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Brief Reports

Working memory and the attentional blink: Blink size is predicted by individual differences in operation span

Lorenza S. Colzato, Michiel M. A. Spapé, Merel M. Pannebakker, and Bernhard Hommel
Leiden University, Leiden, The Netherlands

The attentional blink (AB) is often attributed to resource limitations, but the nature of these resources is commonly underspecified. Recent observations rule out access to short-term memory or storage capacity as limiting factors, but operation bottlenecks are still an option. We considered the operation span of working memory (WM) as a possible factor and investigated the relationship between individual WM operation span (as measured by OSPAN), fluid intelligence (as measures by Raven's SPM), and the size of the AB. WM operation span was negatively correlated with the AB, whereas fluid intelligence was associated with higher overall accuracy but not with AB magnitude. These results support the idea that individual processing limitations (with regard to either attentional allocation policies or the speed of global cortical integration processes) play a key role in the AB.

A well-established method of studying attention measures the amount of information that can be processed within a fixed time interval. In 1976, Potter published a classic series of experiments to investigate how fast people can process real-world scenes. In the so-called *rapid serial visual presentation* (RSVP) task she used, people are presented with streams of briefly visible stimuli and asked to recognize these as fast as possible. While detecting single targets under these conditions is surprisingly easy, detecting two targets is rather difficult, as demonstrated by the attentional blink (AB; Raymond, Shapiro, & Arnell, 1992). The AB occurs when the second (T2) of two targets appears about 100–450 msec after the first (T1). The only exception is the lag-1 condition, hence, in which T2 immediately follows T1: In many (but not all: Visser, Bischof, & Di Lollo, 1999) task versions, performance on T2 is then about as good as at very long lags, which is why this phenomenon is called "lag-1 sparing."

The most prominent capacity-limited account of AB refers to limited attentional resources (Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Vogel, Luck, & Shapiro, 1998). According to these theories, the AB is due to what is called a structural bottleneck: Reporting a stimulus presupposes that its sensory representation is transferred to, and consolidated in working memory (WM), a process that is assumed to draw on attentional resources. If these resources are allocated to consolidating T1—to a degree that depends on how severely T1 is masked by following items—fewer resources are left to consolidate T2. This makes T2 codes vulnerable to interference from other items competing for representation in WM, so that it is less likely to be maintained and reported later on. In other words, processing T1 and consolidating it in short-term memory (STM) for conscious report is assumed to draw on these resources, which therefore are not available for processing T2 if it appears before T1 processing is completed. However, how such resources are to be characterized has remained more or less of a mystery. Importantly, recent studies have shown that people can process and report even more than two targets if only these targets are presented in a sequence, that is, if they are not separated by distractors (Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Nieuwenstein & Potter, 2006; Olivers, van der Stigchel, & Hulleman, 2007). Together with the observation of lag-1 sparing, these findings are inconsistent with the idea that the AB might reflect limitations in terms of storage space or access to STM. Hence, the processing bottleneck may not be structural but functional, in the sense that people allocate more attentional resources to T1 than necessary, either voluntarily (i.e., strategic) or involuntarily (e.g., attentional capture by the stimulus). That is, an "early" T2 is only excluded from crucial processing stages if it does not manage to become part of the same attentional episode as T1 (for variations on this theme, see Di Lollo et al., 2005; Hommel & Akyürek, 2005; Jolicœur, Tombu, Oriet, & Stevanovski, 2002; Raymond et al., 1992)—be it because the appearance of a distractor triggers the closing of an episode (Di Lollo et al., 2005) or because it is closed by top-

L. S. Colzato, colzato@fsw.leidenuniv.nl

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down mechanisms (Akyürek & Hommel, 2006; Akyürek, Riddell, Toffanin, & Hommel, 2007).

The idea of a functional or operational bottleneck brings WM into the picture. Simply put, WM comprises of a storage component (STM proper) and an operational, executive component (Baddeley, 1996), which according to our consideration might well play a role in the AB. Consistent with this picture, Postle, Berger, and D'Esposito (1999) have reported a functional neuroanatomical double dissociation (in perisylvian cortex and in dorsolateral prefrontal cortex) of mnemonic and executive control processes contributing to working memory performance. In particular, individuals with a higher operation WM (i.e., people who are more efficient in handling and operating on the contents of STM) might be expected to exhibit a smaller AB. To investigate whether they do, we obtained individual measures of WM operation span from participants in a RSVP study and tested whether these measures would correlate negatively with the sizes of the individual ABs. However, WM capacity is well known to correlate with fluid intelligence (for an overview, see Kane & Engle, 2002), which raises the possibility of a confound. We therefore also determined the level of fluid intelligence for each participant, which allowed us to disentangle the independent contributions of fluid intelligence and WM operation span. The main question thus was whether individual WM operation span would predict the size of the AB even if fluid intelligence is controlled for—even though an effect of intelligence would of course be interesting in itself.

