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Dynamic states in working memory modulate guidance of visual attention: Evidence from an n-back paradigm

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Items held in working memory (WM) can automatically bias attention when they reappear in visual displays. Recent evidence, however, suggests that WM biases of attention may be reduced under certain conditions, for example with increasing memory load. We employed a dual task paradigm to investigate how WM biases are affected by dynamic updating of memory contents. 1-back and 2-back versions of a memory task with colour stimuli were interrupted at intervals by an unrelated visual search task. Reappearance in the search display of the item that was currently active in WM guided attention, while suppressed or inactive items did not. We conclude that the rapid updating of memory contents facilitates the shifting of memory representations into different activity states on a moment-to-moment basis. The finding is consistent with models that propose that only one item can be “active” in WM at any one time to guide attention.

Keywords: Working memory; Attention; Memory representations; Visual search.

Items held in working memory (WM) have the power to guide attention in visual search paradigms (Duncan & Humphreys, 1989; Soto, Heinke, Humphreys, & Blanco, 2005). The contents of WM have been shown to capture attention even when they are irrelevant to behavioural goals, and may in fact hinder task performance (Soto, Hodsoll, Rotshtein, & Humphreys, 2008). This guidance of attention is however reduced or eliminated when more than one item is held in

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WM, i.e., when WM capacity is taxed by larger memory loads (Soto, Greene, Chaudhary, & Rotshtein, 2012; Soto & Humphreys, 2008; van Moorselaar, Theeuwes, & Olivers, 2014; Zhang, Zhang, Huang, Kong, & Wang, 2011; but see Beck, Hollingworth, & Luck, 2012 who found that multiple search templates could guide attention where the templates were directly relevant to task goals).

Another factor that constrains the expression of WM biases of attention is whether the defining properties of the search target remain the same across trials or whether they change across trials. Strong biases from items held in WM are found when the search target remains the same and the WM stimuli are updated on a trial-by-trial basis (Downing, 2000; Olivers, Meijer, & Theeuwes, 2006; Soto et al., 2005; Soto & Humphreys, 2007). In contrast, biasing effects from WM decrease when the search target also changes on a trial-by-trial basis (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Olivers, 2009). This result also fits with the WM capacity constraint highlighted above, as the capacity of WM may be more taxed when both the WM content and the search template need to be updated on a trial-by-trial basis relative to when the search template remains the same across trials. In the latter case, maintenance of the search template may not rely on WM capacity as it may be retained in long-term memory (Carlisle, Arita, Pardo, & Woodman, 2011; Woodman, Luck, & Schall, 2007).

The aim of the present study was to provide evidence for the hypothesis that different states of information within WM may co-exist, and that only the item which is most “active” has the power to drive attention (Olivers, Peters, Houtkamp, & Roelfsema, 2011). Recent work suggests that only a single item in WM can be “active” at any one time, and that this item is held in the focus of internal attention within WM, thereby automatically guiding attention. Additional items held in memory, which are currently not directly relevant for ongoing search behaviour, may be held outside the focus of WM and hence remain effectively shielded from the contents and processes that guide visual search.

Here we devised a novel n-back paradigm to ask how the dynamic updating of WM contents under 1-back and 2-back memory constraints influences performance in an unrelated visual search task. We hypothesized that n-back memory test constraints would successfully manipulate the activation state of items in WM. The simplest version of this task is the 1-back, in which participants view a continuous stream of colours and are required to indicate whether the currently presented colour matches that presented on the previous trial. In the 2-back version of the task, participants respond on each trial with respect to the colour presented two trials previously, requiring that the two preceding colours (from trial n-1 and trial n-2) be held in WM. The contents of WM must be updated on every trial and, hence, unlike in the 1-back task, the relative activation state of the contents of WM must vary. For accurate performance on each trial, the 2-back item (the item presented two trials previously) must be “actively” maintained in WM while the 1-back item is temporarily “suppressed”; however, on progressing to the next trial, the 1-back item becomes the 2-back item and is brought into the focus of attention within WM (see Oberauer & Bialkova, 2009). Critically, a search display was presented at intervals throughout the n-back task allowing us to assess how attention during search was captured by a stimulus matching the memorized colour presented one or two trials previously in the n-back task. In Experiment 1, we compared the effect of performing a 1-back or 2-back task on search trials in which the cued colour surrounds either the target (valid trial) or a distractor (invalid trial). We predicted that during performance of the 1-back task, the presence of the 1-back item in the search array would speed response when it surrounded a target and slow response when it surrounded a distractor. During performance of the 2-back task, in contrast, we did not expect the presence of the 1-back item in the array to have any effect on search. Rather, we predicted that the “active” 2-back item would guide attention, speeding response to the target during valid trials and slowing response during invalid trials.

