Research Article

Fractionating Working Memory

Consolidation and Maintenance Are Independent Processes

Geoffrey F. Woodman[1] **and Edward K. Vogel**[2]

[1]Vanderbilt University and [2]University of Oregon

ABSTRACT—*In the present study, we required subjects to remember simple objects that were masked to interrupt consolidation and allow us to estimate the rate of information accrual in visual working memory. We compared a consolidation-baseline condition with a consolidation-during-maintenance condition in which subjects needed to remember a set of unmasked items and then were shown to-be-remembered masked items. We hypothesized that if the control processes of consolidation and maintenance are performed by common mechanisms, then consolidation should be less efficient when performed during maintenance than when performed alone. However, we found that an identical amount of information was encoded per unit time in the two conditions. These results indicate that working memory consolidation is not slowed by maintenance and suggest a two-step model of encoding in visual working memory.*

The ability to efficiently encode, maintain, and manipulate information that briefly engages one's sensory systems affords remarkable flexibility during information processing. Consequently, the temporary storage and use of previously presented information has long been a topic of study (e.g., Baddeley, 1986; Blankenship, 1938; Smith & Jonides, 1997). Many recent reports have specifically examined storage in visual working memory (VWM), a modality-specific store within the multicomponent working memory system (Baddeley & Logie, 1999; Logie, 1995). Studies using change-detection tasks have demonstrated that a limited amount of information can be maintained in VWM (Luck & Vogel, 1997; Phillips, 1974; Simons, 1996; Vogel, Woodman, & Luck, 2001). A different aspect of VWM has been examined with paradigms that use rapid rates of stimulus presentation. These studies indicate that the encoding of information into working memory, also known as consolidation, is temporally and cognitively demanding (Chun & Potter, 1995; Jolicoeur & Dell' Acqua, 1998; Potter, 1976; Vogel, Luck, & Shapiro, 1998).

The relationship between the elemental control processes of working memory consolidation and maintenance is not well understood. It is possible that encoding and maintenance operations use the same limited-capacity mechanism; that is, a single mechanism may both encode information into VWM and maintain representations after they are encoded. In contrast, it is possible that separate mechanisms perform consolidation and maintenance operations. These competing hypotheses are difficult to evaluate with existing data for several reasons. First, few behavioral studies have examined the relationship between encoding and maintenance in VWM (Logie, 1995). Studies using dual-task interference paradigms simply indicate that VWM encoding is interfered with by the concurrent performance of complex spatial tasks, but not verbal interference tasks (Morris, 1987; Quinn, 1988). Second, few neurophysiological studies have drawn a distinction between working memory encoding and maintenance, but instead have generally classified neural activity as related to working memory if it is sustained during a retention interval. Moreover, a recent functional magnetic resonance imaging study that recognized this distinction found that similar neural substrates appeared to be involved in encoding and maintenance (Pessoa, Gutierrez, Bandettini, & Ungerleider, 2002). However, this finding could have been due to the operation of a common control mechanism or independent mechanisms that utilize separate networks of neurons that cannot be resolved with current neuroimaging techniques.

The final reason hypotheses about consolidation and maintenance are difficult to test is that the process that forms VWM representations and the process that maintains them operate in the same cognitive work space. That is, evidence suggests that VWM can hold three to four simple object representations (Irwin, 1996; Luck & Vogel, 1997; Vogel et al., 2001) and that both consolidation and maintenance must operate within this space. Thus, the nature of the relationship between consolidation and maintenance has been obscured by insufficient data and the

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Address correspondence to Geoffrey F. Woodman, Department of Psychology, Wilson Hall, 111 21st Ave. South, Vanderbilt University, Nashville, TN 37240-1103; e-mail: geoffrey.f.woodman@vanderbilt.edu.

necessary proximity of these processes to one another. Are the control processes of consolidation and maintenance independent, or does the same mechanism perform both operations? In the present study, we examined this question by comparing the rates of VWM consolidation in a baseline condition and in a condition requiring maintenance of previously stored representations.