METHOD

Participants

Eighty volunteers (52 women and 28 men, between 18 and 30 years old) took part for pay. They were recruited through an advertisement posted on a dedicated Web site of Leiden University. Our sample covered the IQ range from 80–140 and the WM operation span range from 31–59 (as measured by OSPAN; see below). All participants reported having normal or corrected-to-normal vision and were not familiar with the purpose of the experiment.

Apparatus and Stimuli

The RSVP experiment was controlled by a Targa Pentium III computer. All stimuli were presented at a resolution of 800×600 pixels in 16-bit color on a 17-in. CRT refreshing at 100 Hz. Participants were seated at a viewing distance of about 50 cm from the fixation mark ("+"), and all RSVP items were presented centrally in black on a gray background (RGB 128, 128, 128). Each item was set in 16 point Times New Roman font. Letters were drawn randomly without replacement from the full alphabet. Digits were drawn from 1 to 9.

Procedure and Design

The study consisted of three sessions, including a task used to determine individual WM operation span, a fluid intelligence test, and the RSVP task. The sessions were held always in the same morning. Participants always started with the RSVP task followed by the other two sessions counterbalanced between subjects. Participants were allowed to take a short break (maximal 10 min) between sessions.

Individual WM operation span scores were determined using the OSPAN (operation word span) task adapted from Turner and Engle (1989). This task requires participants to solve simple mathematical operations while remembering words for later recall. Participants are presented with an operation–word pair and required to read the operation aloud, say "yes" or "no" to indicate whether the given answer is correct or incorrect, and then report the to-be-remembered word aloud. Sixty operation–word combinations were presented in a total of 15 trials: 3 trials of each combination of calculation–word combinations (2–6). These different trials were completely randomized; so were the calculations and words. The OSPAN score can vary between 0 and 60. The OSPAN task measures a combination of storage and processing capacity (Engle, Kane, & Tuholski, 1999), with the latter being of particular importance for our present study.

Individual IQs were determined by means of a 30-min reasoning-based intelligence test (Raven's Standard Progressive Matrices [SPM]). Each item of this test consists of a pattern or sequence of a diagrammatic puzzle with one piece missing, the task being to complete the pattern or sequence by choosing the correct missing piece from a list of options. The items get more difficult as the test taker proceeds through the test. The SPM assesses the individual's ability to create perceptual relations and to reason by analogy independent of language and formal schooling; it is a standard, widely used test to measure Spearman's *g* factor and fluid intelligence in particular (Raven, Court, & Raven, 1988).

In the RSVP task, participants were asked to identify and report two digits (T1 and T2) presented in a stream of letter distractors. After having read the instructions, which included a slow demonstration of the RSVP, and indicating to have fully understood the task, participants were required to go through 24 trials of training. If more than 50% of the responses were incorrect during the training, the experiment was automatically restarted. An initial fixation plus sign, which was shown for 2,000 msec, marked the beginning of each trial. After a blank interval of 250 msec, the RSVP commenced, consisting of 20 items with a duration of 40 msec each and an interstimulus interval of 40 msec.

A full experimental session lasted 30 minutes and contained one block of 360 trials (3 locations of T1 $\times$ 4 lags $\times$ 30 repetitions). The design consisted of one within-participants variable: T2 lag. Lag was determined by the number of items between T1 and T2. T1 position was randomly varied between Positions 7, 8, and 9 of the stream in order to reduce the predictability of target onsets. T2 was presented directly thereafter (lag 1), or after another 2, 4, or 7 distractors (lags 3, 5, and 8, successively; see Figure 1). Both targets were to be reported directly (order of report was not considered) after the RSVP—the question being, "Which two targets did you see?"—by pressing the corresponding digit key.

Half of the participants began with OSPAN, the other half began with SPM. All the participants performed the RSVP task as last session. They had a short break between the sessions.

