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Competition in visual working memory for control of search

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Recent perspectives on selective attention posit a central role for visual working memory (VWM) in the top-down control of attention. According to the biased-competition model (Desimone & Duncan, 1995), active maintenance of an object in VWM gives matching (Downing, 2000) or related (Moores, Laiti, & Chelazzi, 2003) objects in the environment a competitive advantage over other objects in gaining access to limited processing resources. Participants in this study performed a visual search task while simultaneously maintaining a second item in VWM. On half of the trials, this item appeared as a distractor item in the search array. We found no evidence that this item interferes with successful selection of the search target, as measured with response time in a target detection task and accuracy in a target discrimination task. These results are consistent with two general models: One in which a representation of the current task biases the competition between items in a unitary VWM, or one in which VWM is fractionated to allow for maintenance of critical items that are not immediately relevant to the task.

Recent theoretical perspectives have proposed a key role for visual working memory (VWM) in the guidance of selective attention. For example, the biased-competition model (Desimone & Duncan, 1995) emphasizes the role of the target ‘‘template’’, a representation in VWM of the to-be-detected item, in visual search. According to this account, active maintenance of the template provides a competitive advantage for matching stimuli in the visual scene. These objects will then become the focus of attention, gaining access to mechanisms for recognition and control of action. Selection will occur more efficiently to the extent that distracting items are both similar to each other and different from the target—that is, when the biasing effects of the template act uniquely on a single item (Duncan & Humphreys, 1989).

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Single-unit neurophysiological studies provide important evidence on the relationship between attention and VWM. Chelazzi and colleagues (Chelazzi, Miller, Duncan, & Desimone, 1993; see also Chelazzi, Duncan, Miller, & Desimone, 1998; Chelazzi, Miller, Duncan, & Desimone, 2001) have examined the activity of macaque IT neurons during a simple visual search task. Monkeys were presented with a single search target, followed after a delay by a search array containing two objects, one of which matched the target. During the delay period some IT neurons continued to show selective activity dependent on the identity of the target. When the search array then appeared, neural activity was initially unselective but soon responded essentially as if only the target were present, a hallmark of selection. Chelazzi et al. (1993) suggest that VWM maintenance of the sample, via delay period activity (perhaps sustained in prefrontal cortex; Miller, Erickson, & Desimone, 1996), biases the competition among objects in the search array in favour of the target, leading to its eventual selection (see also Desimone, 1996).

In spite of the hypothesized close relationship between VWM and attentional selection, there is little evidence on whether irrelevant information in VWM can interfere with visual search. Woodman, Vogel, and Luck (2001) tested the effects of a VWM load on a visual search task. In one experiment, they compared search slopes in a difficult search task performed either alone or in conjunction with a VWM task. This task was designed to load VWM to its capacity, as measured in recent reports (Vogel, Woodman & Luck, 2001). The stimulus items used in the memory and search tasks were taken from the same restricted stimulus set, creating further opportunity for interference between the two tasks. While a VWM load had an effect on the intercept of the search RTs, it had no effect on search slopes themselves, suggesting that interference takes place before or after the search process. These results challenge theories that closely relate attention and working memory.

The present study was conducted to further test whether nontarget items held in VWM interfere with visual search. Our strategy was to test the effects of a direct match between a single distractor in the search array and an item held in VWM. Participants were asked to search among an array of novel shapes for a target (the ‘‘search target’’), while simultaneously maintaining a second item in working memory (the ‘‘memory target’’; see Figure 1). At the end of each trial (or on separate trials, in Experiments 2 and 3), retention of the memory target was probed, to ensure that it had been encoded in VWM. To preclude encoding of items in verbal working memory, participants performed a concurrent articulation task throughout the duration of each trial (Baddeley, 1986). On half of the trials, the memory target appeared as one of the distractors in the search array. The primary question was whether this item would interfere with selection of the search target.

