Journal of Experimental Psychology:
Human Perception and Performance
2005, Vol. 31, No. 5, 889–900

0096-1523/05/$12.00 DOI: 10.1037/0096-1523.31.5.889

Associative Learning Improves Visual Working Memory Performance

Ingrid R. Olson
University of Pennsylvania

Yuhong Jiang
Harvard University

Katherine Sledge Moore
University of Pennsylvania

The ability to remember visual stimuli over a short delay period is limited by the small capacity of visual working memory (VWM). Here the authors investigate the role of learning in enhancing VWM. Participants saw 2 spatial arrays separated by a 1-s interval. The 2 arrays were identical except for 1 location. Participants had to detect the difference. Unknown to the participants, some spatial arrays would repeat once every dozen trials or so for up to 32 repetitions. Spatial VWM performance increased significantly when the same location changed across display repetitions, but not at all when different locations changed from one display repetition to another. The authors suggest that a major role of learning in VWM is to mediate which information gets retained, rather than to directly increase VWM capacity.

Keywords: visual short-term memory, learning, training, change detection, chunking

The human cognitive system is stunningly powerful in some respects yet surprisingly limited in others. As human beings, we can recognize an object (Thorpe, Fixe, & Marlot, 1996) or a face (Liu, Harris, & Kanwisher, 2002) in a single glimpse and type 70 words per minute, yet we cannot hold more than four objects at a time in visual working memory (VWM) (Luck & Vogel, 1997) or split our attention to several locations (Pylyshyn & Storm, 1988). Attention and working memory impose major capacity limitations in cognitive processing. This study is concerned with how learning affects the ability to retain information in VWM.

Overview of VWM

VWM[1] allows us to hold a visual display in mind for a few seconds after its disappearance (Phillips, 1974). A briefly presented array of items is first held in an iconic memory, in a largely retina-based format, for approximately 100 to 200 ms (Neisser, 1967; Phillips, 1974; Sperling, 1960). Information is kept in this format before the icon decays, during which time a small subset is transcribed into VWM. The capacity of VWM is limited to approximately four visual items (Alvarez & Cavanagh, 2004; Cowan, 2001; Luck & Vogel, 1997; Pashler, 1988; Phillips, 1974) and six spatial locations (Irwin, 1992; Jiang, Olson, & Chun, 2000). These items are represented allocentrically, as a visual pattern (or configuration) encoded with reference to one another (Bor, Duncan, & Owen, 2001; Jiang et al., 2000; Phillips, 1974; Sanocki, 2003; Santa, 1977; Yantis, 1992).

The small capacity—approximately four items—varies little with differences in features (e.g., colors, orientations, size; Vogel, Woodman, & Luck, 2001) or with familiarity (e.g., letters vs. upside-down letters; Pashler, 1988). But items retained in this limited capacity may vary in complexity according to an object-based representation (Luck & Vogel, 1997) or perceptual grouping (Lee & Chun, 2001; Woodman, Vecera, & Luck, 2003). Luck and colleagues showed that chunking features into objects can increase the number of features retained in VWM. When each object is a conjunction of several features, four visual objects can be held with the same ease and fidelity as four simple features (Luck & Vogel, 1997). However, costs become apparent when features are drawn from the same feature category (e.g., color–color conjunctions; Wheeler & Treisman, 2002), suggesting that feature heterogeneity of the to-be-remembered information modulates memory capacity (Olson & Jiang, 2002; Xu, 2002). In addition to object-level chunking, multiple items can also be grouped on the basis of

Ingrid R. Olson and Katherine Sledge Moore, Center for Cognitive Neuroscience, University of Pennsylvania; Yuhong Jiang, Department of Psychology, Harvard University.

We thank James Brockmole, Amishi Jha, David Linden, Steve Luck, and Jon Winower for helpful comments and Sidney Burks for data collection. The study was supported in part by the Clark Fund and National Science Foundation Grant 0345525 to Yuhong Jiang.

Correspondence concerning this article should be addressed to Ingrid R. Olson, Center for Cognitive Neuroscience, University of Pennsylvania, 3720 Walnut Street, Room B51, Philadelphia, PA 19104. E-mail: iolson@psych.upenn.edu

---

[1] The terms *visual short-term memory* and *visual working memory* connote different things, with *short-term memory* emphasizing the storage aspect of memory and *working memory* emphasizing both the storage and the manipulation of information held in memory. Although the distinction between storage and manipulation is of theoretical interest, in practice, these terms have been used somewhat interchangeably. The change detection paradigm used here, with short retention interval between two arrays, is sometimes referred to as *visual working memory* (e.g., Luck & Vogel, 1997) and sometimes referred to as *visual short-term memory* (e.g., Alvarez & Cavanagh, 2004). Because there is no reason to believe that this paradigm is only tapping into the storage and not into the manipulation aspects of immediate memory, we have decided that *visual working memory* is a more neutral term to use for this study.

depth (Xu & Nakayama, 2003) or they can be remembered as a single, complex pattern rather than as several isolated items (Jiang et al., 2000).

Role of Learning

In this study, we examine the effects of learning on VWM. We ask, can humans hold more information in VWM from familiar visual displays than from unfamiliar displays? Will they remember a display better if it is repeated over and over again? These are important questions because unlike laboratory stimuli, natural scenes often remain stable over time. This affords plenty of opportunities to learn from repeated encounters. A previous encounter with a scene leaves a long-term memory trace (Hollingworth, 2004; Hollingworth & Henderson, 2002) that may affect working memory for that scene.

To date, most studies have focused on characterizing VWM for nonrepeated visual displays, neglecting the role of learning. This forms a critical gap in the literature because learning plays a significant role in many other aspects of visual cognition: the speed of visual search is improved by practicing the same search task for several sessions (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977), dual-task interference is largely reduced after thousands of trials of practice (Schumacher, Seymour, Glass, Kieras, & Meyer, 2001; Van Selst, Ruthruff, & Johnston, 1999), and visual search is more efficient on familiar (e.g., *2*s and *5*s) than on unfamiliar items (rotated *2*s and *5*s; Wang, Cavanagh, & Green, 1994). In addition to general procedural learning and familiarity, specific information about visual targets can be acquired in an implicit manner. The visual system is highly sensitive to repeated target locations (Maljkovic & Nakayama, 1996), to incidental features such as target color (Maljkovic & Nakayama, 1994), to sequences of target locations and motor responses (Nissen & Bullemer, 1987; Reber, 1989; Segar, 1994), and to the association between targets and distractors (Chun & Jiang, 1998, 1999, 2003; Olson & Chun, 2001a, 2001b; Olson, Chun, & Allison, 2001).

General procedural learning can enhance performance on VWM tasks, but only modestly. Olesen, Westerberg, and Klingberg (2004) gave participants an extensive amount of training for 35 sessions on a spatial VWM task. Participants were required to remember several sequentially presented locations and then recall all locations after a brief retention interval. At the end of the extensive training period, accuracy improved modestly in one experiment and not at all in another. The modest improvement seen after such an extensive amount of training can be contrasted to the large, and at times rapid, changes in learning observed in visual search tasks (Shiffrin & Schneider, 1977) and perceptual discrimination tasks (Fahle & Edelman, 1993; Poggio, Fahle, & Edelman, 1992; Ramachandran & Braddick, 1973; Shiu & Pashler, 1992; Vaina, Sundareswaran, & Harris, 1995).

