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The contents of visual memory are only partly under volitional control

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When we look around within a visual scene, is visual information automatically placed in visual memory during each saccade, or can we control which information is retained and which is excluded? We examined this question in five experiments by requiring participants to remember sequentially presented visual shapes or faces—some of which were marked for encoding (targets) and others that were supposed to be ignored (distractors)—over a 1-sec delay. The results show that distractors were retained in visual memory, regardless of stimulus category, suggesting that it is a general phenomenon. Whether or not participants were allowed to prepare for a target or distractor did not modulate distractor intrusion. When attention coupled with eye movements could be used to select targets, distractors were no longer encoded into memory. When eye movements were constrained, distractors once again intruded into memory. These findings suggest that top-down control processes are insufficient to filter the contents of visual memory.

The goal of this article is to gain a foothold in understanding the role of visual attention in visual memory. One role of attention is to act as a gatekeeper by selecting which objects will be consolidated into visual memory. Palmer (1990) studied this by requiring participants to remember line lengths over short durations under two different encoding conditions: one in which participants were required to remember two cued items out of four items in the memory display, or one in which they had to remember two items out of two items on the memory display. The results showed that attention biased which information did and did not enter visual working memory (VWM), because instructions to remember a subset of items in a display with distractors led to memory performance equivalent to that for just showing the subset with no distractors. In other words, distractors did not intrude into VWM (Palmer, 1990). Jiang, Olson, and Chun (2000; Experiment 4B) found similar effects of attention on VWM for colors.

Other studies have shown that shifts of attention to cued locations can enhance the transfer of information that resides at that location into iconic memory. In early studies of iconic memory, participants were presented with a brief array of alphanumeric characters and were asked to report all of the characters—the whole-report condition—or a subset of cued characters—the partial-report condition. The cue, either a tone or a visual mark, was presented after the array of characters, and it indicated which characters to report. The results showed that recall of characters was accurate for arrays of four to five characters in the whole-report condition. In contrast, performance was highly accurate for large array sizes in the partial-report condition. These findings suggest that participants used the cue in the partial-report condition to selectively transfer the cued characters into iconic memory (Averbach & Coriell, 1961; Sperling, 1960). A study of a later stage of mnemonic processing, VWM, found that precues cause shifts of attention that bias which information is transferred to VWM (Schmidt, Vogel, Woodman, & Luck, 2002), suggesting that bottom-up attentional processes also affect which information enters VWM.

Attention may also be important during memory maintenance, to help sustain information over delays. Several studies have now shown that when sample stimuli are followed by an attentional cue, memory for the cued items is enhanced (see, e.g., Griffin & Nobre, 2003). This suggests that VWM representations are volatile and prone to degradation unless they receive the benefits of focused attention (Makovski, Sussman, & Jiang, 2008).

However, it is not known whether visual attention is the sole determinant of what does and does not enter visual memory. It is possible that even when an item is visually attended, participants can still exert control over its entry into memory. The experiments in this article were designed

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to answer this question by testing memory for both target and distractor information. The task in Experiments 1–3 consisted of the sequential presentation of a number of items to remember. We chose a sequential task because we reasoned that participants would not be able to easily filter distractors by using strategies such as averting gaze when items were presented sequentially. In other words, all items are attended because they all appear alone at fixation. Relevant information (targets) was cued by a white surround box (cue). The absence of a visual cue around an item was a de facto cue to ignore (distractors). After a short retention interval, the probe image, containing one item, was presented. The task was to decide whether the probe item matched (match trials) or did not match (nonmatch trials) any of the target items held in memory. Unknown to participants, there were two types of nonmatch trials: (1) lure trials, consisting of a distractor item from the memory sequence, and (2) novel trials, consisting of an item that was completely new. A sample display is shown in Figure 1.

The question of interest is, Given that a distractor is attended, can participants block entry of that item into visual memory? The "perfect control" model predicts that the presence of distractors will have no effect on memory performance because participants can exert control after a stimulus is attended. In comparison, the "imperfect control" model predicts that some portion of distractors will be stored in memory, because once a stimulus is attended, it automatically enters memory. If so, then accuracy should be lower on nonmatch lure trials than on nonmatch novel trials.

EXPERIMENT 1
Distractor Intrusion With Shape Stimuli

In Experiment 1, participants were required to remember novel shapes in a memory intrusion task (see Figure 1). Novel shapes were used because they are difficult to verbalize; hundreds of them can be generated, so there is little stimulus repetition; and they have been successfully used in prior memory studies with similar task designs (Jiang et al., 2000). Although it is possible that participants attempted to generate names for the shapes, doing so would have provided little benefit, since the shapes had high lev-