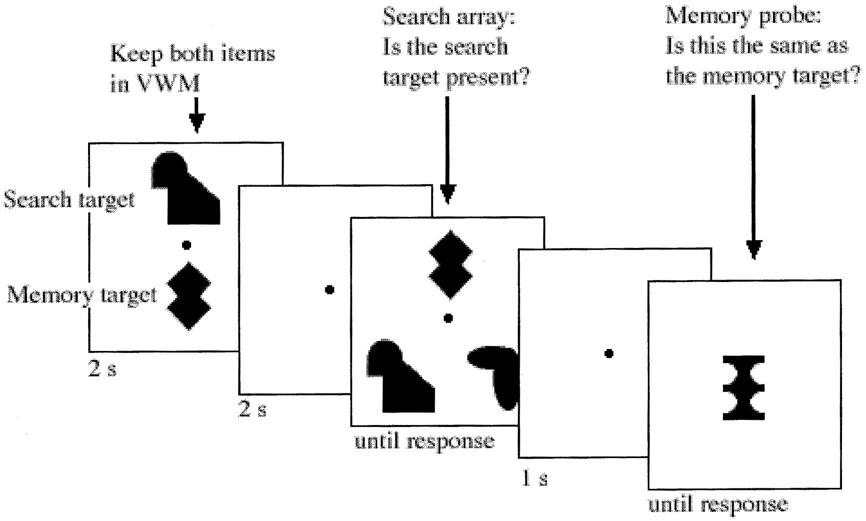

Figure 1. Schematic illustration of the task used in Experiment 1. Participants performed a search task and a working-memory task on each trial. The search target and the memory target were presented simultaneously in the first frame. After a delay, the search array was presented. Participants reported whether the search target was present, which was true on half of trials. On an orthogonal half of trials it also contained the memory target. Each trial concluded with a test item which participants were required to compare to the memory target. Display timing is indicated below each frame. The spatial relationships between items are not shown to scale. Participants performed a concurrent articulation task throughout each trial.

EXPERIMENT 1

Methods

Participants. Eight volunteers from the Bangor community participated. Each was paid £5 for participating.

Stimuli. A set of 26 novel shapes (those above the border in Figure 2) was used in the experiment. Each subtended approximately 2 cm^2. (Sizes are reported in centimetres as viewing distance, which varied from approximately 40–70 cm, was not fixed.)

Design. The experiment was a 2 × 2 × 2 within-subjects design. The set size of the search array was either three or six items, and the search target and the memory target were either present or absent in the search array. These three factors were varied orthogonally. The order of presentation was block