RESULTS

We adopted a significance level of $p < .05$ for all statistical tests and tested our hypothesis in three ways. First, we analyzed performance on T1 (absolute accuracy) and T2 (accuracy and those trials where T1 was correctly reported—i.e., T2|T1) separately, with lag as within-participants variable. For each measure, we ran an ANOVA and an ANCOVA (Type III sum of squares) with WM operation span, and fluid intelligence added as continuous covariates.[1] Second, we ran correlation analyses that looked into the association between operation span and fluid intelligence on the one hand and performance on T1 and T2, and AB size in particular, on the other. Third, we conducted a stepwise regression analysis, in which we used operation span and fluid intelligence measures to predict AB size, so we could directly compare the relative contributions from these two predictors.

ANOVAs

We first looked into T1 performance (see Figure 2). The ANOVA with lag as within-participant factor showed

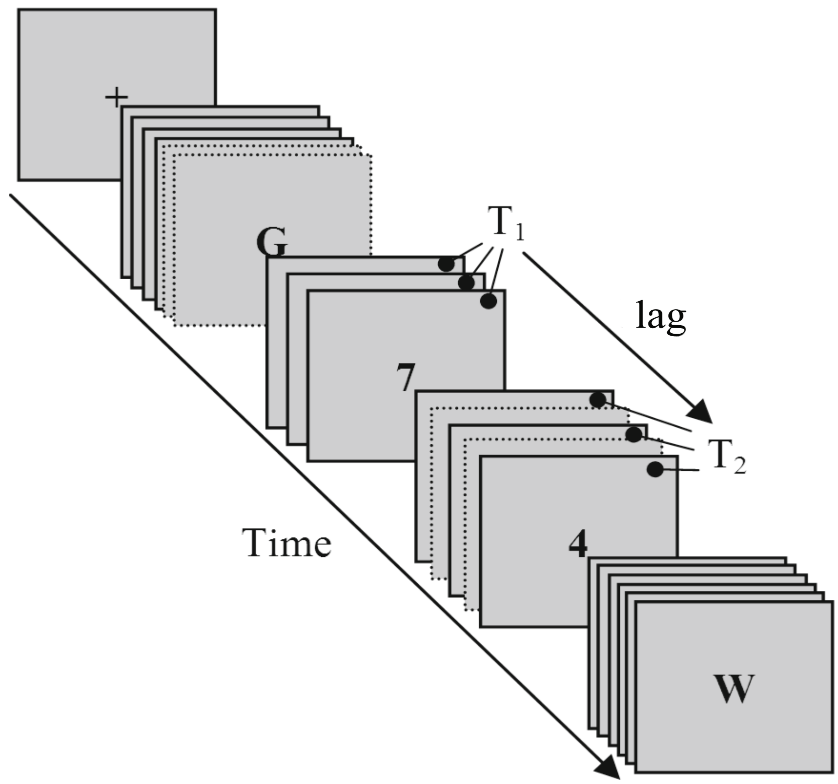

Figure 1. Events in the RSVP trial. A new display appeared every 80 msec. The two targets (T1, T2)—digits among letters—were separated by either one, three, five, or eight nontarget displays, defining the *lag*. The first digit was presented at Position 7, 8, or 9 of the visual stream.

a significant lag effect [$F(3,237) = 473.58$, $p < .001$]. As the figures show, the lag effect was due to a dip in performance at lag 1, where the two targets appeared in close succession. This pattern[2] is often observed if T1 and T2 are defined in the same way (so that they satisfy the same selection criteria) and the presentation rate is fast, suggesting that under these circumstances the two targets compete for selection (Hommel & Akyürek, 2005; Potter, Staub, & O'Connor, 2002). Adding WM operation span and IQ as covariates eliminated the lag effect (suggesting multicollinearity between lag and fluid intelligence) but yielded a main effect of fluid intelligence [$F(1,77) = 11.59$, $p < .001$], indicating that participants with higher IQs are doing better in general.

The analysis of conditional T2 performance (T2|T1) revealed a different picture. The ANOVA yielded a significant lag effect [$F(3,237) = 63.09$, $p < .001$], indicating a marked AB with good performance at lag 1 (lag-1 sparing; Visser et al., 1999) and a considerable dip at lags 3 and 5. This is the standard pattern comparable to that reported by Chun and Potter (1995) and others, demonstrating that we were able to obtain a healthy AB. Adding WM operation span and IQ as covariates yielded a lag effect [$F(3,231) = 5.43$, $p < .001$] that interacted with operation span [$F(3,231) = 3.95$, $p < .01$] but not with IQ ($F < 1$). Hence, the AB was modulated by WM operation span, just as the idea of a functional bottleneck would suggest: The blink was more pronounced in participants with low, as compared to high WM operation span (see Figure 2).