As has been described by previous authors (e.g., Soto, et al., 2005), when a memorized item validly cues the target more frequently than chance, there exists the possibility that participants may make the strategic choice to use that item as a search template to improve their search performance. In order to discount this possibility, Experiment 2 included search trials in which the 1-back or 2-back colour either surrounded a distractor (invalid trial) or did not appear in the search array at all (neutral trial). The memorized colour never surrounded the target, and so there could be no strategic advantage to orienting towards that colour during search. We predicted that the reappearance of the 1-back item surrounding a distractor stimulus would slow response to the target during performance of the 1-back task but not the 2-back task, while the appearance in the search array of the 2-back item would slow search response during performance of the 2-back task.

Note that in the 2-back version of the task the representations that are relevant for the immediate WM goal vary dynamically, while the overall WM load is kept constant. Hence, the present design implies a departure from the paradigms used in prior studies assessing WM/attention interactions where the number of items held in WM varied or where the search target “template” varied on a trial-by-trial basis. As noted above, the modulation of WM biases of attention in these latter cases may be explained by the associated increase in WM load. Hence we argue that the present paradigm offers a more direct test for the hypothesis that changes in memory state (rather than load) are critical to the modulation of expression of WM biases of attention in search.

EXPERIMENT 1

Methods

Participants

Twenty-four healthy participants (13 female, mean age = 28.8 years, *SD* = 8.01 years), with normal or corrected-to-normal vision, were recruited by means of an advertising campaign and were paid £10 for their participation. This research was approved by the Hammersmith and Queen Charlotte's & Chelsea Research Ethics Committee, and all participants provided informed written consent.

Apparatus and stimuli

Stimuli were presented using E-Prime 2.0 software (Psychology Software Tools, 2002) on a HP desktop computer with 1024 × 768 screen resolution. Responses were acquired via a standard computer keyboard (for the n-back task) and mouse (for the search task). The following colours (with RGB values) were used for the presentation of stimuli: red (255, 0, 0), blue (0, 0, 255), yellow (255, 255, 0), green (0, 128, 0), cyan (0, 255, 255), pink (255, 0, 255), orange (255, 90, 0). Circle stimuli during the n-back tasks were presented centrally with a radius of 0.65° visual angle. During the search tasks, the circle stimuli had a radius of 1.15° visual angle and contained straight (0.5°) and diagonal (0.35°) white lines. The vertical and diagonal lines were 20 pixels in length and 2 pixels in width.

Procedure

Participants performed a colour n-back task in which they were required to judge whether the colour of a circle presented on every trial matched that presented n trials previously, where n is either 1 or 2. Participants indicated the presence of a match by pressing the Z key with the left middle finger while a no-match was indicated by pressing the X key with the left index finger. A match occurred on 1 in 4 trials, on average. Each memory stimulus was presented for 1 second, with a 1 second interstimulus interval. The 2-back task was formulated such that no-match trials were any trial in which the 2-back colour was not presented. There are seven possible colours presented in any trial; on a no-match trial there was therefore a 1-in-6 chance that the 1-back colour would be presented.

Performance of the n-back task was interrupted at intervals by the presentation of a search display. The search trials were presented after a minimum of seven n-back trials. An element of randomness was built in to ensure that the search trials were not too predictable; thus, 81% of search trials were presented after seven n-back trials, 13.5% after eight n-back trials, 4% after nine trials, 1% after 10 trials and the remaining 0.5% after 11, 12 or 13 trials. Olivers and Eimer (2011) found that the effect of a memorized item on search was higher when the order of the search and remember tasks was unpredictable; in the case where participants had an expectation that they might be required to recall the memorized item on the next trial, the presence of that item as a distractor in the search array slowed response relative to trials in which participants were expecting the search task. The paradigm presented here relies on a similar phenomenon: while the search array was presented on roughly 1 in 8 trials, it did not appear on every 8^{th} trial. This element of unpredictability meant that participants were required to behave as though a new n-back item would appear on every next trial. The search display consisted of four coloured circles, three of which contained a straight bar and one of which contained the search target, a bar tilted 45° from vertical to either right or left. Participants were required to indicate the direction of the tilt by means of a mouse-click, using the right hand. The search display was presented 1 second after the offset of the preceding colour stimulus and remained onscreen for 100 ms. Participants had 1500 ms to respond before the resumption of the n-back task. The n-back task was reset after each search trial so participants did not have to recall the colour presented prior to the search.