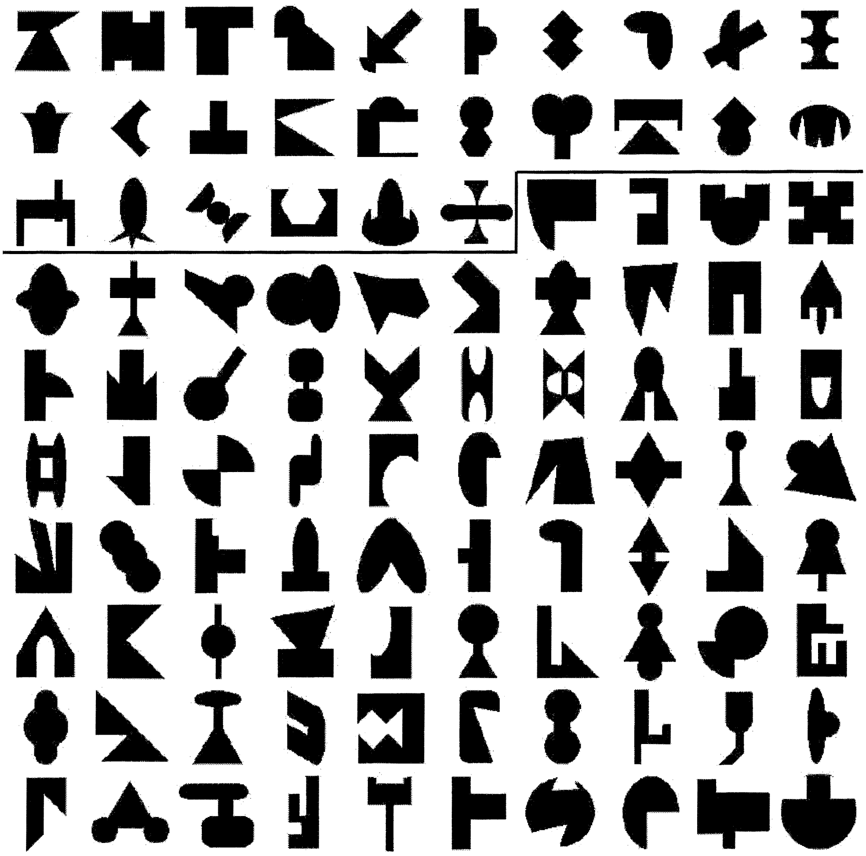

Figure 2. Stimuli used in the experiments. Stimuli above the border were used in Experiment 1. All 100 stimuli were used in Experiment 2.

randomized, individually for each participant, so that each combination of conditions appeared exactly twice in each block of 16 trials. The memory probe was selected randomly on each trial either to match the memory target or not, with equal probability. Thirteen blocks of trials were run. The first block was treated as practice and discarded from the analysis.

Procedure. At the beginning of each trial either the word ''letters'' or ''numbers'', selected randomly, appeared on the screen. According to this cue, participants recited either ''1, 2, 3, 4'' or ''A, B, C, D'', repeatedly throughout the trial, at a rate of about 3–4 items per second. An experimenter was present throughout the session to ensure compliance with this task. Once they had begun the verbal task, participants pressed the space bar to begin the trial.

First, two different shapes were presented for 2 s, one centred 2 cm above fixation (the ''search target'') and the other 2 cm below (the ''memory target''). The display was then erased and a fixation point was presented for 2 s. Next, the search array was presented, consisting of three or six equally spaced items at a radius of approximately 4 cm from fixation. Two configurations were used equally often in the three-item arrays: One item above fixation and two below, or the inverse. The locations of the search and memory targets were determined randomly. Distractors were chosen randomly from the remaining set of items. Participants pressed the ''/'' key with their right hand if the search target was present, and the ''z'' key with their left hand if it was absent. The search array was erased upon response, or at the response deadline of 1.5 s, whichever came first. After a delay of 1 s, a single item was presented in the centre of the screen. Participants pressed the ''/'' key if the item matched the memory target, and the ''z'' key if it did not. Response time on the search task was emphasized, and participants were encouraged to perform both tasks as accurately as possible. Participants were given a short break every 16 trials.

Results

Accuracy averaged 85% on the search task and 71% on the memory task. Participants were accurate on both tasks on an average of 62% of trials (see Table 1).

Analyses of RT data included only trials in which both responses were correct (see Figure 3). To account for outliers, median RTs for each subject in each condition were used in the analysis of this and the following experiments. The main effect of set size on RT was significant, $F(1, 7) = 49.4$, $p < .001$, as was the main effect of search target, $F(1, 7) = 17.6$, $p < .005$, and the interaction of these factors, $F(1, 7) = 21.5$, $p < .005$. The three-way interaction of set size, search target, and memory target did not approach significance, $F < 1$. When the search target was absent, there was a marginal main effect of memory target, $F(1, 7) = 3.3$, $p = .11$, and no interaction with set size, $F < 1$. When the search target was present, there was no effect of the memory target, nor was there an interaction of this factor with set size, both Fs < 1.

Analysis of errors on the search task showed a significant three-way interaction of set size, search target, and memory target, $F(1, 7) = 12.6$, $p < .01$. This interaction can be understood by separately considering search target present and absent trials. When the search target was present, there was a significant interaction of set size with memory target, $F(1, 7) = 14.3$, $p < .01$. In contrast, when the search target was absent, this interaction was not significant, $F < 1$, while the main effect of set size was significant, $F(1, 7) = 6.3$, $p < .05$. This pattern suggests a speed–accuracy tradeoff in search target absent trials. Responses were faster but less accurate when the memory target was present compared to when it was absent.