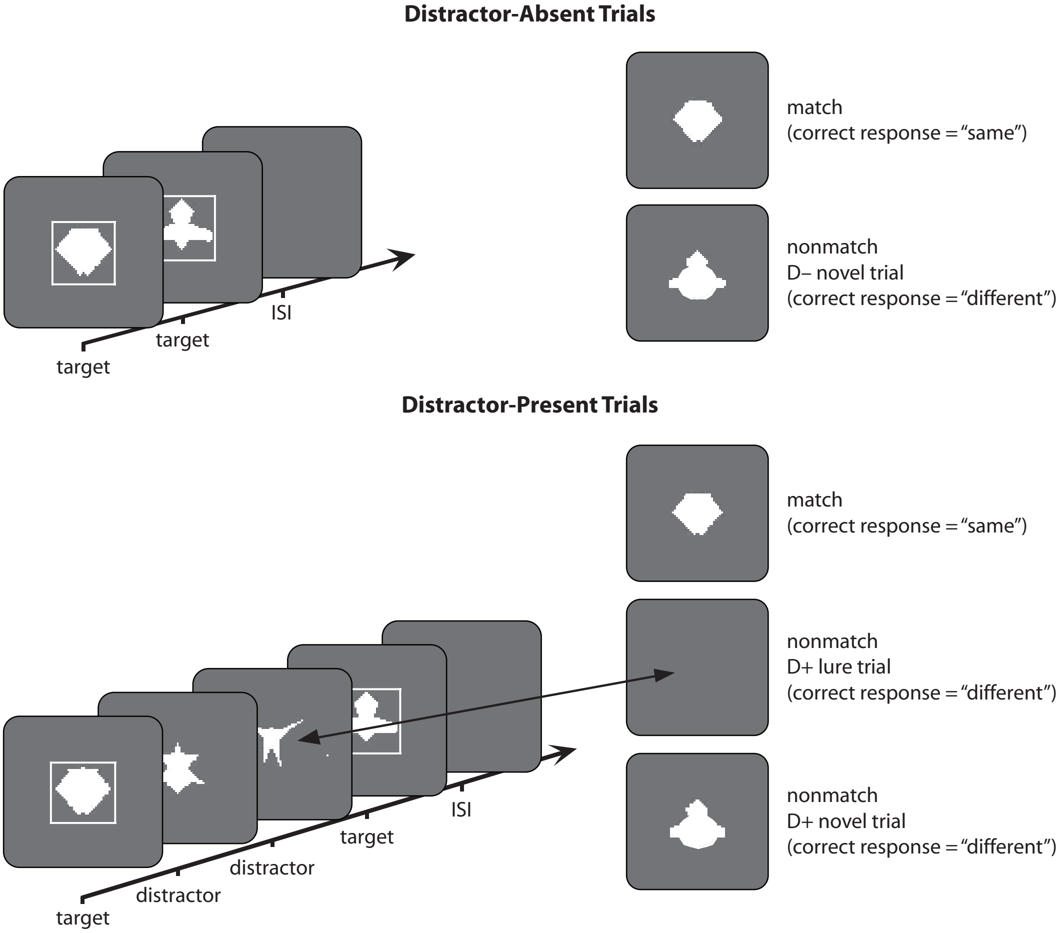

Figure 1. A schematic illustration of the stimuli and trial design used in Experiment 1. Each stimulus was presented for 500 msec and was followed by a blank delay of 100 msec (not shown). Targets were indicated by the presence of a distinctive white box. In the actual experiment, the stimuli were relatively smaller in regard to the screen size. The upper panel illustrates a distractor-absent trial, whereas the bottom panel illustrates a distractor-present trial. The former trial type was analyzed separately, after Experiment 6. ISI, interstimulus interval.

els of interitem similarity and any particular shape was used on no more than two trials.

Method

Participants. All participants who were tested in the experiments discussed in this article were undergraduate students ranging in age from 18 to 23 years and were recruited from either the University of Pennsylvania or Temple University for payment of $10 or course credit. All study participants had normal or corrected-to-normal visual acuity, and they signed an informed consent form prior to the experiment. Twenty participants were tested in Experiment 1.

Materials. Hundreds of 2-D abstract shapes (henceforth referred to as *shapes*) were generated by a computer algorithm that chose five to eight random points in the right half-plane and then reflected them to produce a white, bilaterally symmetric object. Shapes ranged in size from 2.8º to 2.9º of visual angle and were presented in the center of the screen on a gray background (RGB 127). The cue consisted of a thick (0.1º), white surround square that was 5.2º × 5.2º in size. The cue was distinctive and easy to see. Pilot studies showed that memory capacity for these shapes was not diminished under articulatory suppression conditions, suggesting that verbal memory is not necessary for one to accurately remember these shapes.

Design. There were equal numbers of match (i.e., the probe item matched one of the targets) and nonmatch (i.e., the probe item did not match any of the targets) trials (see Figure 1). On all match trials, the probe item matched a target item from the memory sequence. Match trials were of secondary interest in this study. Match trials were equally apportioned into two trial types: trials in which distractors were presented and trials in which no distractors were presented, termed *distractor-absent trials*.

Of primary interest were the nonmatch trials, because these trials allowed us to study a specific type of error—intrusion errors—when distractors were present. Nonmatch trials were equally apportioned to three trial types: trials in which the probe item was novel and did not match any of the target or distractor items (termed *novel* trials), trials in which the probe item did not match any of the target items but did match one of the distractor items from the memory sequence (termed *lure* trials), and distractor-absent trials, illustrated in the top panel of Figure 1. The latter trial type was included to assess the general role of distractors in visual memory and will not be discussed until after Experiment 6. On novel trials, test items were drawn from a set of shapes that were not used in any other capacity and were never repeated.

One last factor that was manipulated was target set size (referred to as *set size*). Target set size in all experiments was either two or four target items. This number was manipulated in order to gather information about whether distractor processing interacted with memory load. There is evidence that distractors are processed more readily when perceptual load is low (Lavie, 1995; Lavie & Tsal, 1994), and other evidence from a dual-task verbal working memory procedure shows that working memory load is a determinant of distractor processing (de Fockert, Rees, Frith, & Lavie, 2001; Lavie, Hirst, de Fockert, & Viding, 2004). If visual memory load significantly affects control over distractor processing, there should be different levels of distractor processing at different set sizes. The distractor set size was held constant at two.

Task and trial sequence. The task was to remember target shapes that were cued with a white surround box and to decide whether the shape on the probe image matched one of the target shapes held in memory. Participants were explicitly instructed to disregard the distractor stimuli.

Each trial began with a "get ready" prompt for 500 msec, followed by a blank screen for 100 msec and then the sequential presentation of either four or six randomly selected shapes (memory sequence). Each shape was shown for 500 msec and was followed by a blank interval of 100 msec. There was a retention interval of 1,000 msec, and then a probe image containing a single shape lasted until a response was made. Participants pressed one of two keys to respond. The probe display was cleared, and auditory accuracy feedback was provided. Accuracy—not speed—was emphasized. The next trial commenced after a 500-msec intertrial interval.