During 1-back blocks, 50% of the search trials were valid as the target was surrounded by the colour presented on the n-back trial immediately preceding the search. In the remaining invalid trials, the 1-back colour appeared in the search display but surrounded a distractor. The 2-back colour never appeared in the search array.

During 2-back blocks, search validity was defined with reference to either the 1-back or 2-back colour; i.e., to the colour immediately preceding the search display, or to the colour presented before that. In trials where the validity referred to the 1-back colour (1-back reference trials), validity was defined as for the 1-back blocks, described above. In trials where search validity referred to the 2-back colour (2-back reference trials), the 2-back colour surrounded either the target (valid trial) or a distractor (invalid trial). The 1-back colour did not appear in the display during 2-back reference search trials. Figure 1 illustrates the task procedure. Each block contained 120 n-back trials and 13–15 search trials. Participants performed three blocks of the 1-back task and six blocks of the 2-back task in order to ensure a comparable number of search trials in which validity referred to the 1-back and 2-back item.

Results

1-back blocks

Accuracy in the 1-back memory test trials was calculated separately for match and no-match trials as match trials were considerably less frequent. The mean of these two figures was used as an index of overall task performance. Two participants whose averaged match and no-match accuracy was less than 60% were excluded from further analysis. Among the remaining 22 participants, mean accuracy of 90.23% (*SD* = 7.19) in match trials and 90.05% (*SD* = 6.75) in no-match trials was recorded. Accuracy on the search task during 1-back blocks was 90.58%