TABLE 1
Summary data for both experiments

Experiment	*Set size*	*Search target*	*Memory target*	*Search RT*	*Search accuracy*	*Memory accuracy*	*Conjoint accuracy*
1	3	+	+	711	90%	75%	68%
		+	–	726	93%	62%	58%
		–	+	799	82%	76%	65%
		–	–	834	85%	70%	63%
	6	+	+	830	93%	71%	67%
		+	–	818	82%	72%	60%
		–	+	1040	76%	73%	58%
		–	–	1063	78%	68%	56%
2	3	+	+	829	90%		
		+	–	865	87%		
		–	+	1044	85%		
		–	–	970	94%		
	9	+	+	1040	89%		
		+	–	1086	86%		
		–	+	1423	87%		
		–	–	1476	90%		

Search-target-present and memory-target-present conditions are indicated with a ‘‘+’’, target absent conditions with a ‘‘–’’. Data columns represent mean of median search RT on correct trials, mean accuracy on the search task, mean accuracy on the memory task, and mean conjoint accuracy on both tasks. Memory accuracy is not shown for Experiment 2 as it was assessed on different trials from the search task.

Finally, analysis of errors on the memory task showed a significant interaction of set size with memory target, $F(1, 7) = 7.1$, $p < .05$. At set size 3, participants made significantly more errors when the memory target was absent than when present, $F(1, 7) = 8.0$, $p < .05$. At set size 6, there was no effect of memory target, $F < 1$.

Discussion

We draw two main conclusions from Experiment 1. First, and most relevant to our key hypotheses, we found no effect on the response time to find a target when an item held in visual working memory appeared as a distractor. Error rates showed, if anything, a benefit (at set size 6) in this situation. Second, overall accuracy on the task was relatively low. Low accuracy on the working memory task raises the possibility that the memory target is only weakly sustained in visual working memory, which could explain its failure to interfere with visual search.

In Experiment 2 we modified the procedure of the preceding study in a number of ways in order to address this and other issues. First, we modified the

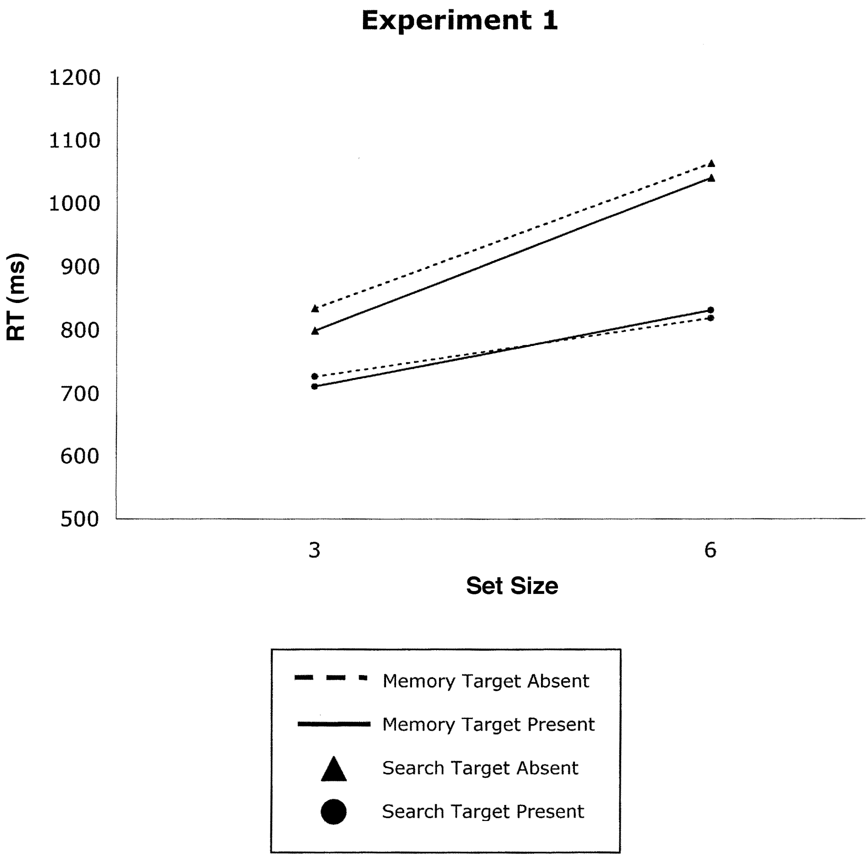

Figure 3. Mean of median search times (from accurate trials) for Experiment 1. Data are shown as a function of set size and of whether the search and memory targets were present or absent in the array.

