplot showing the negative relationship between AB magnitude and OSPAN score residualized on forward and backward digit span

Table 4 Results from simultaneous regression predicting T2 sensitivity with non-RSVP performance measures

Predictors	Standardized regression coefficients (β)	Semipartial correlations	*t* values
OSPAN	0.23	0.19	1.32
Digits forward	−0.01	−0.01	−0.08
Digits backward	0.02	0.01	0.09
Ravens	0.27	0.24	1.69
Reading comprehension	−0.04	−0.03	−0.23
Reading rate	−0.07	−0.06	−0.40

Table 5 Results from simultaneous regression predicting T1 accuracy with non-RSVP performance measures

Predictors	Standardized regression coefficients (β)	Semipartial correlations	*t* values
OSPAN	0.25	0.20	1.39
Digits forward	−0.04	−0.03	−0.21
Digits backward	0.01	0.01	0.05
Ravens	0.21	0.19	1.31
Reading comprehension	0.11	0.09	0.62
Reading rate	−0.21	−0.17	−1.15

Discussion

In the present study, individual differences in cognitive performance measures were not significant predictors of individual differences in AB magnitude except for scores on the OSPAN WM task, which predicted AB magnitude once the variability the OSPAN shared with forward and backward digit span was removed. Higher WM scores were associated with smaller AB magnitudes. This pattern was observed even when variability due to general fluid intelligence, reading ability, and T1 and T2 accuracy were partialled out. These results support those of Colzato et al. (2007) who also observed that WM performance was negatively related to AB magnitude even after variability due to fluid intelligence was removed. However, in contrast to Colzato et al., who observed a significant relationship between WM performance and AB magnitude in the zero-order correlations, our relationship between WM scores and AB magnitude was apparent only once the variability due to digit span was removed. Notwithstanding, the present results support and extend those of Colzato et al. (2007) in three ways.

The first contribution of this study is that it provides further support for the relationship between WM and AB magnitude. This support is timely in that Martens and Johnson (2008) have recently observed no relationship between WM and AB magnitude, and argued that no relationship may exist between these measures. In contrast to the present work, and that of Colzato et al., Martens and Johnson used the symmetry span task as a measure of spatial WM and the reading span task as a measure of verbal WM (see http://psychology.gatech.edu/renglelab) instead of the OSPAN task. The use of different WM measures may explain the different pattern of results. However, both of the WM measures used by Martens and Johnson are similar in nature to the OSPAN measure in that to-be-remembered material is presented along with irrelevant information that prevents verbal rehearsal and requires some central resources at the expense of the to-be-remembered material. While we have no ready explanation for the discrepant results across studies, the present results do support the conclusions of Colzato et al. that individual differences in executive control of working memory are negatively related to AB magnitude.

The second contribution is that the present results provide evidence that WM is not only related to AB magnitude when variability due to general fluid intelligence is removed, but also when variability due to reading ability (reading rate and comprehension) is removed. This is noteworthy given that the vast majority of AB tasks use alphanumeric materials, with many using words.

The last, and most important, contribution of the present work is that it allows us to conclude that it is the executive control component of WM that underlies its relationship with AB magnitude, not its storage capacity. As discussed in the Introduction, measures of WM such as the OSPAN are thought to tap two aspects of WM, a storage capacity component and a more dynamic executive control component that reflects the efficiency of handling information in WM (Baddeley, 1996). Indeed, several studies have provided neurophysiological evidence for this dissociation between storage and executive control in WM, suggesting that prefrontal cortex supports the executive control aspect of WM while the information may be stored more posteriorly (e.g., Curtis & D'Esposito, 2003; D'Esposito et al., 2006; Postle, 2006; Postle et al., 1999). Although Colzato et al. (2007) posited that individual differences in executive control of information in WM was the factor responsible for the relationship between WM and AB magnitude, they were unable to separate the executive control component of WM from the storage capacity component of WM. In the present study forward digit span was used as a measure of simple WM storage capacity, and backward digit span as a measure of capacity with relatively modest executive control demands (given that no competing irrelevant information was presented and verbal rehearsal should be relatively unimpaired; Kaufman & Lichtenberger, 1999). Despite the fact that forward and backward digit span were moderately correlated with OSPAN scores and several other cognitive performance measures, neither digit span measure predicted AB magnitude in any analysis, suggesting that WM capacity was unrelated to AB magnitude. Furthermore, the relationship between OSPAN scores and AB magnitude increased when variability shared between the OSPAN and digit span was removed. If individual differences in storage capacity and executive control both contributed to OSPAN scores, but digit span reflected storage capacity with little variability due to executive control, then the overlapping variability between digit span and OSPAN (variability that was removed in the regressions) should predominantly reflect variability due to storage capacity, and the variability unique to the OSPAN (variability remaining for OSPAN in the regression) should reflect (at least in part) variability related to executive control. Therefore, we agree with Colzato et al. (2007) that individual differences in the executive control of WM underlie the relationship between WM and the AB, but here we provide direct evidence for this conclusion.

