The relationship between sustained inattention blindness and working memory capacity

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Abstract Inattention blindness, whereby observers fail to detect unexpected stimuli, has been robustly demonstrated in a range of situations. Originally research focused primarily on how stimulus characteristics and task demands affect inattention blindness, but increasingly studies are exploring the influence of observer characteristics on the detection of unexpected stimuli. It has been proposed that individual differences in working memory capacity predict inattention blindness, on the assumption that higher working memory capacity confers greater attentional capacity for processing unexpected stimuli. Unfortunately, empirical investigations of the association between inattention blindness and working memory capacity have produced conflicting findings. To help clarify this relationship, we examined the relationship between inattention blindness and working memory capacity in two samples ($N_s = 195, 147$) of young adults. We used three common variants of sustained inattention blindness tasks, systematically manipulating the salience of the unexpected stimulus and primary task practice. Working memory capacity, measured by automated operation span (both Experiments 1 & 2) and N -back (Experiment 1 only) tasks, did not predict detection of the unexpected stimulus in any of the inattention blindness tasks tested. Together with previous research, this undermines claims that there is a robust relationship between inattention blindness and working memory capacity. Rather, it appears that any relationship between inattention blindness and working memory is either too small to have practical significance or is moderated by

other factors and consequently varies with attributes such as the sample characteristics within a given study.

Keywords Visual awareness · Working memory · Attention: Divided Attention and Inattention

Introduction

Imagine that you are in your car, waiting at a red light. When the light turns green, you accelerate immediately, narrowly missing a pedestrian. Startled, you realise that you did not notice the person crossing in front of your vehicle because you were monitoring the traffic light. You experienced *inattention blindness* (IB; Mack & Rock, 1998), the failure to notice an unexpected object when attention is preoccupied. IB has theoretical importance, highlighting the extent to which our attention determines our perception, and profound practical implications, through its contribution to understanding incidents such as “looked-but-failed-to-see” road crashes (Beanland, Lenné, & Rößger, 2015). IB has been consistently demonstrated in both computerised displays (Beanland & Pammer, 2010a, b; Mack & Rock, 1998; Most et al., 2001) and naturalistic stimuli (Furley, Memmert, & Heller, 2010; Neisser, 1979; Simons, 2010; Simons & Chabris, 1999). The archetypal IB experiment entails an attention-consuming primary task, often presented in isolation for several trials before an unexpected stimulus is added during the *critical inattention trial*. Participants who do not detect this stimulus are deemed to have experienced IB. For the final *full attention trial*, observers are instructed to simply watch the display and, in the absence of an attention-consuming primary task, detection of the critical stimulus reaches ceiling.

Whereas much is known about how task demands and display characteristics influence the detection of unexpected stimuli (see Jensen, Yao, Street, & Simons, 2011, for a review),

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there is currently limited understanding of the extent to which individual differences predict IB. Most IB-related individual differences research has focused on working memory capacity (WMC), on the assumption that attentional control, and consequently one's ability to consciously perceive unexpected stimuli, fundamentally relies on WMC (Seegmiller, Watson, & Strayer, 2011). Although this logic is plausible, experimental investigations have yielded contradictory results. The following discussion focuses on sustained IB, which refers to IB for an unexpected stimulus that appears for several seconds during a prolonged display of dynamic stimuli (Most, Simons, Scholl, & Chabris, 2000), because researchers have postulated static and dynamic IB may reflect distinct underlying mechanisms (Most, 2010) and performance in static and dynamic IB tasks is not correlated (Horwood & Beanland, *in press*; Kreitz, Furley, Memmert, & Simons, 2015a). For research examining the relationship between WMC and static IB, readers may refer to Calvillo and Jackson (2014) and Kreitz et al. (2015a).