Correlations

Table 1 presents the correlations between the individual scores of WM operation span, IQ, the maximal AB (measured as T2|T1 at lag 8 minus the minimum of T2|T1 at lag 3 and at lag 5), lag-1 sparing (measured as T2|T1 at lag 1 minus the minimum of T2|T1 at lag 3 and at lag 5; see Visser et al., 1999), and the mean accuracy in reporting T1 (unconditional) and T2|T1 (both computed by averaging across lags). Figure 3 shows the scatterplots for the relationship between WM operation span and IQ, and T1 performance and AB.

As anticipated, WM operation span and our measure of fluid intelligence correlate with each other.[3] As is well known in the literature (Ackerman, Beier, & Boyle, 2002; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Süβ, Oberauer, Wittmann, Wilhelm, & Schulze, 2002),

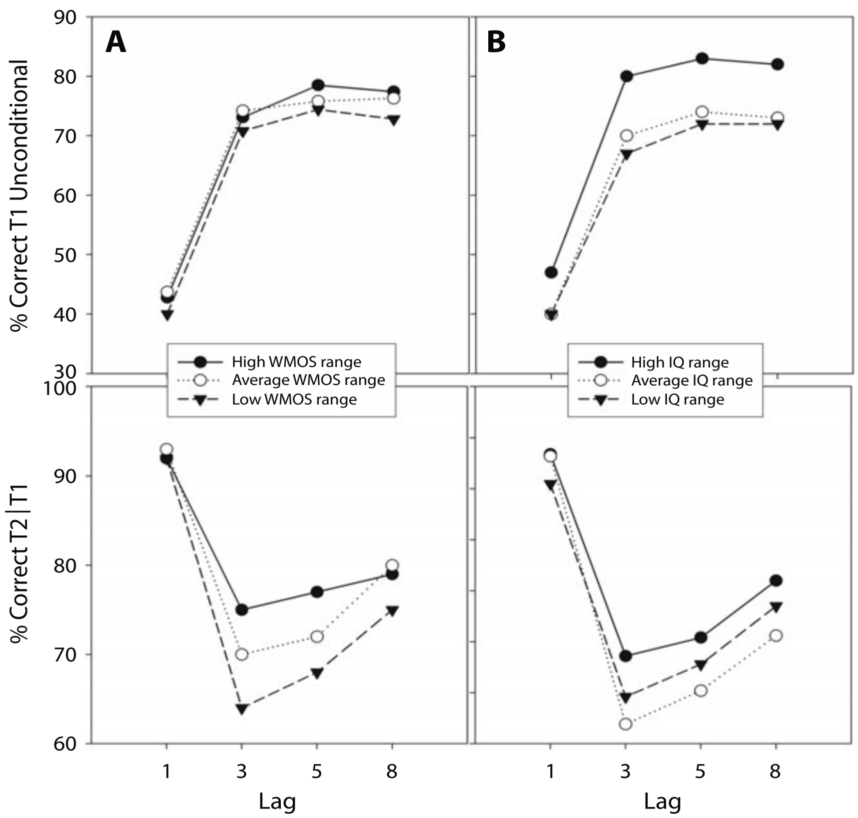

Figure 2. T1 (unconditional) performance for high (48–58), average (41–47), and low (27–40) working memory operation span (WMOS—panel A, top) and for high (121–140), average (111–120), and low (80–110) IQ (panel B, top). T2 performance given T1 correct (T2|T1) for high, average, and low WMOS (panel A, bottom) and for high, average, and low IQ (panel B, bottom).

WM capacity and *g* are indeed highly related but are not the same construct. Conway, Kane, and Engle (2003) suggested that WM capacity accounts for about one third of the variance in *g*.

IQ further correlated with the mean accuracy of reporting T1 and reporting T2. Together with the corresponding ANOVA results, these findings support the widely shared assumption that people high in fluid intelligence are not only faster but also more accurate (Deary, 2000; Jensen, 1993; Vernon, 1987) and, indeed, under time constraints as they are present in RSVP tasks faster processing implies higher accuracy. With regard to the impact on general performance shown in Figure 2, one might hypothesize that fluid intelligence is associated with the enhanced initial detection of target features. As suggested by Miller and Cohen (2001), executive control involves the active maintenance of the goals and rules of a task. In the case of our study, this comprises of the detection of the two targets in a stream of distractors, which requires the active maintenance of target templates to guide target selection. Much as people high in fluid intelligence are better able to maintain task goals (Duncan, Burgess, & Emslie, 1995; Duncan, Emslie, Williams, Johnson, & Freer, 1996), they may also be better in maintaining selection criteria.