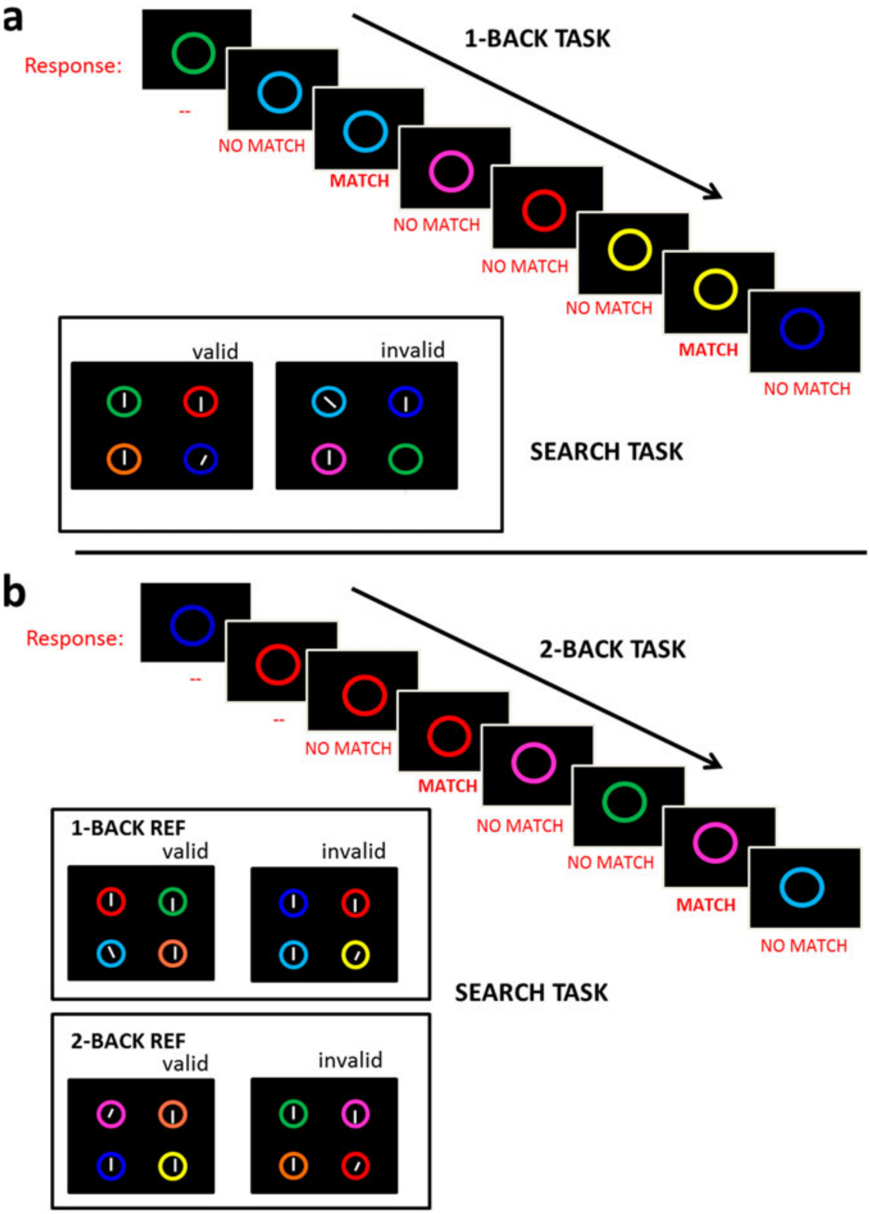

Figure 1. Experimental procedure in (a) 1-back and (b) 2-back blocks. During 1-back blocks, validity in the search task always refers to the 1-back item; the 2-back item does not reappear in the search display. During 2-back blocks either the 1-back or the 2-back item reappears in the search task.

(*SD* = 13.8), and was reduced during invalid trials (M = 88.2%, *SD* = 14.8%) relative to valid trials (M = 94.4%, *SD* = 9.9%; $t_{21} = -3.03$, $p < .05$). A paired samples *t*-test was conducted to compare median search RT on correct search trials in valid and invalid trials. A significant validity effect ($t_{21} = 2.25$, $p < .05$) was observed, such that search responses were slower when the 1-back item surrounded a distractor (invalid trial; M = 735.21, *SD* = 137.3) relative to when it surrounded the target (valid trial; M = 686.12, *SD* = 120.3). Bayesian analysis using the JZS prior and a scale factor of $r = 1$ (Rouder, Speckman, Sun, Morey, & Iverson, 2009) indicated that the alternative hypothesis was 1.47 times more likely than the null hypothesis.

2-back blocks

Accuracy in the 2-back task was also calculated separately for match and no-match trials. Three participants whose average accuracy was less than 60% were excluded from further analysis. Mean accuracy in the 2-back task among the remaining 21 participants was 76.24% (*SD* = 10.37) on match trials and 82% (*SD* = 11.3) on no-match trials. Mean accuracy on the search task during 2-back blocks was 90.83% (*SD* = 12.66) and did not differ significantly as a function of search validity ($F_{1,20} = 0.38$, $p > .05$) or validity reference ($F_{1,20} = 0.69$, $p > .05$).

A 2 × 2 ANOVA was conducted to assess the effect of search validity and validity reference on median search reaction time in correct search trials only. No main effect of validity reference was observed ($F_{1,20} = 0.03$, $p > .05$), indicating that search RTs were not affected by whether the search validity referred to the 1-back item (M = 681.1 ms, *SD* = 139.96) or 2-back item (M = 682.18 ms, *SD* = 125.78). There was a significant main effect of validity ($F_{1,20} = 8.97$, $p < .05$, partial $\eta^2 = 0.31$) such that search RTs were slower on invalid (M = 694.85 ms, *SD* = 132.62) relative to valid trials (M = 668.42 ms, *SD* = 133.12). Critically, an interaction between validity and validity reference was observed ($F_{1,20} = 6.6$, $p < .05$, partial $\eta^2 = 0.25$) such that the validity effect was larger in 2-back reference trials than 1-back reference trials (see Figure 2). Post-hoc *t*-tests indicated that median RT differed significantly between valid and invalid trials when validity referred to the 2-back item ($t_{20} = 4.95$, $p < .001$) but not to the 1-back item ($t_{20} = 0.53$, $p > .05$). Bayesian analysis indicated that the null hypothesis was 5.24 times more likely than the alternative hypothesis for the effect of validity with respect to the 1-back item, and that the alternative hypothesis was 365.05 times more likely than the null hypothesis for the effect of validity with respect to the 2-back item. Attention was therefore drawn to the 2-back item but not to the 1-back item during visual search that took place during 2-back task performance.