At least four papers, detailing five experiments, have reported a statistically significant relationship between WMC and sustained IB (Hannon & Richards, 2010; Richards, Hannon, & Derakshan, 2010; Richards, Hannon, & Vitkovitch, 2012; Richards, Hellegren, & French, 2014). All emanate from the same research group and use highly similar methodologies: most use sample sizes of 66–82 with wide age variation (e.g., 18–60 years). In all but one variant, the IB task contained a single trial, so observers had no opportunity to practice the primary task before the unexpected stimulus appeared. This is relevant given research indicating that primary task practice significantly reduces IB (Neisser, 1979; Richards et al., 2010). The unexpected stimulus was a red cross that appeared midway through a sustained object-tracking task in which observers tracked four white targets while ignoring four black distractors, with IB rates of 47–90 %. Noticers of the red cross scored higher than non-noticers on WMC as measured by operation span (OSPAN; Hannon & Richards, 2010; Richards et al., 2010) and automated OSPAN (AOSPAN; Richards et al., 2012, 2014). The effects reported have borderline statistical significance: Richards et al. (2012) report a one-tailed *t* test with $p = .05$; Richards et al. (2010) report odds ratios (OR) of 0.92 and 0.95 with an upper 95 % confidence interval (CI) of 0.99; and Hannon and Richards (2010) report an OR of 0.932 with an upper 95 % CI of 0.996. (Note that in their variable coding, ORs < 1 indicate decreased likelihood of IB.) Thus, it appears that the effect size for IB-WMC association, even in studies that find a statistically significant relationship, is considerably smaller than the effects of task manipulations, such as attentional set (Most et al., 2001) and primary task load (Beanland, Allen, & Pammer, 2011; Simons & Jensen, 2009).

In addition to studies finding an overall IB-WMC association, one publication reported a relationship between sustained IB and WMC among a subsample of participants. Using a sample of 197 adults aged 18–35 years, Seegmiller et al. (2011) found no

main effect of WMC on IB. After adding an interaction term (WMC*primary task accuracy) to their logistic regression model, both the main effect of WMC (OR 1.06) and the interaction (OR 0.97) reached statistical significance. Among “on-task” participants with primary task accuracy above 80 %, participants in the upper WMC quartile (AOSPAN ≥ 55) were less susceptible to IB than participants in the lowest WMC quartile (AOSPAN ≤ 27). WMC did not predict IB among off-task participants. The experimental design shared similarities with studies that found a main effect of WMC: it used AOSPAN and a single-trial IB task. The task was Simons and Chabris' (1999) video, in which a gorilla unexpectedly walks through an informal basketball game. Participants were required to follow black-shirted players, ignoring white-shirted players, meaning the unexpected stimulus (black gorilla) resembled the observers' attentional set (humans wearing black), whereas the studies reporting an overall IB-WMC relationship used a visually distinctive unexpected stimulus (Richards et al., 2010).

Finally, three recent papers have reported no relationship between WMC and sustained IB across four experiments (Bredemeier & Simons, 2012; Kreitz et al., 2015a, b), using larger samples (*N*s 115, 134, 198, 207) of young adults. In all four studies, participants completed several trials of the primary task before the unexpected stimulus appeared. Similar to Richards and colleagues (Hannon & Richards, 2010; Richards et al., 2010, 2012, 2014), the IB tasks required observers to track four white targets while ignoring four black distractors, or vice-versa. Although the unexpected stimulus was distinctive (a grey cross), it was not as salient as the red cross used in other research; however, Most et al. (2001) found that salience of the unexpected stimulus does not necessarily influence IB rates. In the two studies by Bredemeier and Simons (2012), all participants were shown the same unexpected stimulus (lighter grey in Study 1, darker grey in Study 2) with the same motion path, whereas Kreitz et al. (2015a) systematically manipulated whether the unexpected stimulus was near or far from the focus of attention, and Kreitz et al. (2015b) systematically manipulated whether the unexpected stimulus was more similar to the attended or unattended items. These parameters yielded IB rates varying from 5–73 %. WMC, measured by both AOSPAN and *N*-back tasks, was not associated with IB in any of these experimental conditions. Bredemeier and Simons (2012) noted three methodological differences between studies that find an association and those that do not, which could explain the discrepant IB-WMC findings: participant age range; primary task practice; and unexpected stimulus salience. Specifically, the IB-WMC association seems to emerge in samples with a wide age range, when observers have minimal or no practice at the primary task, and the unexpected stimulus is salient (red in a monochromatic display).