Specific practice, in the form of repeating the same exact displays many times, also fails to enhance performance (Olson & Jiang, 2004). Participants in Olson and Jiang's (2004) study were required to remember an array of locations or shapes and to detect whether one item had changed on a second display. Unknown to participants, some arrays of stimuli were repeatedly presented over 20 times in the experiment, but the item that might change on the test image was randomly chosen from the stimulus array. In other words, repeating a specific array did not help predict which location would be queried on the test image. Surprisingly, participants did not benefit from the repetition of memory displays, even though they recognized the repeated displays on a posttask recognition exam. These findings suggest that display repetition and familiarity is insufficient to enhance VWM performance.

Taken together, previous studies suggest that while the visual perceptual system can gradually increase its acuity through practice, VWM is relatively insensitive to practice. General practice in a VWM task produces only a small improvement in performance with extensive training, and specific practice on repeated displays does not make these displays easier to remember.

Present Study

The studies outlined in this article test the hypothesis that learning has a limited role in enhancing how much information is stored in VWM but that it can significantly change which information is placed in VWM. This hypothesis is based on the observation that past experience creates knowledge, either implicit or explicit, about what parts of the visual input are important and which parts are unimportant. It is possible that the important parts of the visual input have priority for entrance into VWM. The *prioritization hypothesis* (Hypothesis 1) can be contrasted with two alternatives: that VWM is always impervious to learning (Hypothesis 2: *rigid VWM hypothesis*) or that VWM capacity always increases with learning (Hypothesis 3: *modifiable capacity hypothesis*). Experiments 1 through 3 were designed to test these hypotheses. A fourth experiment examined whether learning affected VWM processing during the encoding or during the comparison process.

Experiment 1: Transfer From Nonassociative Learning to Associative Learning

In previous experiments (Olson & Jiang, 2004) we showed that performance in a VWM task was not enhanced when a display was repeatedly encountered, even when participants could recognize the displays at above-chance levels. In that study, the item that might change was randomly chosen from the memory display, so learning the repeated display was not predictive of the potential change. Experiment 1 was conducted for two reasons. First, we wanted to replicate these rather surprising findings. Second, we wanted to know whether the repeated displays were learned but not expressed in behavior because they did not predict the probe item location. This question gets at the issue of latent learning, or learning that occurs but is only expressed in particular contexts (Jiang & Leung, 2005).

Experiment 1 used a change detection procedure to test how repeated presentation of the same memory image affects participants' VWM performance. On each trial a memory image containing N items—6, 9, or 12—was presented for 500 ms. After a blank interval of 1,000 ms, a probe array containing $N - 1$ items was presented until the participant made a response by clicking on the missing location using a mouse button. We counted a response as correct if the mouse click was within 1.6° of the missing square. This distance was chosen because previous studies showed that decision error for recalling a single location was about this size (Dale, 1973; Keefe, Lees-Roitman, & Dupre, 1997).

Unknown to the participants, some memory displays would be repeated once every dozen trials or so. For example, a particular array was presented on Trial 1, and it was presented again on Trials 13, 20, 37, and so on. It is important to note that the square that might disappear—the target location—was randomly selected from the memory array. So even though the memory display was repeated, one could not use such information to predict which location would change. Still, over a 1-hr testing session, the same display had to be held in VWM 32 times. This condition, the *old* condition, was randomly intermixed with novel displays (i.e., the *new* condition), and participants were not told that some displays would be repeating. Figure 1 shows a schematic sample of a trial.

For repeatedly presented displays, working memory has access not only to the preceding perception, but also to the long-term memory trace. In contrast, for novel displays, working memory is established only on the basis of perception alone. Thus, one might expect that VWM for repeated displays would be better than for novel displays, yet that was not what we found previously (Olson & Jiang, 2004).

To address the question of whether there was latent learning that was not expressed because of random target locations, in Experiment 1, the training session was followed by a transfer session. The transfer session consisted of eight blocks of trials that contained a fixed target location for a given repeated display. That is, the same repeated displays that had been shown during training were repeated eight times during transfer, and each display was associated with a particular probe item location. To control for new learning acquired in the transfer session, we also repeated new displays created after the training phase. The two kinds of trials, new repeats and old repeats, were thus identical during the transfer session. The only difference was that the old repeats had been shown 32 times during training. This allowed us to assess whether or not there was any savings from having seen particular displays repeatedly presented before. Any benefit for the old repeats would reflect a saving effect from the training session.

Experiment 1 allows us to test the three hypotheses laid out earlier. In particular, it pitted the modifiable capacity hypothesis against the other two hypotheses. Both the prioritization hypothesis and the modifiable capacity hypothesis predict that performance should be similar in all conditions, but for different reasons. If the role of learning in VWM is to prioritize the important subset of visual information as suggested by the prioritization hypothesis, and a random target location prevents this from occurring, then performance should be similar for old and new displays in both training and transfer sessions. Alternatively, if VWM is insensitive to display repetition, as suggested by the rigid VWM hypothesis, then performance should also be insensitive to repetition. In contrast to these two hypotheses, if VWM capacity can be improved by training (modifiable capacity hypothesis) and such learning remains dormant until a consistent target location is probed, then performance should be similar in the *old* and *new* conditions during training, but higher for old repeats than new repeats during transfer. Experiments reported later in this article further differentiated the prioritization and rigid VWM hypotheses.

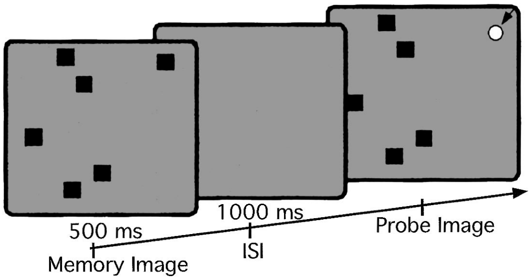

Figure 1. A schematic sample of a trial used in Experiment 1. Participants clicked on the missing filled location on the probe image. The white dot and arrow on the probe image are shown here for illustrative purposes only. Display is not drawn to the actual scale. ISI = interstimulus interval.

Method

Participants

Participants were recruited from the University of Pennsylvania or Harvard University and received course credit or payment. Participants all had normal or corrected-to-normal visual acuity. They were 18 to 30 years old. All signed an informed-consent form prior to the experiment. Eighteen naive participants were tested in Experiment 1.

Equipment

Participants were tested individually in a dark room with a 19-in. (about 48-cm) monitor. They sat at an unrestricted viewing distance of about 57 cm, at which distance 1 cm corresponds to a 1° viewing angle. All experiments were programmed in Psychophysics toolbox implemented in MATLAB (Brainard, 1997) for Macintosh.

Materials

On each memory image, several green squares (1.1° × 1.1°) were presented on a uniformly gray background. The items were presented at randomly selected locations from a 10 × 10 invisible matrix that subtended 17.7° × 17.7°. The stimuli were designed so that squares could not touch one another.

Trial Sequence

Each trial started with a memory image containing 6, 9, or 12 items, lasting 500 ms, followed by a retention interval of 1,000 ms, and then a probe image lasting until a response was made. The participants were required to encode all filled locations presented on the memory image, to maintain a representation of the image across the retention interval, and to decide which location was missing from the array on the probe image. Responses were made by mouse clicking on an unfilled location. The probe display was cleared, and accuracy feedback was provided immediately after the mouse click was made. Responses were coded as correct if the mouse click was within 0.5 cm of the outside edges of the green square (or 1.6° from the center of the square). This distance was chosen because previous studies showed that approximately 0.5 cm of error could be attributed to decision errors in recalling a single location (Dale, 1973; Keefe et al., 1997). The next trial commenced after a 500-ms interval.