The order of targets and distractors was unpredictable and was varied across conditions, with the constraint that distractors occupy all serial positions an equivalent number of times. All other factors were randomly intermixed within a block. There were 24 practice trials followed by five 24-trial test blocks. Blocks were separated by a self-paced rest period.

Equipment. Participants sat at an unrestricted viewing distance of about 57 cm, at which distance 1 cm corresponds to 1º viewing angle. All experiments were programmed in Psychophysics Toolbox implemented in MATLAB (Brainard, 1997) for Macintosh.

Analysis. Data from match trials and nonmatch trials were arcsine transformed and analyzed in separate repeated measures ANOVAs. Means are presented in standard percentages, without transformation. In all cases, we follow standard usage of the ANOVA model as a linear model decomposition of the response variable, not as if the predictor variables were random variables. The Results section of each experiment and the associated figures contain accuracy data from nonmatch trials only (correct rejections and false alarms). This convention is used for all experiments reported in this article. Data from match trials are discussed after Experiment 6 and are shown in Figure 6.

This experiment, and those that follow, were not designed to assess effects of serial order or response time (RT). However, RT for correct responses was assessed to see whether speed–accuracy trade-offs existed. There was no evidence of a speed–accuracy trade-off in any experiment (e.g., faster RTs in the lure condition vs. the novel condition).

Results and Discussion

All participants performed at above-chance levels on the memory task (mean d' for distractor-present trials = 2.08; distractor-absent = 2.08). This was true across every experiment reported in this article. Figure 2 shows accuracy on nonmatch trials as a function of set size and probe type. An ANOVA on set size and probe type was carried out on the accuracy of reporting whether or not a probe shape was in the cued subset from the memory sequence. There was a main effect of set size [$F(1,19) = 14.072, p = .001$] that was due to lower performance at set-size 4 ($M = 69\%$ vs. 80%). There was also a significant main effect of probe type [$F(1,19) = 8.69, p = .01$] that was due to lower accuracy on the lure trials than on both the novel trials (70% vs. 79%). These results show that attending was sufficient for transferring distractors into memory. Did memory load affect distractor processing? The interaction of set size and probe type was not significant ($F < 1$).

These results show that distractors intrude into memory, suggesting that control over the contents of visual memory is imperfect. The results also suggest that memory load does not affect the degree to which distractors are remembered.

EXPERIMENT 2
Distractor Intrusion With Faces

In Experiment 2, we assessed the generality of the effects found in Experiment 1. Prior research has shown that memory capacity differs for different stimulus types (Alvarez & Cavanagh, 2004) and that it is possible that different memory stores exist for different features or stimulus types (Wheeler & Treisman, 2002). Thus, it is important that one assess whether intrusion effects are a general phenomenon

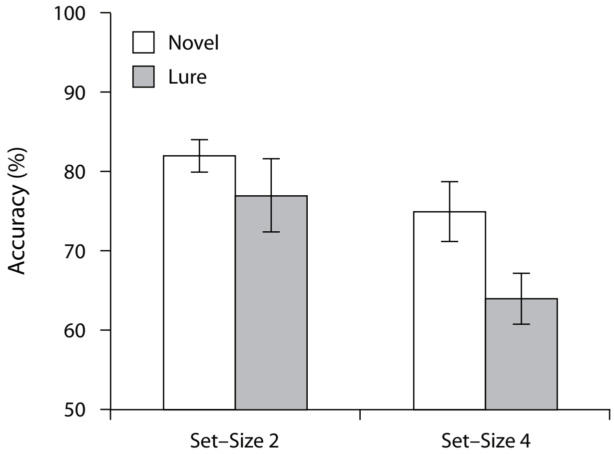

Figure 2. Results from Experiment 1, using shape stimuli, showing accuracy on nonmatch trials (e.g., in which the correct response was "different") as a function of set size and probe type. Error bars represent standard errors. The differentially lower accuracy on the lure trials represents the intrusion of distractors into visual memory.

found for all stimulus types, or a more limited phenomenon found only when unfamiliar stimuli must be remembered. In Experiment 2, participants were required to perform the same task as outlined in Experiment 1, but with face stimuli. If poor control over visual memory is a general phenomenon, there should be a higher error rate on lure trials.

Method

Participants. Eighteen participants were tested.

Materials. Each face used in Experiment 2 was presented on a uniformly black background at central fixation. Faces were drawn from a pool of 200 forward-facing male and female faces that were provided by the Max Planck Institute (faces.kyb.tuebingen.mpg.de/index.php). Faces were standardized to be of similar size, age, and race. Faces were Caucasian in color, had neutral expressions, and were devoid of hair, glasses, or other nonface features. Each face stimulus subtended 4º of visual angle. The cue consisted of a thick (0.1º), white surround square that was 5.2º × 5.2º in size.

Task and trial sequence. The task and design were identical to those used in Experiment 1. All faces that were used in the memory sequence were used on only two trials in the experiment: one in the first half of the experiment and one in the second half.

Results and Discussion

Seventeen participants performed at above-chance levels (mean d' for distractor-present trials = 1.46; distractor-absent = 2.07). Data were analyzed in the same manner as in Experiment 1 (Figure 3). A repeated measures ANOVA on set size and probe type of nonmatch trials was carried out. There was a main effect of set size [$F(1,17) = 7.88$, $p = .01$] that was due to lower accuracy at set-size 4 (66% vs. 74%), and a main effect of probe type [$F(1,17) = 5.97$, $p = .03$] that was due to lower accuracy on the lure trials than on the novel trials ($M = 66\%$ vs. 74%).