Clarifying the role of WMC in IB is an issue of some theoretical importance, because it could shed light on the

mechanisms underlying detection of unexpected stimuli. It also could make a practical contribution in applied settings; for example, if WMC is indeed a robust predictor of IB, it could be used to select candidates for positions in which IB would be particularly problematic, such as surveillance (Näsholm, Rohlfsing, & Sauer, 2014) or medical screening (Drew, Vö, & Wolfe, 2013). We therefore conducted two studies examining the IB-WMC association across three variants of sustained IB tasks.

Experiment 1

For our initial investigation of IB and WMC, we recruited a large sample of young adults to complete a sustained IB task and two WMC measures. The IB task has been used previously in our lab (Beanland et al., 2011; Beanland & Pammer, 2010a, b, 2012) and consisted of white and black objects bouncing around on a light grey background, with a dark grey unexpected stimulus. Because this is more similar to the studies that found no IB-WMC association (i.e., Bredemeier & Simons, 2012; Kreitz et al., 2015a, b), we anticipated that we would most likely find no significant relationship between IB and WMC, which we measured using AOSPAN and *N*-back tasks. We deliberately recruited a sample of 200 participants to maximise the chance of detecting any statistically reliable effects.¹

Method

Participants Overall, 202 students provided informed consent and participated for a course requirement or financial compensation. Data from seven observers were excluded: two were aged >35 years; two realised it was an IB study²; two failed to detect the unexpected stimulus under full attention; and one failed to follow instructions. The remaining 195 participants (139 female) were aged 18–33 years ($M = 20.8$, $SD = 2.2$).

Apparatus Visual stimuli were presented on computer using either a 19" or 21" CRT monitor with 1024×768 spatial

resolution. Viewing distance was 55 cm (19") or 63 cm (21"), yielding a display area of $34.1^\circ \times 25.6^\circ$.

Procedure Participants were tested individually or in pairs on individual workstations separated by a divider, in a quiet laboratory. All completed two measures of WMC (AOSPAN, *N*-back), followed by a sustained IB task. Details of each task are provided below. Prior to the experiment, participants completed a brief visual screening task to confirm they had normal or corrected-to-normal visual acuity.

Automated operation span task The AOSPAN task (Unsworth, Heitz, Schrock, & Engle, 2005) involved 15 trials. Each trial comprised 3–7 problem sets, in which participants were required to quickly solve an arithmetic equation (e.g., “ $(1 * 1) + 8 = ?$ ”) and then memorise a letter. At the end of each problem set, participants were prompted to recall all letters in order. Perfectly recalled sets receive a score equivalent to the set size (i.e., 3–7) and incorrectly recalled sets receive a score of 0, with total possible scores being 0–75. Before completing the main task, participants completed 4 practice trials of the letter recall task in isolation, 16 practice trials of the arithmetic task in isolation, and 2 practice trials of the combined AOSPAN task with set size 2.

***N*-back task** An identity *N*-back task was used, in which participants were required to respond via button press whenever the current item was identical to the one presented *N* items previously, where *N* equals 1, 2, or 3. Items were black letters presented one at a time on a light grey background with a stimulus duration of 500 ms and interstimulus interval of 1000 ms. The value of *N* was provided before each block, which consisted of a 25 letter sequence, comprising 5 targets and 20 distractors. Participants completed six blocks, two at each *N*, in random order. Results were pooled across blocks within each *N*, with *Pr* (hit rate – false alarm rate) used as the dependent measure.

Inattention blindness task An object-tracking sustained IB paradigm was employed, comprising six 15 s trials in which four white targets and four black distractors moved independently on a light grey background. Targets and distractors were squares and circles subtending $1.9^\circ \times 1.9^\circ$. Participants were instructed to count how many times the white targets “bounced” off the screen edges, while ignoring the black distractors. Trials 1–4 were *precritical trials*, which contained only expected targets and distractors, with the targets bouncing 9–11 times during each trial. Trial 5 was the *critical trial*, in which a dark grey diamond ($1.9^\circ \times 1.9^\circ$) appeared and travelled across the horizontal midline. Afterwards, participants were asked whether they had noticed anything other than the white and black shapes during the critical trial. If they answered yes they were prompted to type a description of what

¹ Power calculations for logistic regression are complex due to the range of values that have to be estimated (Hsieh, Block, & Larsen, 1998; Lyles, Lin, & Williamson, 2007). However, using G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009), we estimated that 200 participants would be adequate to detect an odds ratio <0.97 or >1.03, specifying a two-tailed distribution with $p = .05$, power $(1 - \beta) = 0.8$, AOSPAN $M = 39.16$, $SD = 17.41$ (as in Unsworth et al., 2005) and assuming a 0.5 probability of obtaining the null hypothesis (given conflicting results in previous studies).