Sessions

There were three sessions: training, transfer, and recognition. There were 32 blocks in the training session, 8 blocks in the transfer session, and 1 block in the recognition session. Each block contained a random mixture of old and new displays (6 trials each), which were in turn evenly divided into three set sizes (6, 9, or 12). Because the overall pattern of results was similar for all three set sizes, in the *Results* section we collapsed trials across all set sizes.

Training. The training session included nonassociative learning, in which the repeated displays were repeated once per block, for 32 times, but the target location (the square that might disappear) was randomly chosen from the displays in each block. Different old and new configurations were used for different participants. On each trial, a correct response was followed by a high-pitched chirp, whereas an incorrect response was followed by a low-pitched buzz.

Transfer. The transfer session contained an associative learning manipulation. Here, all 12 trials included repeated displays associated with a particular target location, but half of the displays were new repeats, generated at the beginning of the transfer session, whereas the other half were old repeats, containing the same memory displays as those seen during the training session. Accuracy response was provided after every trial.

Recognition. Finally, participants completed a recognition test, during which 12 arrays were presented one at a time, and participants had to decide whether they had seen each display before. Half of the displays were the same as the old repeats, the other half were newly generated. No feedback was given.

Eighteen participants completed the training session, of which the last 8 participants also completed the transfer session and the recognition test.

Results

Data were binned into epochs consisting of two blocks to increase power. Figure 2 shows mean accuracy in the training session and transfer sessions. Table 1 shows performance broken down by set size. Note that because there were about 90 empty locations for participants to click, choosing at random would lead to about 1.1% correct.

Session 1: VWM Training

An analysis of variance (ANOVA) on epoch (1–16) and condition (*old* vs. *new*) was carried out on accuracy of choosing the correct probe item location. The ANOVA revealed a significant main effect of epoch, $F(15, 255) = 3.96$, $p < .0001$, due to improved accuracy as the experiment progressed (Epoch 1 = 60% vs. Epoch 16 = 72%), but no main effect of condition ($F < 1$, *ns*) and no interaction of epoch with condition, $F(15, 255) = 1.19$, $p = .28$, suggesting that there was no learning-dependent improvement in the *old* condition. The lack of training-related difference between the *old* and *new* conditions suggests that VWM for spatial locations was relatively insensitive to nonassociative learning.

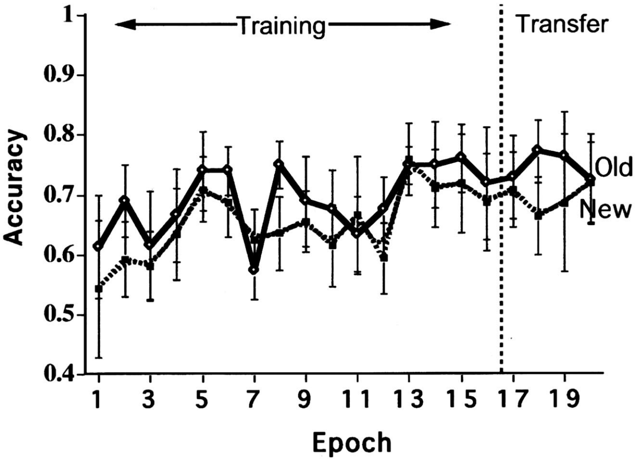

Figure 2. Results from Experiment 1: Accuracy for repeated (i.e., old) and nonrepeated (i.e., new) displays during training, and for old repeats and new repeats during transfer. Error bars represent standard error. Chance performance was 1%.

Because this was a null result, we did an additional analysis of a different dependent measure, mouse click distance. Click distance is a measure of the difference between the center of the (missing) target item and the actual location that was recalled and mouse clicked. The ANOVA on click distance showed that there was a main effect of epoch, $F(15, 255) = 6.96$, $p < .0001$, due to shorter click distances over time (Epoch 1 = 116 pixels vs. Epoch 16 = 65 pixels), but no main effect of condition, $F(1, 17) = 1.04$, $p = .32$, and no interaction of epoch with condition ($F < 1$, *ns*). These results mimic the pattern of findings reported for the accuracy measure.

Session 2: VWM Transfer

We compared observers' performance in the last four training epochs with the four transfer epochs to assess whether there were any savings from the training phase. An ANOVA on session (training vs. transfer), condition (old repeat vs. new repeat), and epoch (1–4) found no significant effects. To highlight some of these null results, the effect of condition ($F < 1$) and of session, $F(1, 17) = 1.31$, $p = .27$, and the interaction of session with condition ($F < 1$) were not significant. These results suggest that there was no acquisition of learning and no savings of learning from a nonassociative VWM learning task.

Session 3: Recognition

Eight of the participants in Experiment 1 completed the recognition phase. The recognition data showed a higher hit rate (identifying the repeated displays as old; 83%) than false-alarm rate (misidentifying newly created displays as old; 46%), $t(7) = 3.09$, $p < .018$. These results suggest that participants could recognize the repeated displays.

Discussion

Can we remember familiar visual displays better than unfamiliar ones? The answer from Experiment 1 was no, at least not with a moderate amount of training. Repeating a few displays 32 times made it possible for participants to recognize them explicitly, suggesting that long-term memories of these displays were established. Yet accuracy to detect a change on a repeated display was not higher than that on nonrepeated displays. This suggests that the capacity of VWM is not easily modified by display repetition, at least when the repeated displays are not predictive of the potential change. In addition, we found no evidence for latent learning of repeated displays. In the transfer phase, when a given repeated display was always associated with a given potential change, change detection was still not better for old repeats than for new repeats. These findings are inconsistent with the modifiable capacity hypothesis. They are more in line with the prioritization hy-

Table 1
Mean Percentage of Accuracy for Each Set Size From the Second Half of the Training Period for Experiments 1 to 4

	Set size											
	6				9				12			
	New		Old		New		Old		New		Old	
Experiment	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
1	78.0	4.9	82.5	3.1	62.5	5.1	64.0	5.4	52.4	7.0	55.4	4.7
2	68.0[a]	5.3	94.8[a]	2.3	59.9[a]	5.0	79.5[a]	4.1	48.4[a]	5.7	67.9[a]	6.9
3	71.5[a]	4.5	86.1[a]	4.4	57.7[a]	6.2	73.4[a]	7.3	52.3[a]	6.1	70.8[a]	7.8
4	78.7[a]	4.0	91.7[a]	3.7	70.7	3.7	75.6	6.3	69.9[a]	3.0	89.1[a]	3.2

[a] In a comparison of accuracy in the new versus the old condition (a comparison made within each set size within each experiment), this value differed significantly from the value with which it was compared (i.e., there was a significant difference between old and new conditions).

pothesis or the rigid VWM hypothesis. Experiment 2 pits these hypotheses against each other.

Experiment 2: Associative Learning and VWM

Is VWM sensitive to learning under some conditions, as suggested by the prioritization hypothesis, or is it always impervious to learning, as suggested by the rigid VWM hypothesis? The former hypothesis postulates that learning can affect the priority of entry into VWM when past experience dictates that a subset of the visual display is more important than the rest.