Effect of the 1-back item during the 1-back and 2-back blocks

A 2 (task context: 1-back or 2-back) × 2 (validity: valid or invalid) ANOVA was conducted to compare the effect of validity with respect to the 1-back item

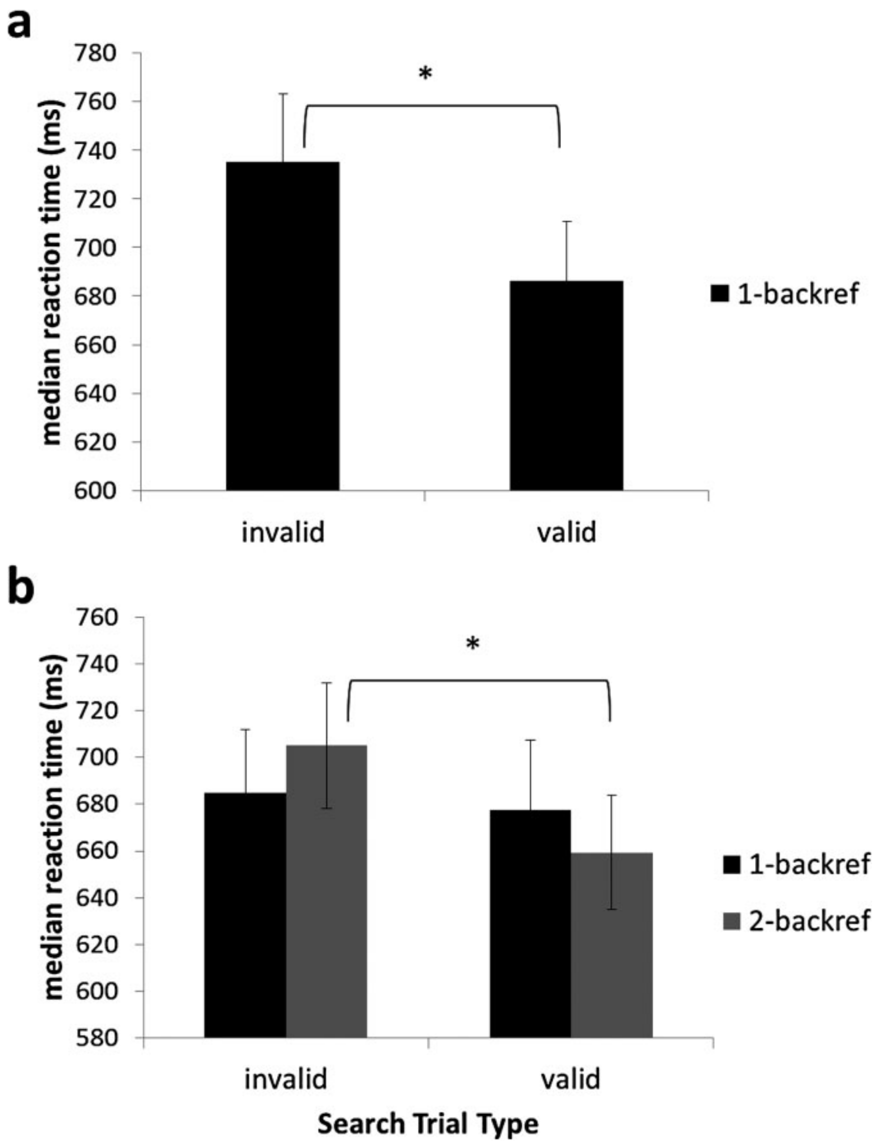

Figure 2. Reaction time data from Experiment 1. (a) Median reaction time to valid and invalid trials during 1-back blocks. (b) Median reaction time to valid and invalid trials during 2-back blocks. Error bars represent standard errors of the mean.
*Significant difference at $p < .05$.

during the 1-back and 2-back tasks. The interaction effect did not reach significance ($F_{1,20} = 2.95$, $p > .05$) and Bayes factor revealed weak evidence (scaled BF = 1.58) in favour of the null hypothesis. Nevertheless, the data reported above suggest that the alternative hypothesis (predicting an effect of the 1-back item on search) is more likely than the null hypothesis in the 1-back task context, while the null hypothesis (predicting no effect of the 1-back item on search) is more likely than the alternative hypothesis in the 2-back task context.