² Based on previous research, participants were not excluded if they had previous knowledge of IB but did not realise they were participating in an IB experiment (Beanland & Pammer, 2010a; Simons, 2010).

they saw, and were classified as noticers of the unexpected stimulus if they appropriately described its shape and/or colour. During the final *full attention trial*, participants were instructed to watch the display without completing the primary object-tracking task. In this full attention trial, the same unexpected stimulus appeared again and afterwards participants were prompted to describe whether they had noticed anything that had not appeared during the pre-critical trials. Participants who failed to detect the unexpected stimulus during the full attention trial ($n = 2$) were excluded from analyses, consistent with previous research.

Results and discussion

Overall, 65 participants (33 %) noticed the unexpected stimulus. Proportional object-tracking error rates were calculated using the formula: (actual – reported bounces)/actual bounces. Across the four precritical trials average primary task error rates were similar for noticers ($M = 0.12$, $SD = 0.08$) and non-noticers ($M = 0.11$, $SD = 0.08$) of the unexpected stimulus, $t(193) = 1.00$, $p = .319$, $d = 0.15$, consistent with previous research (Simons & Jensen, 2009).

On the critical trial, error rates were significantly higher for noticers ($M = 0.08$, $SD = 0.07$) than non-noticers ($M = 0.04$, $SD = 0.07$), $t(193) = 3.27$, $p = .001$, $d = 0.50$. Our primary task was very easy, with nearly all participants (92 %) reporting the correct tally ± 1 on the critical trial. The remaining 8 % met Seegmiller et al.'s (2011) criteria of being “off-task” with more than 20 % error. The proportion of off-task participants was not significantly different among noticers (12 %) and non-noticers (7 %) of the unexpected stimulus, $\chi^2(1, N = 195) = 1.30$, $p = .393$. Due to the lack of variability in object-tracking error rates, it was not possible to correlate primary task error rates with AOSPAN scores, as has been done in previous research (Bredemeier & Simons, 2012; Seegmiller et al., 2011).

We conducted a logistic regression to determine whether WMC (indicated by AOSPAN and N -back accuracy) predicted noticing of the unexpected stimulus. Data were excluded for 40 participants who either: failed to complete AOSPAN ($n = 4$); achieved <85 % arithmetic accuracy on AOSPAN ($n = 31$); and/or exhibited chance performance on the N -back task, i.e., their hit rate was not higher than their false-alarm rate ($n = 7$). The pattern of results did not differ if these participants were included. The full model with all predictors was not significantly different to the constant-only model, irrespective of whether N -back performance was entered as a single overall variable, $\chi^2(2, N = 155) = 1.15$, $p = .562$, Nagelkerke $R^2 = .01$ (Table 1, Model 1), or as separate variables representing each N , $\chi^2(4, N = 155) = 2.19$, $p = .700$, Nagelkerke $R^2 = .02$ (Table 1, Model 2). As shown in Table 1, none of the variables significantly predicted IB. Furthermore, as shown in Fig. 1,

neither the means nor the distribution of scores differed significantly between noticers and non-noticers. Adopting Seegmiller et al.'s (2011) approach of including only on-task participants did not change the results.³

In conclusion, the results of Experiment 1 are consistent with previous studies that used similar tasks, with several opportunities to practice the primary task, completely monochromatic stimuli with a grey unexpected stimulus among white and black expected objects, and a sample of young adults (Bredemeier & Simons, 2012; Kreitz et al., 2015a, b). This provides accumulating evidence suggesting the relationship between WMC and sustained IB is not robust or reliable, but rather the association must depend on the specific tasks and/or participants in a given study.