Experiment 1 was unable to differentiate between these two hypotheses because the training phase involved nonassociative learning. In this case, any location on a memory display could potentially change. This means that all locations were equally important, precluding prioritization from occurring. Associative learning is possible during the transfer phase, yet it was equally available to new repeats and old repeats. To differentiate between the rigid VWM hypothesis and the prioritization hypothesis, one must create learning conditions in which a subset of the visual field acquires priority during training. Experiment 2 provided chances for prioritization by inducing consistent associations between a repeated display and a potential change.

We modified the training procedure slightly. As in Experiment 1, novel spatial displays (*new* condition) were contrasted with displays that occasionally repeated (*old* condition). A critical feature of Experiment 2 was that the location that might disappear on the probe image was consistently associated with a specific repeated display. In other words, each time a repeated display was presented, the same location would later disappear.

If associative learning prioritizes the probe item location to enter VWM, then VWM performance in the *old* condition should gradually improve and become better than that in the *new* condition, consistent with the prioritization hypothesis. Alternatively, if VWM completely lacks any plasticity, then performance in the two conditions should not differ with training. The latter finding would be consistent with the rigid VWM hypothesis.

Previous studies using the "contextual cuing" paradigm have shown that associative learning affects how attention is allocated in repeated visual search displays (Chun & Jiang, 1998). We discuss the relationship between contextual cuing and the current study after presentation of the results.

Method

Participants

Ten naive participants were tested in Experiment 2.

Design

The design was similar to the training phase of Experiment 1, except that for old displays, the item that might disappear was always the same one, for any particular old pattern, across the 32 blocks. In other words, Old Pattern 1 was always associated with a target item in the upper right corner, and so on. Each block included six repeated (i.e., old) displays, each of which had a different target location. These were randomly intermixed with six novel displays generated on each trial. Different old and new displays were generated for each participant. Immediately after the 32 training blocks, participants were tested in a recognition task identical to that used in Experiment 1.

Results

Session 1: VWM Training

Mean accuracy as a function of epoch and condition is plotted in Figure 3. In this experiment, as well as Experiments 3 and 4, click distance is not reported because the data provide results similar to the accuracy measure. A repeated measures ANOVA on epoch (1–16, each epoch = two blocks) and condition (*old* vs. *new*) was carried out on accuracy of choosing the correct probe item location. There were significant main effects of epoch, $F(15, 135) = 2.02$, $p < .018$, showing improvement of accuracy over time, and condition, $F(1, 9) = 13.34$, $p < .005$, suggesting that performance was influenced by repetition of the old displays. The interaction of interest, that between condition and epoch, was significant, $F(15, 135) = 3.17$, $p < .0002$, suggesting that learning modulated VWM performance as the experiment progressed. Planned contrasts confirmed that the *old* and *new* conditions were not significantly different in Epoch 1, $t(9) = 0.36$, $p = .97$, but they were significantly different in Epoch 16, $t(9) = 6.60$, $p < .0001$.

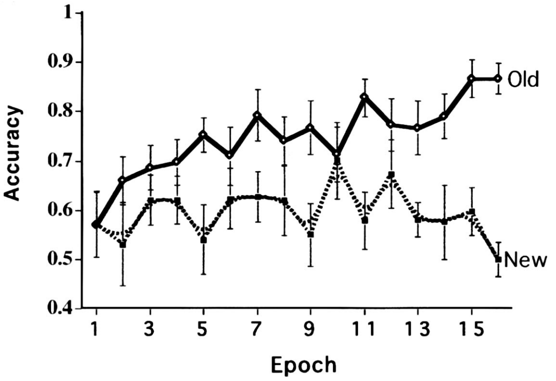

Figure 3. Results from Experiment 2. Each old display was consistently associated with a particular target location. (One epoch = two blocks.) Error bars represent standard error.

Session 2: Recognition

Because of computer failure, recognition scores were obtained from only 8 of the 10 participants. The probability that participants would correctly identify a repeated display as old was 94%, which was significantly higher than the probability that they would misidentify a novel display as old (31%), $t(7) = 7.64$, $p < .001$. Thus, participants were able to recognize repeated displays.

Discussion

In sharp contrast to previous studies that showed modest or no improvement in VWM performance after training, we found a highly significant improvement after a single training session. These findings are inconsistent with the rigid VWM hypothesis. They suggest that associative learning can enhance VWM. These findings support the prioritization hypothesis, according to which associative learning allows the target location to be prioritized in VWM. The target location is then better retained.

The significant enhancement of change detection can be contrasted with inconsistent improvement reported in a prior study of training in VWM (Olesen et al., 2004). In that study, no memory sequences were repeated, so any improvement after training could be attributed to a genuine increase in VWM capacity. This procedure was analogous to the *new* condition of the current experiment, in which performance failed to improve over a 1-hr training session.

The results of Experiment 2 can also be contrasted with the absence of repetition-related effects in Experiment 1. The only difference between the two procedures was that the repeated display was consistently associated with a potential change in Experiment 2, but not in Experiment 1. Had performance improved in Experiment 1, it would have constituted genuine capacity increases for familiar visual displays.

The lack of improvement in Experiment 1 and the presence of improvement in Experiment 2 suggest that first of all, the overall capacity of VWM is relatively insensitive to display repetition. One does not retain more familiar than unfamiliar information. Second, the role of learning in VWM is to prioritize a subset of visual displays. Such prioritization is possible only if a subset of the display—the potential change—is designated as more important than other sets. A consistent association allows the target to be prioritized, whereas nonassociative learning does not.

These results are reminiscent of repetition effects in visual search. In their studies on contextual cuing, Chun and Jiang (1998) repeated a few visual search displays occasionally and paired the repeated displays with particular target locations consistently. They observed significant improvement in search reaction time to the repeated displays compared with nonrepeated ones. However, when the target location randomly changed from repetition to repetition, learning was largely abolished. Similarly, Wolfe and colleagues (Wolfe, Klempen, & Dahlen, 2000; Wolfe, Oliva, Butcher, & Arsenio, 2002) showed participants the same visual search display repeatedly, sometimes for as many as 300 times. They found that participants could not search repeated displays faster than nonrepeated ones if the target changed from one trial to another.

The difference between these studies and the present one is that visual search taps into the allocation of attention whereas the current study taps into VWM directly. The visual search task requires only that participants find the target. It does not explicitly require participants to hold all locations in working memory for later retrieval.[2] In contrast, change detection explicitly requires participants to hold the first display in memory for a later comparison. No items are explicitly designated as distractors, especially in the nonassociative learning of Experiment 1, so all items must be maintained by VWM. The difference in task requirement is important: Participants in visual search tasks are rarely aware of display repetitions, but participants in change detection tasks quickly realize that some displays are repeatedly presented. Nonetheless, both lines of research converge on the conclusion that whether it is visual attention or VWM that is being tapped, a genuine change in capacity is rare. Rather, the malleability of VWM and visual attention appears to be in modulating which information gets priority. This is not to deny the possibility that more extensive training, on the order of weeks, months, or years, might produce a genuine capacity increase in VWM. Still, we wish to emphasize that although learning can quickly mediate the priority of processing, it does not easily change overall capacity. We come back to these points again in the General Discussion section.

Experiment 3: Transfer From Associative to Nonassociative Learning

The previous experiments show that only when a repeated display was predictive of the potential change was there an improvement in change detection. But what role did a consistent association play? One possibility is that a consistent association enhances VWM for the entire display, including the target location and other, nonprobed locations. Alternatively, as the priority hypothesis postulates, memory for the entire display is not generally better. Rather, having a predictable association allows attention to

---

[2] It is important to note that the word *memory* refers to a heterogeneous set of mechanisms, and that even in visual search, some kind of memory—a memory for which distractor location has been recently visited—is most likely present. Here we simply wish to emphasize that the task requirements of visual search do not oblige participants to hold all item locations in working memory, whereas the task requirements of change detection do.

be focused on the location that will later change, leading to better working memory for this location.