In stark contrast to fluid intelligence, WM operation span correlated with the blink[4] and it did so the way one would expect: More processing capacity reduces the size of the blink. These results nicely replicate the findings of Bleckley, Hollingsworth, and Maki (2005), who also observed that the size of the AB was larger for individuals with low scores of WM operation span. However, as said before WM capacity and psychometric fluid intelligence are highly related constructs (e.g., Kyllonen & Christal 1990). In order to isolate the impact of WM operation span we ran partial correlations: the correlation between WM operation span and the maximal AB was $r^2 = -.309$ ($p = .006$) after partialing out fluid intelligence, whereas the correlation

Table 1
Correlations Among Individually Computed Scores of IQ, Working Memory Operation Span (WMOS), Maximal AB, Lag-1 Sparing (L1S), and Mean Accuracy in Reporting T1 (Unconditional) and T2|T1

	IQ	WMOS	AB_{max}	L1S	T1
WMOS	.25*				
AB_{max}	−.15	−.33**			
L1S	−.11	−.28*	.50**		
T1	.39**	.19	−.21	.43**	
T2|T1	.31**	.20	−.31**	.60**	.88**

*$p < .05$. **$p < .01$.

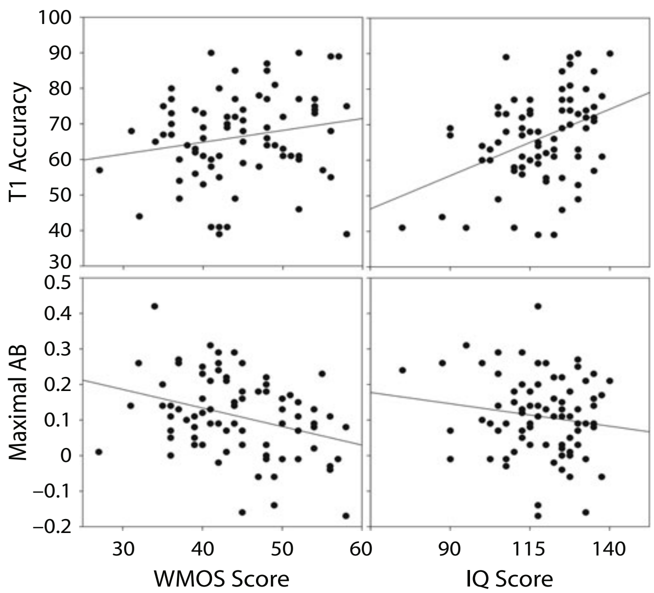

Figure 3. Scatterplots of the relationships between working memory operation span (WMOS) and T1 accuracy, WMOS and the maximal attentional blink (AB), IQ, and T1 accuracy, and IQ and the maximal AB.

between fluid intelligence and the maximal AB was $r^2 = -.069$ ($p = .545$) after partialing out WM operation span. These observations support the assumption that WM operation span, but not fluid intelligence, modulates the AB deficit. Importantly, this failure to find a significant correlation between IQ and AB cannot be attributed to low reliability of our AB size measure, given a Cronbach's alpha of .90.

WM operation span also correlated significantly with lag-1 sparing, and it did so even after partialing out intelligence ($r^2 = -.265$, $p = .018$). The sign of the correlation was the same as for the AB, indicating that higher operation span scores went with less sparing. However, note that sparing scores are not entirely independent of the AB scores, as the former cannot exceed the latter. In other words, we cannot exclude that individuals with high scores of operation span showed lesser lag-1 sparing simply because their smaller AB left them with less to spare.

Regression

The hierarchical regression analysis with individual maximal AB sizes as the dependent variable and individual IQ score as predictor showed that the IQ score alone did not allow for a reliable prediction of the maximal AB size ($\beta = -.15$, $t = 1.30$, $R^2 = .02$, $p = .20$). Adding the operation span scores ($\beta = .32$, $t = -2.85$, $p = .006$) improved the prediction significantly [$F(1,77) = 8.141$, $\Delta R^2 = .09$, $p = .006$]. These observations support the assumption that WM operation span, but not intelligence, modulates the AB deficit.