Experiment 2

In Experiment 1, we found no IB-WMC association, which is consistent with some research (Bredemeier & Simons, 2012; Kreitz et al., 2015a, b) but contradicts other findings (Hannon & Richards, 2010; Richards et al., 2010, 2012, 2014). As noted earlier, there are several systematic differences in both task design and sample characteristics between studies that do versus do not find an IB-WMC association. Notably, studies that have found an IB-WMC association included a highly salient red unexpected stimulus, whereas studies that have found no association used a less salient grey unexpected stimulus. One possibility is that high WMC individuals may efficiently suppress items that resemble distractors, such that if they are ignoring black distractors they will fail to perceive a grey unexpected stimulus, but will notice a red unexpected stimulus because even though it is not a target, it is clearly not a distractor either and therefore may warrant further attentional processing. In other words, there may be distinct reasons why high WMC and low WMC individuals fail to detect a dark grey unexpected stimulus: low WMC individuals may have insufficient processing capacity to detect an unexpected stimulus, whereas high WMC individuals may implicitly process it but suppress it as irrelevant. To examine this possibility, we designed a second experiment that would use a young adult sample, similar to studies that have found no IB-WMC association (i.e., our Exp. 1; Bredemeier & Simons, 2012; Kreitz et al., 2015a, b), but would use an IB task with a salient red unexpected stimulus, similar to studies that have found a

³ For Model 1 (Composite N -back score): $\chi^2(2, N = 144) = 0.94$, $p = .626$, Nagelkerke $R^2 = .01$; AOSPAN OR = 0.99, 95 % CI OR [0.97, 1.01]; N -back OR = 0.99, 95 % CI OR [0.07, 13.91].

For Model 2 (Separate N -back scores for each block): $\chi^2(4, N = 144) = 2.15$, $p = .708$, Nagelkerke $R^2 = .02$; AOSPAN OR 0.99, 95 % CI OR [0.97, 1.01]; 1-back OR = 1.71, 95 % CI OR [0.19, 15.78]; 2-back OR = 1.75, 95 % CI [0.27, 11.25]; 3-back OR = 0.35, 95 % CI [0.04, 2.78].

Table 1 Experiment 1: logistic regression exploring association between working memory capacity (*N*-back and AOSPAN) and inattentional blindness

Parameter	<i>B</i>	<i>SE</i>	Wald χ^2	OR	95 % CI OR	Non-noticers <i>M</i> (<i>SD</i>)	Noticers <i>M</i> (<i>SD</i>)
Model 1: Composite <i>N</i> -back Measure							
Total <i>N</i> -back	-0.37	1.31	0.08	0.69	[0.05, 9.00]	0.66 (0.13)	0.65 (0.14)
AOSPAN	-0.01	0.01	1.01	0.99	[0.97, 1.01]	41.1 (17.7)	37.9 (19.7)
(Constant)	-0.02	0.91	0.00				
Model 2: Multiple <i>N</i> -back Measures							
1-back	0.42	1.08	0.15	1.52	[0.18, 12.56]	0.90 (0.17)	0.91 (0.18)
2-back	0.28	0.88	0.10	1.32	[0.24, 7.37]	0.66 (0.21)	0.66 (0.21)
3-back	-1.03	1.00	1.07	0.36	[0.05, 2.56]	0.41 (0.17)	0.38 (0.20)
AOSPAN	-0.01	0.01	0.76	0.99	[0.97, 1.01]	41.1 (17.7)	37.9 (19.7)
(Constant)	-0.44	1.11	0.16				

OR, odds ratio; CI, confidence interval

Outcome measure is noticing the unexpected stimulus, so $OR > 1$ reflect increased likelihood of detecting the unexpected stimulus. The maximum possible score was 75 for AOSPAN. *N*-back scores represent *Pr* (corrected detection rate; hit rate – false-alarm rate) and thus the maximum possible value is 1

significant IB-WMC association (Hannon & Richards, 2010; Richards et al., 2010, 2012, 2014).