task so that on any one trial participants performed either the search task or the memory task, but never both. Trials of both types began identically, with presentation of the search target and the memory target, followed by a brief delay. On two thirds of trials, a search array was presented, after which the trial ended. On one third of trials, retention of the memory target was tested instead (see below). These trial types were mixed randomly so that participants could not anticipate which task would be required. As a result, performance on memory trials offers a relatively pure measure of the overall accessibility of the memory target in working memory, without interference from the search task. Splitting the search and memory tasks between trials also removes any strategic incentive to attend items in the search array in order to improve memory performance.

In Experiment 1, the search task and the memory task shared much in common. The memory task can be thought of as a visual search for the memory target, where the set size is always one. This functional overlap between tasks may actually facilitate responses to the search task at a decision level, potentially masking perceptual competition effects. Specifically, when both targets appear in the search array, both may signal a ''present'' response, facilitating the decision about which response to make, compared to the situation in which only one target is present and it must first be identified. Therefore in Experiment 2, we modified the memory task following Downing (2000, Exp. 4). On memory trials, participants were asked to answer one of three randomly selected questions about the visual appearance of the memory target. While performance of this task requires a detailed representation of the memory target, it bears little functional resemblance to the visual search task. We reasoned that this would reduce the interaction between VWM items at a decision level, potentially revealing perceptual competition that may have been masked in Experiment 1.

We made further minor changes to the procedure in order to increase its sensitivity to interference effects. First, biased competition from the memory target may be more apparent at larger set sizes, where attentional competition is more acute. To this end we tested set sizes of three and nine in Experiment 2. Second, in the previous study we used a relatively small set of novel items as stimuli. As participants grew familiar with the items in the set, it is possible that trial-to-trial episodic interference could reduce the effect a given item has in biasing competition. Thus, in Experiment 2 the set of novel shapes was expanded to 100. Finally, to increase statistical power, we extended the experiment to collect 48 observations per cell over two sessions run on separate days.

The experimental question remains the same as in Experiment 1: Does the memory target compete for attention when present in the search array, thus interfering with selection of the search target?

EXPERIMENT 2

Methods

Participants. Ten volunteers from the Bangor community participated. None had participated in Experiment 1. Each was paid £10 for participating.

Stimuli. The 26 novel shapes used in Experiment 1 were used here, with the addition of a further 74 shapes of similar size and complexity, bringing the total to 100 (see Figure 2).

Design. Two thirds of trials were visual search trials, and one third were memory probe trials. Three factors were manipulated orthogonally on search trials: Set size (3 or 9), search target (present or absent), and memory target (present or absent). One trial from each of these eight combinations occurred in each block, along with four memory trials. Twenty-four blocks of trials were tested in each of two 1 hour sessions.

Procedure. Each trial began with a cue instructing participants to begin verbal articulation, as in Experiment 1. After pressing the space bar, participants were shown the search target and memory target for 1.2 s, followed by a fixation point for 1.5 s.

On search trials, the search array was then presented. Items were presented in nine equally spaced locations, at a radius of approximately 7 cm from fixation. When the set size was three, the items were placed in three contiguous array locations, centred on a randomly chosen location. Thus the local density of the items was constant in the two set-size conditions. Participants indicated the presence or absence of the search target as in Experiment 1. The search array remained on the screen until a response was made.

On memory trials, a randomly-selected phrase (‘‘Symmetric?’’, ‘‘Any curves?’’, or ‘‘Only right angles?’’) was presented at the centre of the screen. Participants were required to answer the cued question with respect to the memory target. They were instructed beforehand about the meaning of these phrases: If the memory target was symmetric about the vertical axis, contained a curved edge, or was composed only of right angles, the correct answer to the probe questions was ‘‘yes’’ (reported with the ‘‘/’’ key), otherwise the correct answer was ‘‘no’’ (‘‘z’’ key). The phrase remained on the screen until a response was made.