This result replicates the findings reported in Experiment 1 by showing that information about distractors is retained in visual memory, suggesting that cognitive control is poor when visual information is acquired sequentially. The interaction of set size × probe type was not significant ($F < 1$), suggesting that memory load did not affect the proclivity to encode distractors.

EXPERIMENT 3

Precue Versus Simultaneous Cue

In Experiment 3, we tested whether distractor intrusion is modulated by cuing procedure. In our prior experiments, the cue and target were presented simultaneously so that immediately before the appearance of the next item, participants had to prepare to attend to that item, since it might potentially be a target. It is possible that a simultaneous cue could bias the results in favor of finding memory intrusions because it does not give participants a chance not to attend to an item. A recent study failed to find VWM distractor intrusion when participants were presented with a sequence of compound gratings to remember, the last of which was a distractor (Yotsumoto & Sekuler, 2006). It is possible that participants successfully ignored distractors because they could prepare for the onset of each stimulus category. If true, this predicts that a precue would allow for greater control of what is and is not encoded (Schmidt et al., 2002), leading to lower levels of distractor intrusion. To test this prediction, we compared trials in which the target was precued with those in which the target and cue were presented simultaneously.

Method

Participants. Twelve participants were tested.

Materials. Stimuli were the same 2-D shapes that were used in Experiment 1.

Design. The experimental design was similar to that used in Experiments 1 and 2, except an additional factor, cue type, was added. This factor was blocked so that one cue type was presented exclusively for half of the experiment. The cue-type factor was presented in a counterbalanced order. The other factors were randomly intermixed within each block.

Task and trial sequence. There were two types of trials. On simultaneous cuing trials, the cue appeared at the same time as the

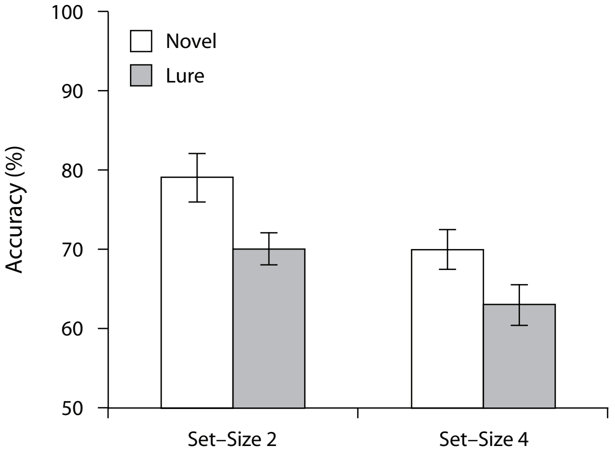

Figure 3. Results from Experiment 2 using face stimuli, showing accuracy on nonmatch trials as a function of set size and probe type. Error bars represent standard errors. The differentially lower accuracy on the lure trials represents the intrusion of distractors into visual memory.

target, just as it did in Experiments 1 and 2. One variable that differed from prior experiments was that the interstimulus interval was 700 msec instead of 100 msec. This change was made to equate timing of the two cuing conditions.

On precue trials, the same series of events occurred except that target items were preceded by cues for 500 msec, followed by a blank delay of 200 msec. No cue was physically present when the target was shown.

There were 24 practice trials, followed by two 120-trial test blocks.

Results and Discussion

All participants performed at above-chance levels (mean d' for distractor-present trials = 1.68; distractor-absent = 1.94). Data were analyzed in the same manner as in Experiment 1 (see Figure 4). A repeated measures ANOVA on set size, probe type, and cue type found a main effect of set size [$F(1,11) = 23.25, p = .001$] that was due to lower accuracy at set-size 4 (M = 70% vs. 85%). There was also a main effect of probe type [$F(1,11) = 12.28$, $p < .00$] that was due to lower accuracy on the lure trials than on the novel trials (M = 72% vs. 78%). The interaction of set size × probe type was not significant ($F < 1$).

Of interest, there was no effect of cue type [$F(1,11) = 2.90$, $p = .12$] and the trend was toward a higher overall error rate in the precue condition (M precue = 76% vs. M simultaneous cue = 79%; see Figure 4). The interaction of cue type × probe type was not significant ($F < 1$), but the interaction of cue type × set size was significant [$F(1,11) = 5.93, p < .03$]; at set-size 2, performance was similar with a precue and a simultaneous cue, but at set-size 4, performance was worse when there was a precue. No other interactions were significant.

These results suggest that distractors intrude into memory regardless of whether the cue precedes or occurs simultaneously with the target item. These results fail to support the preparation hypothesis.

EXPERIMENT 4
Simultaneous Versus Sequential Presentations

The results of Experiments 1–3 suggest that attended items are encoded into visual memory even when participants have top-down information—in the form of a cue—and a reward incentive—in the form of error feedback—to block encoding. Here, we ask whether the ability to restrict perceptual attention to a set of targets blocks the access of unattended objects to visual memory. To test this question, we compared performance on trials in which to-be-remembered information was presented sequentially with performance on trials in which to-be-remembered items were presented simultaneously. On the latter trial type, participants could easily use spatial attention to select which items to encode. In addition, we tested a larger sample of participants in Experiment 4 to rule out the possibility that low power was contributing to the nonsignificant interaction between set size and probe type observed in prior experiments.

Method

Participants. Twenty-six participants were tested.

Materials. Stimuli were the same 2-D shapes that were used in Experiment 1.

Design. The experimental design was similar to that used in Experiments 1 and 2, except that an additional factor, presentation type (simultaneous or sequential), was added. The presentation-type factor was blocked so that one presentation type was presented exclusively for half of the experiment. The presentation-type factor was presented in a counterbalanced order. The other factors were randomly intermixed within each block.