Because there were two key differences in the IB tasks used in previous studies—namely, the colour of the unexpected stimulus (red vs. grey) and whether participants had an opportunity to practice the primary task before the unexpected stimulus appeared—we also systematically manipulated the amount of primary task practice in our revised IB task. The *no-practice condition* was designed to replicate the majority of studies that have found an IB-WMC association (Hannon & Richards, 2010; Richards et al., 2010, Exp. 1; Richards et al., 2012, 2014): participants are required to track white

objects, while ignoring black objects, and a red cross appears during their first attempt at this task. The *practice-trial condition* was designed to replicate a lesser-used variant (Richards et al., 2010, Exp. 2) where participants have limited opportunity to practice the primary task, with two precritical trials before the unexpected stimulus appears during the critical inattention trial. Given that primary task practice reduces IB (Neisser, 1979; Richards et al., 2010), it may be that increasing practice alters the IB-WMC association. Specifically, when a primary task is unfamiliar it is typically more cognitively demanding, and therefore observers may depend more on WMC to detect the unexpected stimulus. This could

Fig. 1 Scatterplots comparing AOSPAN (left panel) and N-back (right panel) scores between noticers and non-noticers of the unexpected stimulus in Experiment 1. Green lines indicate regression lines. (Refer to online version for colour figures.)

Fig. 2 Representative still frames of the dynamic IB tasks used in Experiment 1 (left panel) and Experiment 2 (right panel). White items were attended targets; black items were to-be-ignored distractors. Observers were required to count how many times the targets bounced

off the edges of the screen during each trial. The unexpected stimulus was dark grey in Experiment 1 and red in Experiment 2. (Refer to online version for colour figures.)

explain why high WMC individuals are more likely to detect unexpected stimuli in an IB paradigm with no primary task practice, whereas increasing practice could effectively negate the relative disadvantage of low WMC individuals by reducing the cognitive burden posed by the primary task.

This design permitted us to explore different possibilities regarding factors that might influence the IB-WMC association. If the salience of the unexpected stimulus is most influential, then we should find a significant IB-WMC association in *both* the no-practice and practice-trial conditions, because both include a red unexpected stimulus. Alternatively, if primary task practice is more influential (i.e., if practicing the primary task reduces the influence of WMC on IB), then we should find an association in the no-practice condition but should find a smaller or nonsignificant effect in the practice-trial condition. Finally, if sample characteristics are most influential, then we should not find a significant association between IB and WMC, since our sample comprises young university students similar to previous studies that found no significant IB-WMC association.

Method

Participants Overall, 165 students provided informed consent and participated as part of a class activity. Data from 18 observers were excluded: 2 were aged >35 years; 15 realised it was an IB study; and 1 failed to detect the unexpected stimulus under full attention. The remaining 147 participants (103 female) were aged 18–30 years ($M = 20.4$, $SD = 1.8$).

Apparatus Visual stimuli were presented on computer using 24" LED monitor with 1920×1080 spatial resolution. Viewing distance was approximately 67 cm.

Stimuli and procedure Participants completed AOSPAN and IB tasks on individual workstations in a quiet classroom in groups of 18–26 students. Workstations were arranged in four rows. Within each group, participants were instructed to

commence the AOSPAN task at the same time. Those who finished first were instructed to take a short break before proceeding, so that all participants could then start the IB task concurrently. The IB task was an object-tracking task similar to that used in Experiment 1, with the following differences (Fig. 2): attended items were white Ls and Ts; ignored distractors were black Ls and Ts; the unexpected stimulus was a red cross; and the speed of the objects was increased so that targets bounced 19–21 times during each 20s trial. Each item measured $2.0^\circ \times 1.9^\circ$ and moved within a light grey display area subtending $33.0^\circ \times 24.8^\circ$. These changes were implemented for two reasons: a) make the stimuli as similar as possible to those used in studies that have found a significant IB-WMC association (Hannon & Richards, 2010; Richards et al., 2010, 2012, 2014); and b) to increase the difficulty of the primary task and thus increase variability in error rates.

Participants in the practice-trial condition ($n = 71$) completed four trials: two precritical trials with only the expected white and black items; a critical trial in which the red cross also appeared; and a full attention trial in which the red cross appeared again but they were no longer required to engage in the primary task. Participants in the no-practice condition ($n = 76$) completed only two trials: the critical trial followed by the full attention trial. It should be noted that amount of primary task practice is very low compared with many IB studies (e.g., Bredemeier & Simons, 2012; Kreitz et al., 2015a, b; Simons & Jensen, 2009); however, we chose to include only two precritical trials to be consistent with Richards et al. (2010). Approximately half of each testing group completed each condition. After the IB tasks participants completed a brief questionnaire to report demographics and their prior knowledge of IB, including whether they anticipated the unexpected stimulus appearing.