The conclusion that individual differences in executive control of WM predicts AB magnitude is consistent with imaging and MEG studies (e.g., Gross et al., 2004; Marcantoni et al., 2003; Marois et al., 2000) of the AB which have shown that the AB is associated with activation in areas such as lateral frontal sites and the anterior cingulate - areas thought to be involved in working memory executive control of attention (Miller & Cohen, 2001; Posner & Dehaene, 1994). These results suggest that individual differences in other executive control tasks may also predict individual differences in AB magnitude and we are currently pursuing this idea further.

The present findings and conclusions are also consistent with the pattern of results observed by Akyürek and Hommel (2005, 2006) and Akyürek et al. (2007). Akyürek and Hommel (2005, 2006) found that the size of the WM load and the relationship of the WM items to the items in the RSVP stream did not modulate the AB. However, Akyürek et al. (2007) found that AB size did increase with the size of the WM load when the T1 task required active scanning of WM contents to decide whether T1 was or was not a member of the memory set. Larger memory sets resulted in larger AB magnitudes than smaller memory sets. Akyürek et al. (2007) concluded that maintenance of items in WM does not influence limited capacity attentional processing, but that active use or manipulation of the same information in WM does modulate attentional processing. If maintenance of items in WM does not influence the AB, then it makes sense that individual differences in maintenance of items in WM should not predict individual differences in AB magnitude (as we observed here with digit span). However, if active use of the items in WM does modulate the AB, then it makes sense that individual differences in manipulation of items in WM should predict individual differences in AB magnitude (as we observed here with the OSPAN).

How might executive control of WM modulate the AB? Using event-related brain potentials (ERPs), Martens et al. (2006) showed that individuals with little or no AB (“non-blinkers”) produced large P3 ERP components to T1 that ended earlier than the P3’s from those individuals who showed a larger AB (“blinkers”). They also observed that the “non-blinkers” showed less activation of RSVP distractors than did “blinkers”. Similarly, Dux and Marois (2008) reported that individuals who showed less identity priming of T2 by a previous distractor (suggesting successful inhibition of RSVP distractors) showed a smaller AB and higher T1 accuracy than those who showed more priming from irrelevant T2 distractors. Results from both Martens et al. (2006) and Dux and Marois (2008) suggest that the non-blinkers were better able to suppress or ignore irrelevant distractors, allowing them to attend to critical targets more fully and efficiently. Although Martens et al. (2006) and Dux and Marois (2008) did not measure WM in their studies, it is possible that those individuals who produced little or no AB had greater executive control of WM which may have manifest as greater control and selectivity over the contents of WM. Indeed, Vogel et al. (2005) recently observed that individuals with high visual WM capacity (known as K, see Vogel et al., 2001) are more successful at ignoring the irrelevant visual items in a spatial display (e.g., the blue boxes presented amongst the red boxes) than individuals with low WM capacity. Based on these results, Vogel and colleagues posit that individual differences in WM “size” may have more to do with individual differences in the executive control of regulating access to visual WM than differences in the storage capacity of WM. Based on the present results, and those of Colzato et al. (2007), Martens et al. (2006), Dux and Marois (2008), and Vogel, McCullough, & Machizawa, (2005), we posit that individuals with high OSPAN scores have greater executive control over the contents of WM and that this control allows them to more efficiently select targets over distractors such that distractors are less viable competitors for WM resources while viewing the RSVP stream.

Predicting target accuracy

Both Ravens fluid intelligence scores and OSPAN scores were significant individual predictors of T1 accuracy and T2 sensitivity where greater fluid intelligence and WM predicted higher T1 accuracy and greater T2 sensitivity. However, Ravens and WM appear to explain common variability in RSVP target performance given that neither Ravens nor OSPAN were significant unique predictors of T1 accuracy or T2 sensitivity in the regressions. The positive relationship between Ravens scores and T2 performance, but no relationship between Ravens scores and AB magnitude, replicates Colzato et al. (2007) who demonstrated this same pattern. A similar pattern was observed by Arnell et al. (2006) who found that individual performance differences on tasks such as speeded stimulus naming and manual choice reaction time predicted individual differences in RSVP target accuracy, but not AB magnitude. This pattern is also consistent with Akyürek and Hommel's (2005, 2006) finding that WM load influenced overall T2 accuracy (with lower T2 accuracy at higher memory loads), but not the AB per se. Together these studies show that overall T2 accuracy (the height of the line) may be predicted by an individual's processing speed and capacity, but that AB magnitude (the slope of the line) may be predicted by an individual's attentional control for access into WM. This also underscores the point that T2 accuracy (the height of the line representing accuracy across lag) is dissociable from the AB (slope of the line across lag), and that the AB can only be estimated and predicted accurately when the slope across lag is taken into account—a distinction that is too often forgotten.

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