CONCLUSIONS

We obtained evidence that people high in WM operation span show a smaller AB, while people high in fluid intelligence show better overall performance. Taken together our results support models that attribute the AB to WM in general and to operational resource limitations (Dehaene, Sergent, & Changeux, 2003; Di Lollo et al., 2005; Gross et al., 2004; Hommel et al., 2006) in particular. These results fit well with the idea that differences between individuals with good versus poor working memory reflect differences in the ability to efficiently handle working memory contents and to control attentional selection (Engle, Kane, & Tuholski, 1999; Kane et al., 2004). There are several possible, not mutually exclusive ways in which these differences may affect the AB.

First, higher WM operation span may imply more, or more efficient, parallel processing. Event-related potential studies have revealed that even blinked T2s elicit electrophysiological indicators of visual and semantic processing (Luck, Vogel, & Shapiro, 1996; Vogel et al., 1998) and findings from magnetoencephalography suggest that encoding processes for two targets can overlap in time (Kessler et al., 2005). This means that quite some parallel processing is possible before, or outside, the AB-related bottleneck, and it may be that high operation WM allows for even more parallelism.

Second, while encoding the features of a target may be a local process, so that many encoding operations can go on in parallel, integrating target information with the current context to create an episodic memory trace may be considered a global process (Dehaene et al., 2003; Gross et al., 2004; Hommel et al., 2006; see also Jolicœur & Dell'Acqua, 1998). As observations of Gross et al. (2004) suggest, integrating and consolidating target information for later report in a RSVP task requires the neural synchronization of a widespread attentional network including the inferotemporal, the posterior-parietal, and the lateral-frontal cortex—presumably responsible for stimulus identification, attentional selection, and top-down support of goal-related information, respectively (Hommel et al., 2006). If a new target happens to appear while the attentional network is busy with synchronizing (i.e., integrating other information),[5] it not only fails to receive any top-down support, it will also be excluded from the ongoing integration process. Hence, targets appearing after the synchronization process has started are likely to get "blinked." If we assume that people scoring high in WM operation span are more efficient or faster in building up and carrying out global cortical operations, it is easy to see that they would be faster (though not necessarily better) to integrate T1 and therefore less likely to miss T2.

Third, a higher operation span may allow for the more efficient suppression of distractor-induced interference at short lags, which according to the temporary-loss-of-control model of Di Lollo et al. (2005) is the main reason for the AB deficit. Indeed, WM capacity has been linked to efficiency in handling interference (Kane & Engle, 2002) and the OSPAN task, which requires resolving interference between different tasks, may well measure distractor-suppression efficiency.

Fourth, a higher operation span may permit, or at least be associated with, longer integration windows; that is, people high in operation span may tend to leave attentional gates longer open. This need not affect performance at lag 1, which may be covered even in people with lower spans, but it may extend integration to later lags and, hence, to targets appearing at them.

Finally, people high in operation span may have smarter attentional allocation policies at their disposal. Accordingly, they may avoid overinvesting resources into T1 processing (in the sense of Olivers & Nieuwenhuis, 2005, 2006) and, thus, leave more capacity for T2 processing. Indeed, recent neurophysiological findings suggest that individuals investing less attentional resources into T1 processing exhibit a less pronounced AB (Shapiro et al., 2006).

AUTHOR NOTE

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NOTES

1. Since results of analyses with continuous independent variables are difficult to depict, we for presentational purposes created three bins of WM operation span performance and IQ by taking the cutoff values for WM and IQ scores that were closest to the cumulative percents of 33.3 and 66.6. This yielded three operation span levels—(relatively) low (24 participants, 27–40 score), average (26, 41–47), and high (30, 48–58)—and three IQ levels—(relatively) low (26 participants, 80–110 IQ), average (28, 111–120), and high (26, 121–140).

2. Even if, as compared with these other studies, we obtained a rather large dip in performance at lag 1, this did not affect the interpretation of our results.

3. Note that, given the university population investigated in this study, the range of SPM scores is fairly restricted, with only 7 subjects scoring under 100. Such range restrictions may have limited the potential of IQ scores to correlate with WM operation span, which explains the smaller-than-typical correlation between OSPAN and SPM.

4. Other measures of the AB deficit (e.g., T2 lag 8 | T1 − T2 lag 3 | T1) were also highly correlated with WM operation span ($r^2 = -.32$, $p < .001$), confirming that our results do not depend on how the AB is measured.

5. As mentioned above, the information considered by the hypothesized global operation it unlikely to be fixed in terms of number of stimuli or temporal integration window. Global integration may be triggered (and, thus, the content of the resulting episodic trace be determined) exogenously (e.g., by the presence of a nontarget—Di Lollo et al., 2005) or endogenously (Akyürek et al., in press).

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