Results and discussion

Overall, 93 participants (63 %) noticed the unexpected stimulus. The proportion of noticers was not significantly higher in

Table 2 Experiment 2: logistic regression exploring association between working memory capacity, primary task practice, and inattentional blindness

Parameter	<i>B</i>	<i>SE</i>	Wald χ^2	OR	95 % CI OR
IB Task (Practice vs. No-Practice)	−1.73	1.04	2.76	0.18	[0.02, 1.37]
AOSPAN score	−0.02	0.02	1.67	0.98	[0.95, 1.01]
IB Task × AOSPAN score	0.03	0.02	1.53	1.03	[0.99, 1.07]
(Constant)	1.74	0.80	4.70		

OR, odds ratio; CI, confidence interval

Outcome measure is noticing of the unexpected stimulus, so OR > 1 reflect increased likelihood of detecting the unexpected stimulus

the practice-trial (69 %) versus no-practice condition (58 %), $\chi^2(1) = 1.95$, $p = .175$, risk ratio (RR) = 1.19, 95 % CI RR [0.93, 1.53]. Proportional error rates were calculated as in Experiment 1, and were compared using a 2 (IB: noticer, non-noticer) × 2 (task: practice trials, no-practice) ANOVA. Error rates on the critical trial ($M = 0.08$, $SD = 0.15$) did not differ between noticers and non-noticers or between task versions, and there was no IB × task interaction (all $F < 1$, $p > 0.7$). Overall, 12 % met Seegmiller et al.'s (2011) criteria of being “off-task” with more than 20 % error. The proportion of off-task participants was not significantly different among noticers (13 %) and non-noticers (11 %) of the unexpected stimulus, $\chi^2(1, N = 147) = 0.16$, $p = .790$. However, primary task performance was significantly correlated with AOSPAN scores, $r(147) = -.21$, $p = .011$, consistent with previous research indicating that higher WMC is associated with fewer primary task errors (Bredemeier & Simons, 2012; Seegmiller et al., 2011).

We conducted a logistic regression to determine whether WMC (indicated by AOSPAN) and/or IB task version predicted noticing of the unexpected stimulus. Data were excluded for six participants who achieved <85 % arithmetic accuracy on AOSPAN, including these participants did not alter the pattern of results. The full model with all predictors was not significantly different to the constant-only model, $\chi^2(3, N = 141) = 4.17$, $p = .243$, Nagelkerke $R^2 = .04$, and as shown in Table 2 none of the variables were significantly associated with IB. As shown in Fig. 3, group means and distributions of AOSPAN scores were similar between noticers and non-noticers for both task versions. Adopting Seegmiller et al.'s (2011) approach of excluding “off-task” participants did not alter the pattern of results.⁴

Interestingly, the effect size for AOSPAN was almost identical in both Experiments 1 and 2, with ORs 0.98–0.99 and 95 % CIs from 0.95 to 1.01. In our variable coding, ORs < 1 indicate increased likelihood of experiencing IB, whereas ORs > 1 indicate increased likelihood of detecting the

unexpected stimulus, so these trends reflect higher WMC being associated with *increased* IB. This consistency emerged despite the IB tasks varying in terms of unexpected stimulus salience and the amount of primary task practice. The notable similarities between our two studies were that both recruited participants from the same sample (young adult university students) and both used a similar object-tracking primary task. Given that comparable object-tracking tasks have been used in all but one study examining the association between WMC and sustained IB (i.e., Seegmiller et al., 2011), our results suggest that sample characteristics influence the IB-WMC association.

General discussion

In two large samples of young adults, we found no relationship between WMC and sustained IB, regardless of unexpected stimulus salience. These results shed light on the nature of the IB-WMC relationship. Specifically, the fact that an overall IB-WMC relationship emerges in some studies (Hannon & Richards, 2010; Richards et al., 2010, 2012, 2014) but not others (Bredemeier & Simons, 2012; Kreitz et al., 2015a, b; Seegmiller et al., 2011) suggests that the association is not robust and is consequently unlikely to have much practical relevance. As noted earlier, studies that do find a relationship report effects that barely meet the threshold of statistical significance and use almost identical methods, suggesting that this small association between IB and WMC is highly dependent on the choice of tasks and/or participants.