EXPERIMENT 2

Methods

Participants

Thirty healthy participants (15 female, mean age = 21 years, *SD* = 1.3 years) took part in this experiment. Ethical approval was granted by the University College Dublin School of Psychology Research Ethics Committee.

Apparatus and stimuli

The apparatus and stimuli were as described for Experiment 1.

Procedure

Participants performed the colour n-back task as described in Experiment 1. During the 1-back blocks, 50% of search trials were invalid, as the 1-back colour surrounded a distractor stimulus in the search array. The remaining 50% of search trials were neutral, as the 1-back colour did not appear in the search display. There were no valid trials in this experiment, as the 1-back colour never surrounded the search target. During the 2-back blocks, 50% of search trials were neutral trials, in which neither the 1-back nor the 2-back colour appeared in the search display. In 25% of trials, the 1-back colour appeared in the search array surrounding a distractor stimulus (invalid-1back). In the remaining 25% of trials, the 2-back colour surrounded a distractor stimulus (invalid-2back). There were no valid trials: neither the 1-back nor the 2-back item ever surrounded the search target.

Results

1-back blocks

Accuracy in the 1-back task was calculated separately for match and no-match trials. One participant whose average accuracy was less than 60% was excluded from further analysis. Among the remaining participants, mean accuracy was 87.4% (*SD* = 6.4) on match trials and 96.6% (*SD* = 6.7) on no-match trials. Mean accuracy on the search task during the 1-back blocks was 91% (*SD* = 13.1) and did not differ significantly as a function of search validity (t_{28} = -0.124, $p > .05$). A paired samples *t*-test was conducted to compare median search RT on correct search trials in invalid and neutral trials. A significant difference was observed

(t_{28} = 3.058, $p < .005$) such that response to the target was slowed on invalid trials (M = 828.6 ms, *SD* = 324.17) relative to neutral trials (M = 736.52 ms, *SD* = 252.67). Bayesian analysis using the JZS prior and a scale factor of $r = 1$ indicated that the alternative hypothesis was 7.26 times more likely than the null hypothesis.

2-back blocks

One participant whose average accuracy on the 2-back task was less than 60% was excluded from further analysis. Among the remaining participants, mean accuracy of 78.8% (*SD* = 9.8) was recorded for match trials, and mean accuracy of 93.7% (*SD* = 4.2%) was recorded for no-match trials. Mean accuracy on the search task during the 2-back blocks was 93% (*SD* = 11.5%), and was not modulated by validity condition ($F_{2,56}$ = 0.154, $p > .05$).

Paired samples *t*-tests were conducted to compare median RT during correct search performance in neutral trials with RT in the two types of invalid trials. Following Bonferroni correction, median RT during invalid-2back trials (M = 799.43 ms, *SD* = 281.03) was found to be slowed relative to neutral trials (M = 756.34 ms, *SD* = 253.22; t_{28} = 2.56, $p < .025$). Bayes factor revealed the alternative hypothesis to be 2.52 times more likely than the null hypothesis. There was no significant difference in RT between invalid-1back (M = 771.6 ms, *SD* = 251.01) and neutral trials (t_{28} = 1.67, $p > .05$), with Bayes factor indicating that the null hypothesis was 1.9 times more likely than the alternative hypothesis. These results indicate that, during performance of a 2-back task, the reappearance of the 2-back item surrounding a distractor slowed response to a target. The reappearance of the 1-back item had no significant effect on reaction time when participants were performing a 2-back task, but did slow response when participants were performing a 1-back task (see Figure 3).

Effect of the 1-back item during the 1-back and 2-back blocks

A 2 (task context: 1-back or 2-back) × 2 (validity: invalid or neutral) ANOVA was conducted to compare the effect of validity with respect to the 1-back item during the 1-back and 2-back tasks. A significant interaction effect was observed ($F_{1,28}$ = 7.059, $p < .05$), indicating that the 1-back item had a significantly greater effect on search reaction time during performance of the 1-back task relative to the 2-back task. Bayesian analysis indicated substantial evidence (scaled BF = 3.1) in favour of the alternative hypothesis.