Results

Mean accuracy on the search task was 88% (see Table 1). Analyses of search RTs included only accurate trials (see Figure 4). Mean accuracy on the memory task was 80%, and did not vary significantly as a function of the probe question asked, $F(2, 18) = 1.1$.

When the search target was present, RT analyses showed a main effect of set size, $F(1, 9) = 53.2$, $p < .001$. There was also a significant main effect of memory target, $F(1, 9) = 9.7$, $p < .05$. Participants were faster to detect the search target when the memory target was present, compared to when it was absent. Accuracy was also marginally higher when the memory target was present than when it was absent, $F(1, 9) = 3.4$, $p < .10$. The interaction of these two factors was not significant, $F < 1$. When the search target was absent, only the main effect of set size was significant, $F(1, 9) = 41.6$, $p < .0001$.

Discussion

Experiment 2 showed that when the search target was present, detection time and accuracy were not impaired by the simultaneous presence of the memory target. In fact, the presence of the memory target in the array significantly

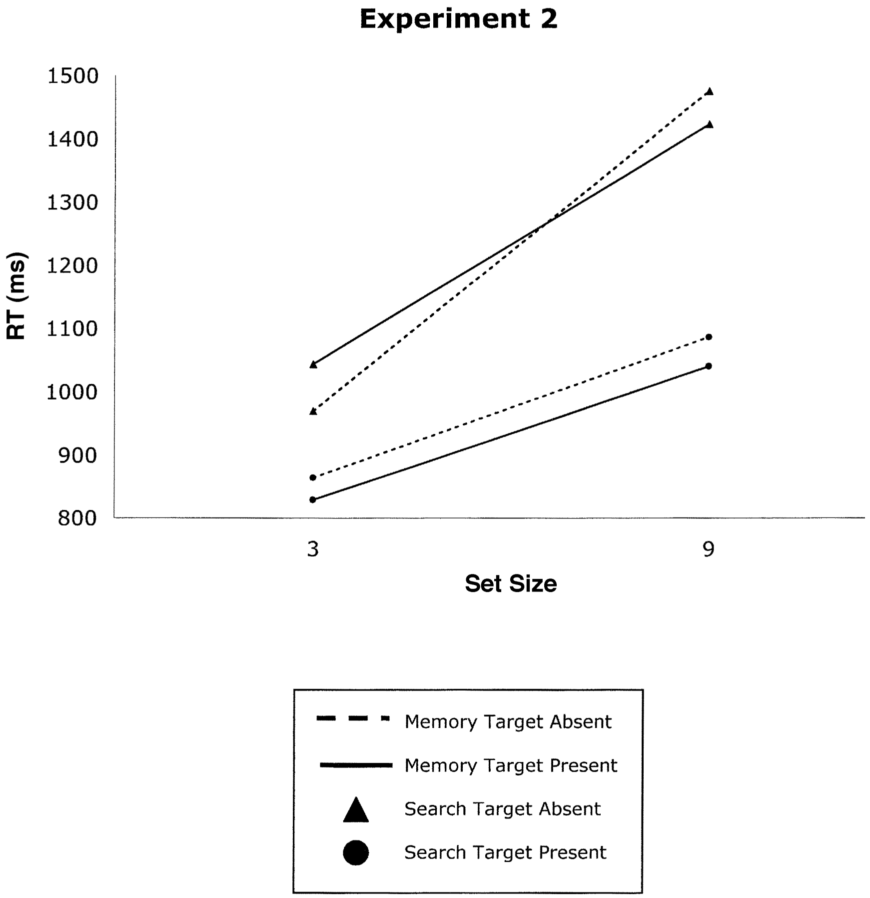

Figure 4. Mean of median search times (from accurate trials) for Experiment 2. Data are shown as a function of set size and of whether the search and memory targets were present or absent in the array.

reduced time to report the search target (and did not increase errors). This finding rules out the possibility that the memory target simply was not maintained in VWM—if that were the case, it could have had no effect on RTs at all.