To test whether associative learning enhances VWM for the entire display, we included a training session and a transfer session in Experiment 3. Here, participants were trained on displays with consistent association: In the first 32 repetitions, a given repeated display was always associated with a certain change. After the training session, participants were tested in a transfer session, in which a different location on a repeated display changed. If associative learning leads to an overall VWM enhancement, then learning should transfer. In contrast, if associative learning allows the target location to be prioritized, then learning should not transfer to new target locations.

A second goal of Experiment 3 is that we wished to rule out the possibility that the improvement in the *old* condition observed in Experiment 2 was due to motor learning. In Experiment 2, the *old* condition used six probe item locations that repeated many times over the course of the experiment, whereas the *new* condition used many probe item locations that were randomly chosen on each trial. To determine whether motor learning accounts for the improvements observed in Experiment 2, we used the same number of click locations—six—in the *new* as well as the *old* condition.

Method

Participants

Thirteen naive participants were tested.

Sessions

Participants were tested in three sessions: training, transfer, and recognition. The training session was similar to that tested in Experiment 2 except that six locations were always used for the probe item in the *new* condition. In other respects, the training session was identical to Experiment 2: Six old displays and six new displays were randomly intermixed in each block for 32 blocks. In the transfer session, participants were tested in 8 blocks of trials during which old displays shown during training were again repeated, but any one of the memory items—except the trained probe item—might become the target location. Thus, a different location than the trained probe item location would disappear on the probe display. This item was randomly chosen in each block. Finally, in the recognition test, participants were asked to judge whether a given display was old or new, identical to the procedure used in Experiment 2. All other aspects of the experiment were the same as in Experiment 2.

Results

Figure 4 shows mean accuracy for the training and the transfer sessions.

Session 1: VWM Training

An ANOVA on condition (*old* vs. *new*) and epoch (1–16) showed significant main effects of epoch, $F(15, 180) = 4.32$, $p < .0001$; condition, $F(1, 12) = 9.74$, $p < .009$; and their interaction, $F(15, 180) = 1.93$, $p < .02$. As in Experiment 2, accuracy was comparable between the *old* and the *new* conditions in Epoch 1 ($t < 1$, *ns*) but was higher in the *old* condition in Epoch 16, $t(12) = 2.95$, $p < .004$. These results suggest that VWM can be improved by associative learning, even when we controlled for motor learning.

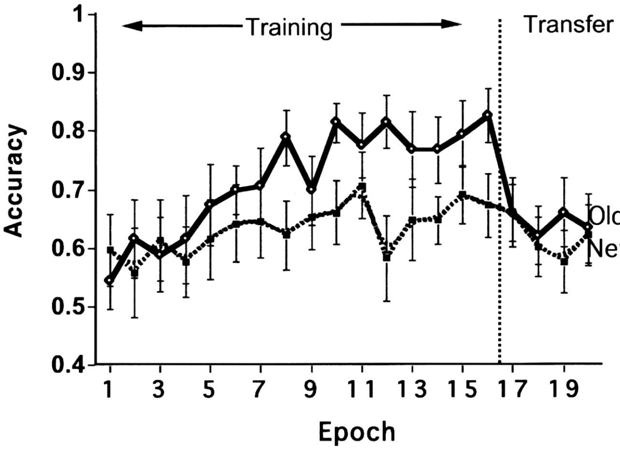

Figure 4. Results from Experiment 3. After training with associative learning, learning was largely abolished when the target location changed to a random location. Error bars represent standard error.

Session 2: VWM Transfer

To assess whether there was any transfer to repeated displays that did not preserve the probe item location, we performed an ANOVA on the four transfer epochs. There was no effect of condition ($F < 1$) or of epoch ($F < 1$), nor was there a significant interaction ($F < 1$). These findings suggest that there was virtually no transfer of learning to new target locations.

To further assess how transfer affected performance, we performed an ANOVA on the last four training epochs and the four transfer epochs. An ANOVA on condition (*old* vs. *new*), epoch (1–4), and session (training vs. transfer) showed significant main effects of condition, $F(1, 12) = 9.66$, $p < .009$, due to higher overall accuracy in the *old* compared to *new* conditions ($M = 72\%$ vs. 64%), and session, $F(1, 12) = 50.63$, $p < .0001$, due to an overall decline in accuracy in the transfer session compared with the training session ($M = 73\%$ vs. 63%). However, there was no effect of epoch ($F < 1$). The interaction between condition and session approached significance, $F(1, 12) = 3.89$, $p = .07$, due to the larger decline from training to transfer in the *old* condition. Analysis using *t* tests showed that accuracy decreased by 15% in the *old* condition between training and transfer ($M = 79\%$ vs. 64%), $t(12) = 4.24$, $p < .001$, but did not significantly decrease between training and transfer in the *new* condition (5% decrease), $t(12) = 1.45$, $p = .17$. None of the other interactions were significant (all *F*s < 1).

Session 3: Recognition

Twelve participants completed the recognition phase. The probability of correctly identifying a repeated display as old was significantly higher than the probability of misidentifying a new display as old ($M = 85\%$ vs. 54%), $t(11) = 4.06$, $p < .002$.

Discussion

Experiment 3 further clarified the learning effect. First, it replicated results from Experiment 2, confirming the observation that performance in a VWM task can improve as participants gain more exposures to the same repeated display–probe item associations. Second, the results from the transfer session suggest that there is little transfer of learning from associative to nonassociative contexts. There was a 15% drop in performance when the probe item locations became randomized in the *old* condition, and the effect of condition was no longer significant. Taken together, these findings suggest that the primary benefit to VWM is from associative learning.

The performance enhancement during the training session was primarily due to associative learning that prioritized the portion of the memory image that would later be probed. In other words, a repeated display may cue attention to the potential probe item's location, allowing this location to be better represented in VWM. One might think that this effect occurs at a cost to memory for the other locations. If true, then after the transfer session, performance in the *old* condition should be worse than that in the *new* condition. However, the results of the transfer session show that performance was similar in the *old* condition and *new* condition. The lack of a negative transfer may be accounted for by the fact that participants noticed the onset of the transfer phase and abandoned prioritization of the previously learned target location.

Experiment 4: Prioritization—Before or After Probe Comparison?

The prior experiments provided evidence that training can easily increase performance on spatial VWM tasks provided that there is an invariant relationship between the long-term memory and a probe item location. In this experiment, we ask, if VWM improves with training, which stage of memory processing is being affected? Does associative learning influence VWM immediately after the presentation of the memory display, or does it affect VWM only after the presentation of the probe display, when explicit comparison is needed? The first account would suggest that observers can quickly deploy attention to the potential target's location immediately after the sample presentation. This allows the target position to be retained in VWM better than other positions. If the second account is true, all sample locations are retained equally well, with the prioritization occurring only during the comparison process when the target location becomes the first to be compared with the stored representation.

If prioritization occurs early, then after some training participants should be able to anticipate the target's location before seeing the probe display. On the other hand, if prioritization occurs late, then participants should not be able to accurately guess which item will disappear before the probe image is shown. To test how early prioritization occurs during the VWM process, we trained participants on a spatial VWM task. At the end of the experiment, participants were presented with the sample displays only and asked to decide (a) whether they recognized the display and (b) which item would likely disappear on the probe image. Participants responded to the first question by a *yes–no* key response and the second question by a mouse click on any of the green squares.