Regarding the choice of tasks, in the current study we considered two possible manipulations that may be driving the IB-WMC association: unexpected stimulus salience and primary task practice. The main effect of AOSPAN scores on noticing was the same in both experiments, demonstrating that unexpected stimulus salience does not moderate the IB-WMC association. We also did not find support for the notion that primary task practice moderates the association; however, this conclusion should be considered tentative pending further research. Notably, in contrast to previous research (Neisser, 1979; Richards et al., 2010) our experiment primary task practice did not significantly reduce IB rates, although the trend was in the expected direction. The most plausible explanation

⁴ Model including only on-task participants: $\chi^2(3, N = 126) = 2.71$, $p = .439$, Nagelkerke $R^2 = .03$; IB Task OR = 0.24, 95 % CI OR [0.03, 2.23]; AOSPAN OR 0.98, 95 % CI OR [0.95, 1.01]; IB Task × AOSPAN OR = 1.02, 95 % CI [0.98, 1.07].

Fig. 3 Scatterplots comparing AOSPAN scores between noticers and non-noticers of the unexpected stimulus in Experiment 2, for participants who completed either two practice trials (left panel) or no

practice trials (right panel). Green lines indicate regression lines. (Refer to online version for colour figures.)

for this was that the level of practice was insufficient to produce a statistically significant effect, especially given that our sample comprised undergraduate psychology students who are well-practiced at similar visual cognition experiments. (Although this was the same amount of practice administered in Richards et al.'s 2010 study, their sample comprised members of the general community who are presumably less familiar with computer-based visual cognition tasks.) Ultimately, if the practice manipulation was insufficient to significantly reduce IB, it stands to reason that it would be insufficient to alter the IB-WMC association. Thus one avenue for future research would be to explore the IB-WMC association in a study that more dramatically varies practice levels.

On balance, however, our results seem most consistent with the hypothesis that the IB-WMC association varies depending on the participant sample recruited. All studies that have reported a significant IB-WMC association have used samples with wide age ranges, with the youngest participants being 18–19 and the eldest being 44–60 (Hannon & Richards, 2010; Richards et al., 2014). Given that age has robust associations with both WMC (Park et al., 2002) and IB (Graham & Burke, 2011; Horwood & Beanland, *in press*; Stothart, Boot, & Simons, 2015), this raises the possibility that the observed IB-WMC relationship may be an artefact of sample age variation. One possibility, for example, is that the effect is driven largely by performance variability in middle- and older-aged adults. O'Shea and Fieo (2014) found that fluid intelligence, which is highly correlated with WMC (Shipstead, Harrison, & Engle, 2015), predicted IB in older adults. However, this study did not directly test the IB-WMC association and used a

relatively small sample, so the results may be affected by a few extreme scores. (Indeed, the authors' reported motivation for recruiting older adults was to obtain greater variability in fluid intelligence scores within a small sample.) If age does moderate the IB-WMC relationship, then future research should be able to reproduce the association when including middle- and older-aged adults in the sample, with IB tasks similar to those employed in the current study. However, it should be noted that there was considerable variability in WMC (i.e., with the full range of AOSPAN scores) in both our samples, which comprised young adult students at a highly ranked university.

Overall, our research indicates that the relationship between IB and WMC is neither large nor robust, given that to date it has only been reproduced using highly specific experimental parameters and participant samples. One point worth noting is that it is notoriously difficult to study individual differences in IB, due to a peculiarity of the paradigm. Because the critical IB stimulus must be unexpected, most paradigms include only one or two trials (Beanland & Pammer, 2010b) and it is nearly impossible to repeatedly test individuals using identical stimuli (Beanland & Pammer, 2010a; Simons, 2010). Classifying individuals as noticers or non-noticers based on a single trial constitutes an unreliable measure compared with related failures of awareness such as attentional blink (Beanland & Pammer, 2012) and consequently limits researchers' ability to identify individual differences that predict IB. This limitation of the IB paradigm could account for discrepant findings regarding the IB-WMC association. An ideal solution would be to test one sample on multiple measures of IB to explore whether stimulus characteristics and task demands moderate the IB-WMC

relationship. However, because this is challenging due to the nature of IB paradigms, future research should focus on testing whether individual differences associated with IB in one setting remain constant across different samples and paradigms, to test the generalisability and relevance of effects obtained.

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