Task and trial sequence. Trials in the sequential presentation type were identical to those used in Experiment 1. Trials in the simultaneous presentation type consisted of the simultaneous presentation of two or four randomly selected target shapes plus two distractors, except on distractor-absent trials. Stimuli were presented at randomly chosen locations within an invisible 3 × 3 grid in the center of the screen that subtended 12°. Targets were marked by a white surround box.

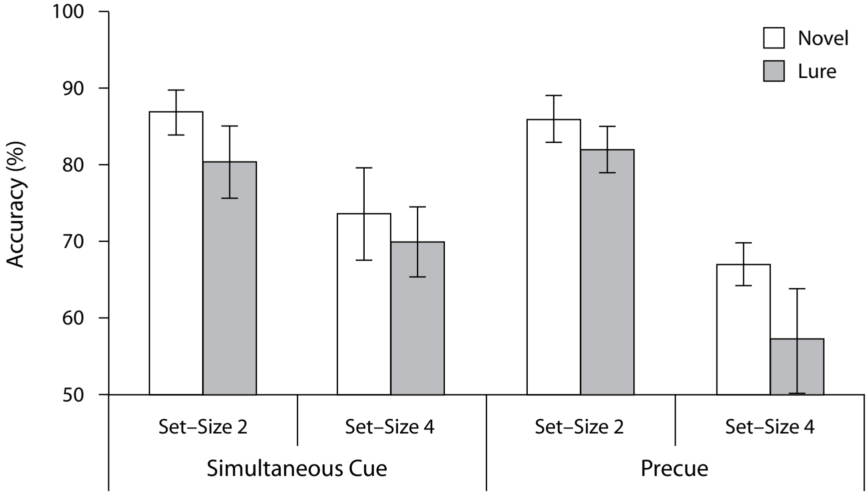

Figure 4. Results from Experiment 3, showing accuracy on nonmatch trials of simultaneous cuing procedure and precuing procedure. Error bars represent standard errors. The differentially lower accuracy on the lure trials represents the intrusion of distractors into visual memory.

Each simultaneous trial consisted of a memory image for 2,166 msec, a retention interval of 1,000 msec, and then a probe image, containing a single shape at central fixation, lasting until a response was made. The duration of the memory image was chosen so that it was equivalent to the weighted-average presentation time of an entire sequential memory sequence, which, of course, varied according to set size. There were 24 practice trials, followed by ten 24-trial blocks.

Results and Discussion

All participants performed at above-chance levels (mean d' for distractor-present trials $= 1.87$; distractor-absent $= 1.77$). Figure 5 shows mean accuracy of the nonmatch trials as a function of set size, probe type, and presentation type. A repeated measures ANOVA was conducted to compare accuracy in the two presentation types, so only data relevant to that comparison are reported. As in the prior experiments, performance was worse at larger set sizes [$F(1,25) = 51.64$, $p < .00$; $M = 82\%$ vs. 70%], and distractors were encoded into memory, as evidenced by poorer performance on lure trials [$F(1,25) = 4.98$, $p = .04$; $M = 75\%$ vs. 78%]. There was also a main effect of trial type [$F(1,25) = 4.57$, $p = .03$] that was due to somewhat lower accuracy on sequential trials ($M = 73\%$ vs. 79%). The interaction between presentation type and probe type was marginally significant [$F(1,25) = 3.35$, $p = .08$] because of the intrusion of lures on sequential trials but not on simultaneous trials. Planned comparisons show that accuracy was significantly lower on the sequential lure trials than on the simultaneous lure trials [$M = 70\%$ vs. 79%; $t(25) = 3.42$, $p = .002$]. However, no such difference was found when the same comparison was made on novel trials (77% vs. 78%; $t < 1$, n.s.). Using a liberal one-tailed t test, we found that at both set sizes on the sequential trials, performance on lure trials was diminished [$t(25) = .03$, $p = .06$], whereas on the simultaneous trials, performance on the lure trials was quite high at both set sizes [$t(25) = .50$, $p = .35$]. Other interactions were not significant (all ps $> .10$).

These findings suggest that attentional control over the contents of visual memory is very good when spatial attention can be used to select critical information (the simultaneous condition).

EXPERIMENT 5

Simultaneous Presentation With Controlled Eye Movements

An alternative explanation for the results observed in Experiment 4 is that they were due to differences in eye movements between conditions. The exclusion of distractors on the simultaneous condition could have occurred because those objects were not fixated. In contrast, every item was fixated in the sequential condition. Objects that are not fixated, or that are seen only with parafoveal vision, may create low-resolution representations that are too poor to give rise to memory intrusions. Indeed, change detection is quite poor if the changed object is not fixated prior to probing (Hollingworth & Henderson, 2002).

Experiment 5 assessed the contribution of eye fixations to distractor processing during simultaneous presentations by precuing and minimizing eye movements. The purpose of the precue was to predirect attention to one side of the display. The purpose of minimizing eye movements was to control any differential effect this variable might have on target versus distractor processing. Three changes made to the stimuli and trials in comparison with those used in Experiment 4 to minimize eye movements were as follows: (1) Stimulus size was reduced; (2) stimuli were presented near fixation; and (3) stimuli and cue were presented for only 100 msec on the encoding screen.

Method

Participants. Sixteen participants were tested; 2 were excluded for below-chance performance across all conditions.

Materials. Stimuli were the same 2-D shapes that were used in Experiment 1, except that the size was reduced 50% so that stimuli subtended approximately 1º–1.5º of visual angle.