Method

Participants

Thirteen naive participants were tested.

Sessions

Experiment 4 included two contiguous sessions. During the training session, participants completed 20 blocks of old and new trials, as described in Experiment 3. Consistent association between repeated displays and potential targets was available. The possible number of target locations was 6 for old and 6 for new displays, controlling for motor learning.

During the transfer session, participants completed eight blocks (12 trials each) of old and new trials. Each trial consisted of the presentation of a sample memory display to which participants had to make a *yes–no* recognition judgment. The entry of this response caused the sample display to disappear for 300 ms and reappear, signaling that the second response was now needed. Participants then indicated which item might disappear by clicking on any green square. No feedback was provided during the transfer session.

Results

Session 1: VWM Training

Results of the repeated measures ANOVA for the training and transfer session are shown in Figure 5. There was a main effect of condition, $F(1, 12) = 5.192$, $p < .042$, with higher accuracy in the *old* condition ($M = 79\%$ vs. 72%); a main effect of epoch (1–10), $F(9, 108) = 4.64$, $p < .0001$, due to improved accuracy over time; and an interaction of condition and epoch that approached significance, $F(9, 108) = 1.73$, $p = .09$. Planned contrasts showed that accuracy was similar in the *old* and *new* conditions at Epoch 1, $t(12) < 1$, *ns*, but was higher in the *old* condition at Epoch 10, $t(12) = 2.45$, $p < .031$.

Session 2: Transfer and Recognition

There was a main effect of condition, $F(1, 12) = 44.49$, $p < .0001$, with higher accuracy at guessing the target's location in the *old* condition ($M = 63\%$ vs. 16%), suggesting that participants could accurately predict which item would disappear on the probe image in the *old* condition. However, there was no effect of epoch

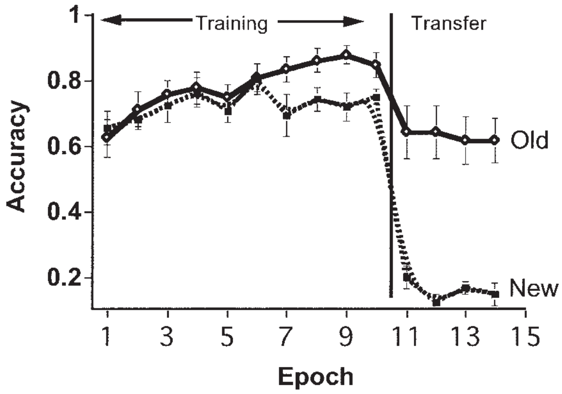

Figure 5. Results from Experiment 4. After being trained in an associative learning task, participants were tested in a transfer session in which they had to guess the target's location upon the presentation of a memory display. Chance performance was 1% in the training session and 12% in the transfer session, due to the fact that the task now required participants to mouse click on one of the filled squares. Error bars represent standard error.

($F < 1$) and no interaction of condition and epoch ($F < 1$), showing that there was no learning during the transfer session.

To test whether performance dropped between training and transfer, we conducted a second ANOVA on the last four epochs of training and the four epochs of transfer. Of interest, this showed that there was a significant effect of session, $F(1, 12) = 89.13$, $p < .0001$, due to a general drop in performance in the guessing phase, and a significant interaction of condition and session, $F(1, 12) = 18.18$, $p < .001$, due to the more dramatic drop in the *new* condition. Performance dropped during the transfer session in both conditions: *new*, $t(12) = 10.03$, $p < .0001$; *old*, $t(12) = 4.0$, $p < .002$. The 23% drop in *old* condition performance suggests that retrieval was imperfect during the transfer session.

The recognition task showed that participants were able to correctly identify a repeated display with a significantly higher level of accuracy than that for misidentifying a new display as old ($M = 84\%$ vs. 42%), $t(12) = 6.89$, $p < .0001$.

Relationship Between VWM Performance and Recognition

To assess whether there was any relationship between training-related VWM performance change and explicit recognition, we conducted a correlational analysis on the data from all participants who completed the recognition phase of each experiment (see Figure 6). Two scores were calculated from each participant. The VWM learning score was the slope of the learning function during the training session for the *old* condition minus the *new* condition. The VWM learning score was correlated with the recognition score from the recognition session and consisted of the hit rate minus the false-alarm rate. The correlation was nonsignificant, $r(39) = -.162$, $p = .28$.

Discussion

The results of Experiment 4 showed that after 20 repetitions, participants could accurately guess which item was going to disappear, just by looking at the memory image. These data support the hypothesis that associative learning affects VWM by rapidly prioritizing a region of the memory display before the test display was presented. The guessing accuracy (e.g., Epoch 11) was supported completely by long-term memory of the repeated display. This can be contrasted with change detection accuracy (e.g., Epoch 10), which could be supported both by long-term memory of the display and by VWM. The significantly lower accuracy in the guessing phase compared with the training phase suggests that VWM can provide additional details or increased fidelity over that held by visual long-term memory (Olson & Jiang, 2004).

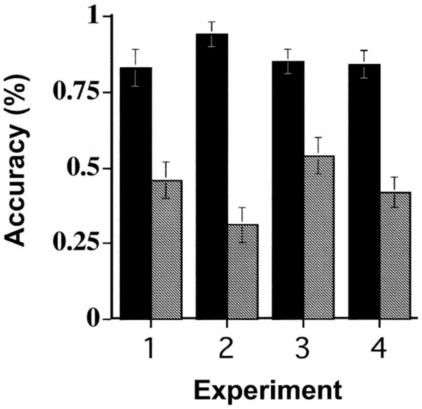

Figure 6. Results from the recognition session of all experiments. Solid bars show the hit rate (*old* condition); hatched bars show the false-alarm rate (*new* condition).

As in prior experiments, participants were able to recognize repeated displays. There was no correlation between recognition performance and the amount of learning in this experiment (not shown) or in the group analysis of all experiments. The lack of a positive correlation suggests that the mechanism that supports recognition is not identical to that supporting accurate-learning-related changes in VWM.

General Discussion

Each time an individual moves his or her eyes to a new part of a scene, some memory of previously visited locations and objects is retained, helping to maintain continuity across saccades. VWM and visual search are tightly linked because visual memory "pushes" vision to search through areas that were not searched in the recent past. Although at least one model of visual search proposes that search is amnesic, and has no memory for what was recently searched (Howowitz & Wolfe, 1998, 2001), there is accumulating evidence that visual search has memory on par with that of VWM (Klein & MacInnes, 1999; McCarley, Wang, Kramer, Irwin, & Peterson, 2003; Peterson, Kramer, Wang, Irwin, & McCarley, 2001). The reciprocal relationship between visual attention and VWM is the topic of this article.

The idea that certain subsets of visual input are prioritized is deeply rooted in studies of attention. At a given moment, an infinite amount of visual information is received, but only a small subset can be selected and responded to (Pashler, 1988). The human attentional system thus uses many mechanisms to ensure that salient and relevant information gains prioritized processing. Salient stimuli such as sudden onsets receive prioritized processing (Egeth & Yantis, 1997), and potentially important items such as new objects also receive priority (Watson & Humphreys, 1997). In addition, relevance can be defined by past experience. In visual search, when a display is repeatedly presented and it is consistently associated with a given target location, then visual search is facilitated (Chun & Jiang, 1998). The current study reveals an example in which learning modulates how attentional priorities are set in VWM (see also Schmidt, Vogel, Woodman, & Luck, 2002).