Thus, in two experiments we find that when a specified visual target must be detected, response times and accuracy are not impaired (and indeed may benefit) when one of the distractors in the search array is concurrently held in working memory. One possibility that must be considered, however, is that response time measures may not be sufficiently sensitive to detect existing interference effects. Response times reflect a combination of search, decision, and response selection; perhaps interference from working memory items is obscured by variability in the time it takes to execute this series of processes.

Therefore to provide a further test of our hypothesis, we adapted the present paradigm to measure accuracy on a target discrimination task using brief, masked displays. In each trial, the search target was always present in an array of four shapes, and participants were required to determine its contrast (black or white on a grey background). The duration of the search display was varied with a staircase procedure to keep overall performance across conditions at about 75% correct. On half of the search trials, as in the previous studies, the memory target appeared as one of the distractor items. Here we tested whether accuracy on target discrimination would be impaired when this was the case, relative to when all of the distractors were novel items.

EXPERIMENT 3

Methods

Participants. Fifteen members of the Bangor community participated. None had participated in the previous studies. Each was paid £5 for participating.

Design. Two thirds of trials were visual search trials, and one third were memory probe trials. Two factors were manipulated orthogonally on search trials: The memory target was present or absent from the search array, and the search target appeared in either black or white. One trial from each of these four combinations occurred in each block, along with two memory trials. Thirty-six blocks were tested, the first four of which were excluded as practice.

Stimuli. The same 100 novel shapes shown in Figure 2 were used. A white and black version of each shape was created. Additionally, an outline version of each shape was created using a high-pass filter in Adobe Photoshop. The resulting figure had a thin edge composed of two adjacent lines (one white and one black), with a surface in the same medium grey as the background.

Procedure. All stimuli were presented on a medium-grey background. Each trial began with a cue to begin performing the concurrent articulation task as in the previous experiments. After pressing the space bar, participants were presented with the search and memory targets for 2.5 s. As previously the search target appeared above fixation, and the memory target appeared below fixation. Both items were presented in outline form to avoid biasing selection of either black or white items in the search array. A 1.5 s delay followed, during which the screen was blank.

On search trials, four items were presented, above, below, and to the left and right of the fixation point. They were centred at approximately 2.5 cm from fixation. Two figures were always filled in black and two were always white.

The search target was always present and was black or white on half of search trials. Presentation of the search array was followed by a pattern mask (133 ms). Participants were required to indicate the contrast of the search target, pressing the ‘‘up’’ arrow to indicate white and the ‘‘down’’ arrow to indicate black. They were instructed to respond as accurately as possible, and were told that their response times were irrelevant.

The duration of the search array was initialised at 10 screen refreshes (133 ms). After each block, performance was assessed on the contrast discrimination task for the preceding four search trials. If accuracy was 100%, the duration of the search array was decreased by one refresh (13 ms) for the following block. If accuracy was 75%, the duration was unchanged. If accuracy was 50%, the duration was increased by one refresh, and if accuracy was below 50%, the duration was increased by 2 refreshes (26 ms). The duration of the search array was capped so that it could not fall below 13 ms and could not rise above 400 ms. This staircase procedure was blind to experimental condition so that performance in each condition could vary while keeping average performance, across conditions, at approximately 75% correct.

Memory test trials were as in Experiment 2: A cue phrase appeared on the screen, indicating the question participants should answer about the memory target. A ‘‘yes’’ answer to the memory question was given with the ‘‘1’’ key at the top of the keyboard, and a ‘‘no’’ response was given with the ‘‘2’’ key.

Results and discussion

Accuracy on the memory test trials averaged 78%. Accuracy on the search task did not differ on trials in which the memory target appeared as a distractor (75%) compared to trials in which it did not (76%), $F(1, 14) < 1$, n.s. To test whether this difference might have changed over the duration of the experiment, we divided the trials into quartiles (with eight blocks in each), and tested the interaction of quartile with presence or absence of the memory target. This effect was not significant, $F(3, 42) < 1$, n.s. The mean duration of the search display was 150 ms, and this did not vary significantly across quartiles of the experiment, $F(3, 42) < 1$, n.s., indicating that performance had stabilized after completion of the practice trials.