Design. General aspects of the experimental design were similar to those in prior experiments, except only one set size was tested

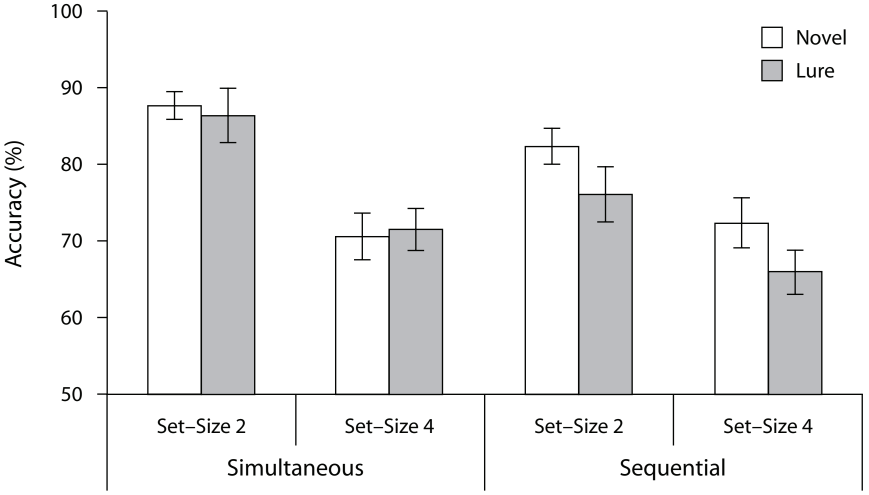

Figure 5. Results from Experiment 4, showing accuracy on nonmatch trials of the simultaneous trials and the sequential trials. Error bars represent standard errors. The differentially lower accuracy on the lure trials represents the intrusion of distractors into visual memory.

minus two target items (two targets, two distractors) because of the greater difficulty of this task as compared with the other tasks discussed in this article. One half of all targets appeared on the left side of the display; the other half appeared on the right. This variable was randomized across trials and participants.

Task. Each trial consisted of fixation, followed by two red surround cue boxes on either the left or the right side of the screen for 100 msec, followed by a 100-msec delay. The purpose of the precue was to predirect attention to one side of the display. The memory image consisted of the simultaneous presentation of two randomly selected target shapes plus two randomly selected distractor shapes for 100 msec. Stimuli were presented at four locations within an invisible 2×2 grid in the center of the screen that subtended 2º. After a retention interval of 1,000 msec, the probe image—consisting of a single shape—was presented, lasting until a response was made. There were 12 practice trials, followed by four 24-trial test blocks.

Results and Discussion

Data were analyzed in the same manner as in Experiment 1 and are illustrated in Figure 6. A *t* test on probe type was carried out on the accuracy of reporting whether or not a probe shape was in the cued subset from the memory sequence. Performance was worse on the lure trials than on the novel trial condition [$t(13) = 2.26$, $p = .035$; $M =$ 79% vs. 70%], suggesting that distractors were encoded into memory. These results qualify the findings of Experiment 4 by suggesting that fixations are an important variable in determining which information is shunted into the visual memory store.

EXPERIMENT 6
Representations of Targets and Distractors in Long-Term Memory

How long-lasting are distractor representations? In Experiment 6, we examined whether distractor representations exist not only in short-delay memory, but also in long-term memory (LTM). LTM was assessed with a surprise forced-choice memory task at the end of the testing session.

Method

Participants

Participants were 13 young adults. One was excluded for below-chance accuracy.

Materials

Stimuli were the same 2-D shapes that were used in Experiment 1.

Trial Sequence and Design

Part I: Working memory. Each trial was similar to that used in Experiment 1. The experimental design and number of trials were also similar.

Part II: LTM. At the end of the experiment, a surprise LTM task was given. Each LTM trial consisted of the presentation of a shape to which participants were required to make a forced-choice response as to whether or not they recognized the shape from Part I of the experiment. After the response was entered, the screen was cleared, and the next trial commenced. Twenty of the trials contained stimuli that had previously been probed target stimuli, 20 of the trials contained stimuli that had previously been probed distractor stimuli, and 40 of the trials contained stimuli that were newly generated for the LTM task. Target and distractor stimuli had been presented the same number of times in the VWM portion of the experiment. All trial types were randomly intermixed.

Results and Discussion

All participants performed at above-chance levels (mean d' for distractor-present trials $= 1.78$; distractor-absent $= 1.88$). Data for the VWM portion of the experiment were analyzed in the same manner as in Experiment 1. An ANOVA on set size and probe type was carried out on the accuracy of reporting whether or not a probe shape was in the cued subset from the memory sequence. Performance was marginally worse at larger set sizes [$F(1,11) = 4.13$, $p = .07$; $M = 70\%$ vs. 78%], and distractors were encoded into memory as evidenced by lower performance on lure trials than on the novel trials [$F(1,11) = 4.89$, $p = .05$; $M = 69\%$ vs. 78%]. However, the interaction of set size × probe type was not significant ($F < 1$). These results replicate the findings reported in our prior experiments.

Recognition of both targets and distractors in the surprise LTM task was higher than the false alarm rate of 54% (both ps $< .0001$). Sensitivity (d') to target familiarity was 1.6, whereas sensitivity to distractor familiarity was 1.31. Recognition accuracy was higher for items that had served as targets than for items that had served as distractors [$M = 83\%$ vs. 76%; $t(11) = 2.43$, $p = .03$]. These findings show that distractors were retained in LTM, but at lower levels than were targets. It is possible that because the distractors had previously served as probes, the relatively good LTM retention resulted from their encoding as probes, not as distractors.