Learning and VWM

The current study extended the utility of associative learning to modify the efficiency of VWM. By prioritizing important information, acquired through associative learning, training allows one to circumvent capacity limitations without directly increasing the overall capacity of VWM significantly.

We started our investigation by examining nonassociative learning. Experiment 1 required participants to perform many spatial VWM trials with repeated displays but randomized probe locations. There was no benefit of repetition to VWM. This was not because our manipulation of display repetition was too subtle. In a recognition test, participants were able to recognize repeated displays at high accuracy. Nonassociative repetition also failed to produce any savings when the previously repeated displays were now associated with a particular target location. Such old repeats were not more advantageous than new repeats. Thus, a moderate amount of nonassociative learning failed to enhance VWM, whether measured by directly comparing repeated and nonrepeated displays or by comparing the saving effects.

In sharp contrast, Experiment 2 showed that when the repeated displays were consistently associated with particular target locations, change detection improved dramatically in a single training session. The improvement depended on associative learning, as the performance enhancement disappeared when new target locations were probed (Experiment 3). A further experiment suggests that consistent association between repeated displays and their targets allows the target location to be prioritized soon after the presentation of the same display: Participants were able to anticipate and guess the potential target without seeing the probe display (Experiment 4).

The guessing accuracy in the *old* condition did not quite match the level of change detection accuracy when the probe display was provided. This suggests that having both VWM and long-term memory was more beneficial than having long-term memory alone. The reverse is not necessarily true: In a nonassociative learning task (Experiment 1), having long-term memory as well as VWM was not more beneficial than having VWM alone (see also Olson & Jiang, 2004). These findings suggest that the long-term memory, formed through nonassociative learning in a single session, was less precise than what could be extracted on the fly by VWM. For instance, an individual might be able to bring to mind the shape of the star constellation *Big Dipper* upon hearing the term, but the precision of that image may be poorer than an image formed immediately after seeing the Big Dipper itself.

It is possible that extensive training will lead to long-term memory traces whose fidelity is on par with that extracted on the fly by VWM. For instance, one change detection study found that performance was superior for highly familiar faces as compared with novel faces or recently learned faces (Buttle & Raymond, 2003). Nonetheless, with a moderate amount of training, the long-term memory trace is unlikely to be more precise than that produced by immediate VWM. The poor precision may have caused the absent nonassociative repetition effect in Experiment 1.

However, once a consistent association is provided, the nature of the VWM task changes. Associative learning allows the potential target location to become prioritized in VWM, allowing this location to be better retained. Thus, the primary role of learning is not to increase the total amount of information held in VWM but to affect which subset of information gets priority. This is not to deny that an extensive amount of practice could change VWM capacity (Olesen et al., 2004). Still, it may be extremely difficult to modulate the actual capacity of VWM, whereas it is relatively easy to change which information gets into VWM.

Beyond Prioritization

In this study we have emphasized the role of associative learning in prioritizing target information in VWM. Here, we want to outline possible mechanisms for nonassociative learning to enhance VWM. For lack of data, this discussion is necessarily more speculative, but we hope it will help guide future research on the role of learning in VWM.

First, chunking on the basis of long-term knowledge can effectively increase the total number of digits retained in verbal short-term memory (Baddeley & Logie, 1999; Ericsson & Kintsch, 1995). An analogous mechanism could apply to visual stimuli, although such processes may be rare for visual stimuli. VWM is already excellent at chunking information: Features of a single object are effectively chunked into one unit (Luck & Vogel, 1997), and isolated items are obligatorily organized into a visual configuration (Jiang et al., 2000). For learning to further enhance chunking, we conjecture that it is necessary for visual information to be recoded symbolically. Whereas rotated *2*s and *5*s are hard to retain in VWM, upright *2*s and *5*s can be immediately named and retained better in visual and verbal working memory (Alvarez & Cavanagh, 2004). Similarly, chess experts can retain a midgame configuration better than a random, nongame configuration (Gobet & Simon, 1996a, 1996b). Without symbolic recoding, it might be extremely difficult to affect the organization of information in VWM. The current study does not speak directly to the issue of the reorganization of VWM. We hope that future studies will illuminate the utility of this mechanism.

Second, perceptual expertise may develop after prolonged training on a few spatial layouts, novel shapes, or faces. Such familiarity may increase the perceived distinctiveness of the trained items, affecting both encoding and retrieval. Encoding is affected because the trained items appear to be distinctive from one another, decreasing the difficulty of encoding. Retrieval is affected because in a change detection task, for instance, when one trained shape changes into another, the change may be psychologically more salient than when a novel shape changes into another novel shape. This mechanism may account for the *superfamiliarity effect* with faces: Change detection of famous faces is much better than change detection of novel faces (Buttle & Raymond, 2003), presumably because famous faces are psychologically more distinctive from one another than are novel faces.

Finally, task expertise, or procedural learning, may result from prolonged training on any given working memory task. Procedural learning may enhance the ability to rapidly extract information from a sample display, increasing encoding efficiency, or may decrease internal noise that degrades the internal image held during memory maintenance. Procedural learning may account for the results of Olesen et al. (2004). Whether such changes constitute genuine capacity increases is debatable.

Explicit Recognition

It is tempting to suggest that participants relied on explicit recognition of a display to improve VWM performance. Although explicit recognition is a by-product of repeating some of the VWM displays, it is unlikely the cause of the VWM improvement. In particular, even in nonassociative learning tasks (e.g., Experiment 1), participants were able to recognize the repeated displays with high accuracy. Yet explicit recognition was insufficient to enhance VWM. In addition, in associative learning tasks (e.g., Experiments 2–4), participants who performed better with explicit recognition were not necessarily showing a larger enhancement in VWM. The lack of a significant correlation between explicit recognition of a repeated display and VWM performance on that display may result from different requirements of the two tasks. Good VWM performance requires precise visual memory, whereas good recognition performance can be supported by low-resolution, familiarity-based visual memory.

Conclusions

By repeatedly presenting the same visual images in a VWM task, we have clarified the role of learning in enhancing VWM. Our findings show that repetition can enhance change detection performance, but only when a repeated display is consistently associated with a particular change. We suggest that although it is very difficult to increase the overall capacity of VWM through learning, one can easily change which information receives priority in VWM, thereby improving VWM performance.

References

Alvarez, G. A., & Cavanagh, P. (2004). The capacity of visual short-term memory is set by visual information load and by number of objects. *Psychological Science, 15,* 106–111.

Baddeley, A., & Logie, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of working memory* (pp. 28–61). New York: Cambridge University Press.

Bor, D., Duncan, J., & Owen, A. M. (2001). The role of spatial configuration in tests of working memory explored by functional neuroimaging. *Scandinavian Journal of Psychology, 42,* 217–224.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10,* 443–446.

Buttle, H., & Raymond, J. E. (2003). High familiarity enhances visual change detection for face stimuli. *Perception & Psychophysics, 65,* 1296–1306.

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology, 36,* 28–71.

Chun, M. M., & Jiang, Y. J. (1999). Top-down attentional guidance based on implicit learning of visual covariation. *Psychological Science, 10,* 360–365.

Chun, M. M., & Jiang, Y. (2003). Implicit, long-term spatial contextual memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29,* 224–234.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Science, 24,* 87–114.

Dale, H. C. A. (1973). Short-term memory for visual information. *British Journal of Psychology, 64,* 1–8.