We find no interference on a target discrimination task from a distractor that matches an item held in visual working memory, relative to trials in which there is no match between distractors and VWM.

GENERAL DISCUSSION

A prediction of the biased competition hypothesis (Desimone & Duncan, 1995; Duncan & Humphreys, 1989) is that items held in VWM should guide the allocation of visual attention toward matching stimuli in the environment. Results of various studies using a single VWM item are generally consistent with this prediction (Chelazzi et al., 1993; Downing, 2000; Pashler & Shiu, 1999). More recently, this idea has been extended to show that attention is deployed to items that are semantically related to a target (Moores et al., 2003).

Here, however, we found that a second item could be maintained simultaneously in VWM without producing negative competitive effects on detection of a search target. As discussed above, we made several attempts to exclude trivial accounts of the absence of interference effects. These include manipulations to: (1) Reduce the ability of participants to verbally recode working memory items; (2) improve maintenance of the memory target in VWM; (3) reduce the possible facilitation of response selection by the presence of the memory target; and (4) test for effects of the memory target on both accuracy and response time, with both detection and discrimination tasks.

The simplest remaining conclusion is that an additional mechanism either (1) allows efficient switching between items held in a unitary VWM buffer, or (2) moves the critical to-be-remembered items between separate working-memory buffers, each with different effects on the allocation of attention. We discuss each possibility in turn.

The biased-competition account could be extended along the lines of the first possibility by supposing a neural representation of the current task, which serves to bias the competition between items in VWM. Thus each item would gain control as it became relevant during the task, and would bias the competition among incoming stimuli, while the biasing effects of currently irrelevant items would be suppressed. Recent work by Wallis, Anderson, and Miller (2001) suggests a neural representation of the current task which could serve to switch among object representations in VWM. Monkeys were trained to switch between two tasks involving the same stimulus sequences. On each trial a cue indicated whether a ''match'' or ''nonmatch'' rule applied for that trial. A single sample object was then presented, followed after a delay by a target object that was either the same or different. Depending on the task cued for that trial, the monkeys were to respond either when the target object matched or did not match the sample. Many neurons in prefrontal cortex were selective for a particular cue or sample, but 41% of the neurons studied were selective for the rule *per se*. That is, these neurons responded strongly depending on the current rule, independent of how that information was communicated to the animal. An interaction between neurons like these, and those responsible for maintaining objects in working memory, might begin to account for how multiple items can be maintained actively in VWM while control of behaviour is shifted flexibly among them.

The account just offered is consistent with the biased-competition framework, and posits a unitary working memory store. In contrast, recent proposals based on behavioural evidence from healthy and neurologically impaired human participants suggest numerous fractionations of working memory (Baddeley, 1986; Cowan, 1999, 2001; Logie, 1995; Potter, 1993). An account by Cowan

(1999) may be of particular relevance here. Specifically, Cowan (see also Klapp, Marshburn, & Lester, 1983; Oberauer, 2002) has proposed a two-part model in which working memory is divided between the ''focus of attention'' (a capacity-limited store) and the relatively capacity-free activation of portions of long-term memory representations. On this account, in the present study both critical items can be maintained by activation of long-term memory representations, with each item being shifted into the (internal) focus of attention as it becomes relevant to the task. Here, following Cowan (2001), the assumption would be that only items in the focus of attention directly influence behaviour, and, by extension, bias the competition for attention.

In sum, then, the lack of interference on visual search from items held concurrently in working memory, and from generally high working memory load (Woodman et al., 2001), may be explained either by biased competition within VWM from representations of the current task, or by multiple interacting stores within VWM. Both possibilities suggest that further studies in which multiple items are held in VWM will help to clarify the memory- and task-related processes that interact with biased competition to support flexible, goal-directed behaviour.

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