ADDITIONAL ANALYSES

Effects of Distractors on Memory Capacity

The tasks used to assess intrusion effects in Experiments 1–4 and 6 contained a trial type (termed D−) that was not analyzed. In the D− condition, no distractors were presented during the memory sequence. This is in

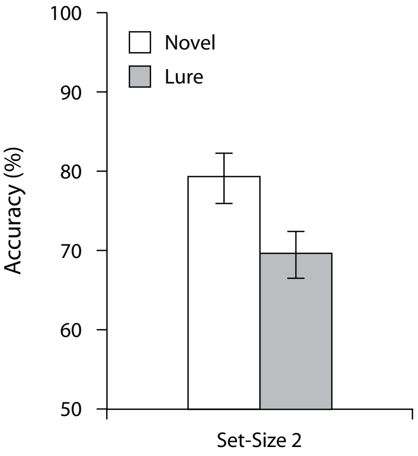

Figure 6. Results from Experiment 5 with simultaneous presentation with controlled eye movements, showing accuracy on nonmatch trials. The differentially lower accuracy on the lure trials represents the intrusion of distractors into visual memory. Error bars represent standard errors.

comparison with the D+ trial type (analyzed earlier), in which distractors were present. The purpose of the D− trials was to allow us to assess whether the presence of distractors generally lowers working memory performance for targets. To address this question, data from D+ and D− match trials and D+ and D− nonmatch trials were analyzed. Memory capacity (K)[1] (Cowan, 2001) was computed for each participant in each experiment and analyzed in a repeated measures ANOVA on set size (2 or 4) and distractor state (present or absent). Analyses relevant to this question are reported here. In Experiments 1, 3, 4, and 6, the presence of distractors did not affect memory capacity (all Fs < 1), and the distractor-state factor did not interact with set size (all ps $> .12$).

In contrast, the presence of distracting faces lowered memory capacity in Experiment 2 from 1.38 faces to 1.01 faces [$F(1,17) = 11.15, p = .004$]. The interaction of distractor state × set size approached significance ($p = .08$). One interpretation of this finding is that distractors are more likely to occupy memory capacity when they are a salient stimulus, such as a face (Jenkins, Lavie, & Driver, 2003).

Analysis of Match Trials

The primary dependent measure in this article was accuracy on nonmatch trials. Were there any interesting effects in the match trials? In separate ANOVAs, we analyzed the effects of set size (2 or 4) and the presence or absence of distractors on match trial accuracy (hit rate; see Figure 7), collapsing across other factors. In every experiment, higher set sizes led to lower accuracy (all ps $< .01$). In Experiment 2, overall accuracy was lower when distractors were present [$F(1,17) = 4.48, p = .05$]; however, t tests showed that accuracy differences were modest and not present when comparisons were made at each set size (all ps $> .08$). However, in all other experiments, there was no main effect of distractor presence (all ps $> .09$). Post hoc t tests showed that distractor presence was associated with higher accuracy in Experiment 4 at set-size 4, but with lower accuracy in Experiment 6 at set-size 2. The paradoxical effect in Experiment 4 may be partially attributed to the fact that we collapsed across sequential and simultaneous trial types. There was no evidence of significant interactions between set size and distractor presence (all ps $> .10$). In sum, the mere presence of distractors did not diminish hit rates in most experiments. However, when distractors were salient objects, such as faces, there was a performance cost.

GENERAL DISCUSSION

The primary question behind the studies reported in this article is, How much control do we have over what is placed in visual memory? To answer this question, participants were asked to remember sequentially presented targets and to ignore distractors. Given that distractors are attended, is their entry in visual memory obligatory? In Experiments 1 and 2, we found that distractor information that was clearly marked was encoded and maintained by visual memory, regardless of stimulus type. Advance preparation in the form of a precue did nothing to ameliorate distractor intrusions into visual memory (Experiment 3). Such a finding is in line with research on the redundant prefix and suffix effects in which irrelevant distractor information presented before or after a list of target items causes a drop in memory performance, even though one can prepare for the onset of the distracting information (Crowder & Morton, 1969; Dallett, 1964). The representation of distractors in memory was precise enough that participants mistakenly recognized them as target items, leading to the high false alarm rate on the lure trials. The representations were so good, in fact, that on a surprise LTM test, distractors were recognized at above-chance levels, even though the similarity between stimuli was high and each item had been seen only once before (Experiment 6). The results of Experiment 6 suggest that distractors were not merely perceived and encoded for a few seconds, but that the memory traces were long-lived. Because the LTM of targets surpassed that of distractors, one effect of top-down control processes (intending to remember) may be to boost the longevity of a signal strength.

A second major question that we asked was whether the ability to restrict attention to targets limits the ability of distractors to access visual memory. The results of two experiments provided mixed results. When participants were allowed to freely move their eyes over spatially arrayed targets and distractors, control over the contents of visual memory was nearly perfect, and distractors were not transferred to visual memory (Experiment 4). This finding shows that unattended distractors are effectively excluded from memory. One decisive difference between the sequential and simultaneous conditions of Experiment 4 was that targets were presumably fixated and distractors were not in the simultaneous condition; this was not the case in the sequential condition. This would potentially cause

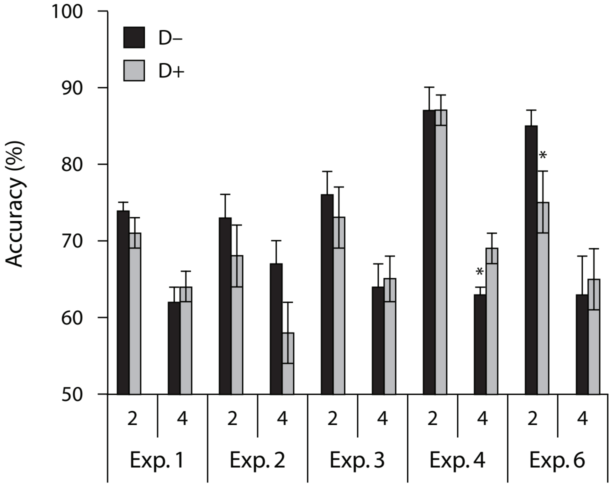

Figure 7. Accuracy on match trials by distractor present/absent for each set size (2 and 4), collapsing across other factors. Error bars represent standard errors. Statistically significant differences ($p < .05$) between distractor-present (D+) and distractor-absent (D−) trials are indicated by an asterisk.

an uneven level of perceptual encoding and, hence, mnemonic representation, with unfixated objects having weak, low-resolution representations that were too poor to cause a sense of familiarity. Because spatial attention and eye movements are tightly linked, it was impossible for us to determine whether eye fixations played an important role in the findings of Experiment 4. To assess this possibility, in Experiment 5, participants again performed a visual memory task with simultaneously presented targets and distractors, but they did so under conditions in which eye movements were severely minimized. Under these conditions, distractors entered visual memory.