Egeth, H. E., & Yantis, S. (1997). Visual attention: Control, representation, and time course. *Annual Review of Psychology, 48,* 269–297.

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review, 102,* 211–245.

Fahle, M., & Edelman, S. (1993). Long-term learning in Vernier acuity: Effects of stimulus orientation, range, and of feedback. *Vision Research, 33,* 397–412.

Gobet, F., & Simon, H. A. (1996a). Recall of rapidly presented random chess positions is a function of skill. *Psychonomic Bulletin & Review, 3,* 159–163.

Gobet, F., & Simon, H. A. (1996b). Templates in chess memory: A mechanism for recalling several boards. *Cognitive Psychology, 31,* 1–40.

Hollingworth, A. (2004). Constructing visual representations of natural scenes: The roles of short- and long-term memory. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 519–537.

Hollingworth, A., & Henderson, J. M. (2002). Accurate visual memory for previously attended objects in natural scenes. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 113–136.

Howowitz, T. S., & Wolfe, J. M. (1998). Visual search has no memory. *Nature, 394,* 575–577.

Howowitz, T. S., & Wolfe, J. M. (2001). Search for multiple targets: Remember the targets, forget the search. *Perception & Psychophysics, 63,* 272–285.

Irwin, D. (1992). Memory for position and identity across eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 307–317.

Jiang, Y., & Leung, A. (2005). Implicit learning of ignored visual contexts. *Psychonomic Bulletin & Review, 12,* 100–106.

Jiang, Y., Olson, I. R., & Chun, M. M. (2000). Organization of visual short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 683–702.

Keefe, R. S. E., Lees-Roitman, S. E., & Dupre, R. L. (1997). Performance of patients with schizophrenia on a pen and paper visuospatial working memory task with short delay. *Schizophrenia Research, 26,* 9–14.

Klein, R. M., & MacInnes, W. J. (1999). Inhibition of return is a foraging facilitator in visual search. *Psychological Science, 10,* 346–352.

Lee, D., & Chun, M. M. (2001). What are the units of visual short-term memory: Objects or spatial locations? *Perception & Psychophysics, 63,* 253–257.

Liu, J., Harris, A., & Kanwisher, N. (2002). Stages of processing in face perception: An MEG study. *Nature Neuroscience, 5,* 910–916.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 309,* 279–281.

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition, 22,* 657–672.

Maljkovic, V., & Nakayama, K. (1996). Priming of pop-out: II. The role of position. *Perception & Psychophysics, 58,* 977–991.

McCarley, J. S., Wang, R. F., Kramer, A. F., Irwin, D. E., & Peterson, M. S. (2003). How much memory does oculomotor search have? *Psychological Science, 14,* 422–426.

Neisser, U. (1967). *Cognitive psychology.* New York: Appleton-Century-Crofts.

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology, 19,* 1–32.

Olesen, P. J., Westerberg, H., & Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience, 7,* 75–79.

Olson, I. R., & Chun, M. M. (2001a). Perceptual constraints on implicit learning of spatial context. *Visual Cognition, 9,* 273–302.

Olson, I. R., & Chun, M. M. (2001b). Temporal contextual cuing of visual attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 1299–1313.

Olson, I. R., Chun, M. M., & Allison, T. (2001). Contextual guidance of attention: Human intracranial event-related potential evidence for feedback modulation in anatomically early temporally late stages of visual processing. *Brain, 124,* 1417–1425.

Olson, I. R., & Jiang, Y. (2002). Is visual short-term memory object based? *Perception & Psychophysics, 64,* 1055–1067.

Olson, I. R., & Jiang, Y. (2004). Visual short-term memory is not improved by training. *Memory & Cognition, 32,* 1326–1332.

Pashler, H. (1988). Familiarity and visual change detection. *Perception & Psychophysics, 44,* 369–378.

Peterson, M. S., Kramer, A. F., Wang, R. F., Irwin, D. E., & McCarley, J. S. (2001). Visual search has memory. *Psychological Science, 12,* 287–292.

Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. *Perception & Psychophysics, 16,* 283–290.

Poggio, T., Fahle, M., & Edelman, S. (1992, May 15). Fast perceptual learning in visual hyperacuity. *Science, 256,* 1018–1021.

Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision, 3,* 179–197.

Ramachandran, V. S., & Braddick, O. (1973). Orientation-specific learning in stereopsis. *Perception, 2,* 371–376.

Reber, A. S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General, 118,* 219–235.

Sanocki, T. (2003). Representation and perception of scenic layout. *Cognitive Psychology, 47,* 43–86.

Santa, J. L. (1977). Spatial transformations of words and pictures. *Journal of Experimental Psychology: Human Learning and Memory, 3,* 418–427.

Schmidt, B. K., Vogel, E. K., Woodman, G. F., & Luck, S. J. (2002). Voluntary and automatic attentional control of visual working memory. *Perception & Psychophysics, 64,* 754–763.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review, 84,* 1–66.

Schumacher, E. H., Seymour, T. L., Glass, J. M., Kieras, D. E., & Meyer, M. E. (2001). Virtually perfect time-sharing in dual-task performance: Uncorking the central attentional bottleneck. *Psychological Science, 12,* 101–108.

Segar, C. A. (1994). Implicit learning. *Psychological Bulletin, 115,* 163–196.

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychological Review, 84,* 127–190.

Shiu, L. P., & Pashler, H. (1992). Improvement in line orientation discrimination is retinally local but dependent on cognitive set. *Perception & Psychophysics, 52,* 582–588.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied, 74,* 1–29.

Thorpe, S., Fixe, D., & Marlot, C. (1996). Speed of processing in the human visual system. *Nature, 381,* 520–522.

Vaina, L. M., Sundareswaran, V., & Harris, J. G. (1995). Learning to ignore: Psychophysics and computational modeling of fast learning of direction in noisy motion stimuli. *Cognitive Brain Research, 2,* 155–163.

Van Selst, M., Ruthruff, E., & Johnston, J. C. (1999). Can practice eliminate the psychological refractory period effect? *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1265–1283.

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 92–114.

Wang, Q., Cavanagh, P., & Green, M. (1994). Familarity and pop-out in visual search. *Perception & Psychophysics, 56,* 495–500.

Watson, D. G., & Humphreys, G. W. (1997). Visual marking: Prioritizing selection for new objects by top-down attentional inhibition of old objects. *Psychological Review, 104,* 90–102.

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General, 131,* 48–64.

Wolfe, J. M., Klempen, N., & Dahlen, K. (2000). Post-attentive vision. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 693–716.

Wolfe, J. M., Oliva, A., Butcher, S. J., & Arsenio, H. C. (2002). An unbinding problem: The disintegration of visible, previously attended objects does not attract attention. *Journal of Vision, 2,* 256–271.

Woodman, G., Vecera, S. P., & Luck, S. J. (2003). Perceptual organization influences visual working memory. *Psychonomic Bulletin & Review, 10,* 80–87.

Xu, Y. (2002). Limitations of object-based feature encoding in visual short-term memory. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 458–468.

Xu, Y., & Nakayama, K. (2003). Placing objects at different depths increases visual short-term memory capacity [Abstract]. *Journal of Vision, 3,* 27a.

Yantis, S. (1992). Multielement visual tracking: Attention and perceptual organization. *Cognitive Psychology, 24,* 295–340.

Received July 26, 2004
Revision received October 29, 2004
Accepted February 22, 2005 ■