DISCUSSION

The experiments presented here tested the hypothesis that the activation state of items in WM can be dynamically altered by means of an n-back task, and that

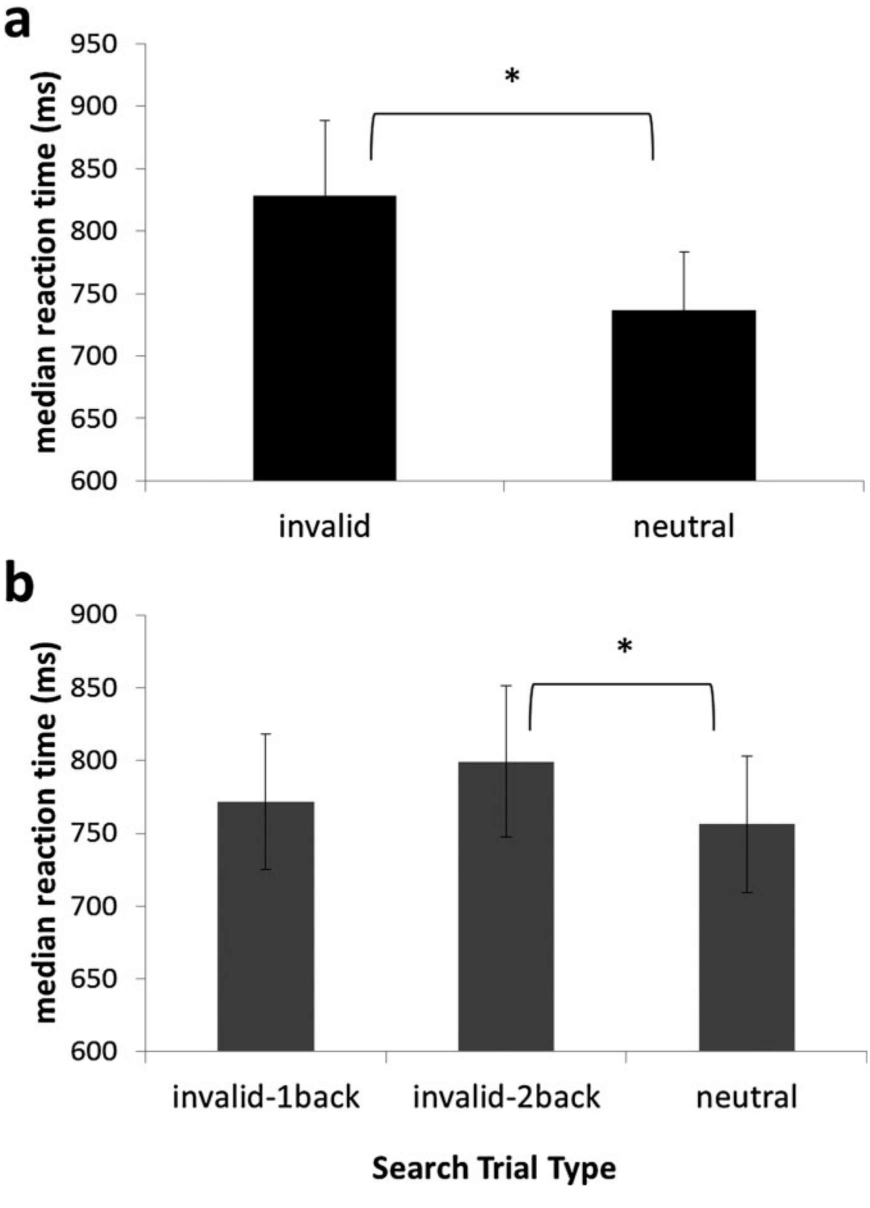

Figure 3. Reaction time data from Experiment 2. (a) Median reaction time to invalid and neutral trials during 1-back blocks. (b) Median reaction times to trials in which a distractor was surrounded by the 1-back colour (invalid-1back) or the 2-back colour (invalid-2back) and neutral trials.

attention in a visual search will be captured by stimuli matching the active, but not the inactive, item held in WM.