This finding was unexpected, although there is some precedence for it in the literature. Hollingworth and Henderson (2002) showed that changes to scenic displays after a brief delay period critically depended on whether the target object had been fixated. A rapid fixation, however, was not sufficient; they also found a positive correlation between fixation time on the target during encoding and subsequent change detection performance. Similarly, LTM for objects in scenes or arrays is very poor if there are few fixations on or near the object during study to the degree that the number of fixations provides a good metric for what will later be remembered (Nelson & Loftus, 1980; Williams, Henderson, & Zacks, 2005). Unlike in these studies, object fixations were minimal in Experiment 5. The timing allowed no objects to be fixated if fixation was centrally maintained; if it was not, then it allowed one object. Because of this, participants may have adopted a distributed attentional strategy—even though they were precued—so that they could effectively process all items in the four-item display. Thus, focused spatial attention could not be used to effectively filter distractors. These findings suggest that top-down control (attention set) or diffuse spatial attention is insufficient to gate working memory. What is required is focused spatial attention.

The Distinction Between Short-Delay and Long-Delay Forms of Memory

Throughout this article, we have referred to our tasks as *visual memory* tasks, even though the delay interval used is typical of working or short-term memory (STM) tasks. Our vague use of terms was purposeful; we feel that the evidence for the distinction between STM and LTM is far from definitive. Although dual-process models of memory have dominated the memory literature for many years, a small faction of researchers continues to favor unitary models of memory. Unitary models assume that similar mental processes limit and promote both STM and LTM. STM is conceived as a storehouse for cues that can be used to reconstruct the recent past, rather than as a limited capacity of veridical representations. Unitary models assume that activation levels, rehearsal processes, and decay rates have little importance for memory success. Instead, these models favor an explanation based on item-based interference. One example unitary model is Nairne's (2002) feature model. In this model, it is proposed that short-term representations consist of a variety of activated cues that the participant can use to reconstruct what he or she just heard or viewed. Memory success is determined by how well retrieval cues uniquely specify the target items perceived at encoding. Poor memory performance occurs when the retrieval cues poorly specify the target items—for instance, when there is a high level of similarity between target material and distracting material. In this case, retrieval cues—such as a sense of familiarity—have low predictive validity for distinguishing targets from distractors (Nairne, 2002). A related conceptualization of STM is that it is simply a state of activated LTM (Cowan, 2001).

An examination of the visual memory and cognitive neuroscience literature suggests that there are few obvious differences between VWM and visual LTM, apart from timescale. The representational format of information held in VWM and LTM is similar (Hollingworth, 2004), and the commonly reported capacity differences between VWM and LTM may be due to differences in testing format that lead to precision/capacity trade-off (Ezzyat & Olson, 2008). The strongest evidence for two distinct memory stores is neuropsychological. These findings have recently been called into question in studies by ourselves and others (Jonides et al., 2008; Ranganath & D'Esposito, 2005) showing that the hippocampus—a region thought to be exclusively critical for LTM—is also critical for VWM (Ezzyat & Olson, 2008; Olson, Moore, Stark, & Chatterjee, 2006; Olson, Page, Moore, Chatterjee, & Verfaellie, 2006). The other half of the evidence upholding the dual-process model—a brain region critical for STM but not for LTM—is also questionable; we have found that bilateral parietal lobe damage impairs certain forms of VWM and LTM (Berryhill & Olson, 2008a, 2008b; Berryhill, Picasso, Phuong, Cabeza, & Olson, 2007). In sum, visual memory findings tend to support the unitary view, although, admittedly, this has not been an active area of investigation in the visual memory literature.

In regard to the findings reported in this article, it is possible to view them through the lens of either the unitary view or the dual-process view. It should be noted that most proponents of the dual-process view agree that LTM plays an important role in STM. In other words, STM is not process pure. For instance, Baddeley proposed that an episodic buffer links the two systems (Baddeley, 2000). In this vein, Oberauer (2001) suggested that irrelevant information can be quickly removed from the capacity-limited part of verbal working memory, but that it lingers on in activated LTM. The residual activation in LTM generates intrusions by increasing familiarity signals, but it does not contribute to overall working memory load, which, by its very nature, is limited (Oberauer, 2001). Because our findings show that target memory was similar whether or not distractors were present (reported in the additional analysis section) and that distractors left LTM traces, our findings fit with the view espoused by Oberauer that distractors either never entered VWM and instead directly entered activated LTM, or were efficiently purged from VWM and were shunted into activated LTM.

Memory Load and Distractor Processing

We failed to demonstrate an effect of memory load on the intrusion of distractors into memory. This may appear to contradict findings showing that distractors are processed more readily when memory load is high (de Fockert et al., 2001). Whether this is due to differences in stimuli or task is not clear, since Lavie's studies tend to use verbal stimuli and dual tasks (see Lavie & de Fockert, 2005).

Conclusions

In conclusion, in six experiments, we showed that distractor information that was clearly marked was nevertheless encoded and maintained in visual memory. Distractor intrusion was dependent on the fixation of distractors. These findings suggest that, in many cases, one has only limited control over whether or how strongly items are encoded into visual memory.

AUTHOR NOTE

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NOTE

1. K = set size $*$ (hit rate $-$ false alarm rate)/(1 $-$ false alarm rate).

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