The results from the 1-back trials in Experiment 1 indicate that attention was biased by the WM contents, such that search RTs were faster when the WM content was valid relative to when it was invalid for search. Similarly, in Experiment 2, search RTs were slower during invalid trials relative to neutral trials, in which the 1-back item did not appear. These findings indicate that participants' attention was inadvertently captured by the memory-matching item, resulting in slowed performance when that colour invalidly cued the search target.

More critical for the aims of the present study was the pattern of performance observed in the 2-back version of the task. A memory-validity effect—i.e., a slowing of RT during invalid relative to valid trials—was found in Experiment 1 when the memory-matching item in the search display corresponded to the 2-back memory cue, but this was absent when it corresponded to the 1-back cue. Note that the probability of validity of the 1-back and the 2-back cue was the same. Hence, this pattern of results is consistent with the hypothesis that different mnemonic states are associated with the 1-back and 2-back cues, which play a critical role in directing attention. The results of Experiment 2, in which WM items appeared as distracters, confirm that, provided the item held in memory is in the relevant activation state, WM guidance of attention may be automatic and occur when it is detrimental to search, even when the capacity of WM is more heavily taxed (cf. Soto et al., 2008).

For accurate performance on the 2-back version of the WM test, the representations of the 1-back and the 2-back cues for each trial must be dynamically updated in WM. Specifically, the colour presented two trials previously must be maintained in an "online" state to meet the requirements of the 2-back test, while the 1-back item—which is not immediately relevant for the WM goals—must be maintained in a low activation state until the next trial, at which point it becomes relevant for the 2-back test. According to this proposal, the 2-back item (but not the 1-back item) is associated with a memory state that drives attention. The "inactive" 1-back item must nevertheless be kept in WM during the two-back trials, but in a low activation state which cannot influence the deployment of attention. Note that the 1-back item did draw attention during 1-back blocks because in this context it was the active representation, however, this was not the case in the 2-back blocks despite the fact that the 1-back item preceded and primed the search display. Our findings can usefully be compared with those of Lange, Thomas, Buttaccio, and Davelaar (2012), who found a recency effect in the influence of items held in WM on search behaviour. Eye movement data revealed that the most recent items from a memorized list had the strongest effects on attentional capture when images of those items were presented as distractors in a search array. Critically, our results cannot be explained by recency effects, as the 1-back (most recent) item did not capture attention during search trials that took place during a block of 2-back task performance.

Although we report similar effects across two experiments here, it should be noted that Bayesian analysis revealed relatively weak evidence in Experiment 2. This suggests that further replication of these results may be required to confirm our findings. We note there are several factors which could lead one to expect weak effects on WM guidance of attention in this 2-back paradigm. A crucial one is the high processing load in WM that is imposed by the 2-back updating demand, as it is known that WM biases of attention are greatly reduced when WM is taxed by increasing processing loads. In addition there may be other factors related to individual differences in cognitive processing, critically individual WM capacity, which may further add variability to the expression of the WM effect under high cognitive loads.

These findings provide further support for the notion that only one item can be held in the focus of attention at any one time (Garavan, 1998; Oberauer, 2002; Oberauer & Bialkova, 2009) and that additional items are maintained in a suppressed or low activity state which is shielded from the control processes that guide behaviour (Olivers et al., 2011). Oberauer and Bialkova (2009) also reported that two items could be maintained in an active state if they were "chunked" together. A profitable avenue for future research may be to investigate whether multiple items that would normally be chunked together can influence visual search independently of each other in the manner observed here.

Here we demonstrate that the shifting of WM contents into different activity states occurs dynamically, and that items can be switched into active and inactive states on a moment-to-moment basis based on memory goals. It has been noted by a number of previous authors (Downing & Dodds, 2004; Soto, et al., 2012; Woodman & Luck, 2007) that guidance of attention by the contents of WM may be reduced under conditions of high cognitive load. Critically, in the current experiment, the number of items maintained in WM did not vary from trial to trial, and remained constant throughout the 2-back task. Hence, the present findings highlight the dynamic nature of attention guidance by the contents of WM, and provide direct support for recent proposals that that only one item can be "active" in WM at any one time to control attention (Olivers et al., 2011).

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