Previous studies using masking paradigms (Gegenfurtner & Sperling, 1993; Phillips & Christie, 1977; Potter, 1976; Shibuya & Bundesen, 1988) and probe tasks (Jolicoeur & Dell' Acqua, 1998) have demonstrated that consolidation requires more time as the amount of to-be-remembered information increases. However, little is known about consolidation rate when the visual store is already partially full. It is possible that VWM consolidation is slowed when existing information is being maintained.

The experimental design utilized in this study is an extension of a masked change-detection paradigm we used recently to estimate the time required to consolidate simple colored objects into VWM (Vogel, Woodman, & Luck, in press). In this previous study, we estimated consolidation rate by manipulating the amount of time observers had to form robust memory representations of sample objects before colored masks were presented. Observers then had to determine whether a test array was identical to the sample or contained an object that had changed color. The slope of the function relating change-detection performance to the amount of time between the sample array and mask array, henceforth called the consolidation function, provided a measure of how much information was encoded into working memory per unit time. Although this previous study provided an estimate of the consolidation rate of colors into VWM, it also provided a general procedure for measuring the efficiency of consolidation under various conditions. In the present study, we used a similar masked change-detection paradigm to measure consolidation efficiency while manipulating whether or not VWM was partially filled before consolidation of the masked objects was undertaken.

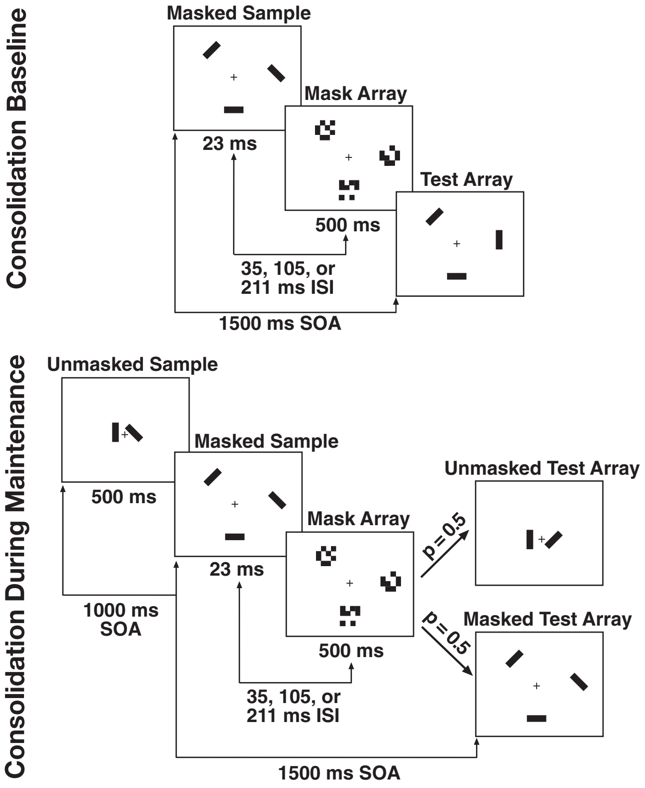

Fig. 1. Examples of the stimulus sequences in the consolidation-baseline condition (top panel) and consolidation-during-maintenance condition (bottom panel) in Experiment 1a. ISI = interstimulus interval; SOA = stimulus-onset asynchrony.

In each experiment, observers performed orientation (Experiments 1, 2, and 5) or shape (Experiments 3 and 4) change-detection tasks. We compared change-detection accuracy in two conditions. In the *consolidation-baseline* condition, observers were briefly shown several objects, which were followed after a variable time by pattern masks (see Fig. 1, top panel). After the retention interval, a memory-test array was presented. On half of the trials, this array was identical to the sample array, and on the rest, one item had changed. To estimate consolidation rate, we measured change-detection accuracy as a function of the interstimulus interval (ISI) between the offset of the sample array and onset of the masks. In the *consolidation-during-maintenance* condition, participants were first shown one or two unmasked items to remember (see Fig. 1, bottom panel). One second later, two or three additional items were briefly presented and followed by pattern masks. At the end of the trial, we tested observers' memory for either the unmasked objects or the masked objects; thus, they needed to try to remember both sets of items until test. As in the baseline condition, we were primarily interested in the consolidation rate of the masked information. In both conditions, recoding and storage in verbal working memory were prohibited by a concurrent articulatory suppression task.

If consolidation rate is independent of maintenance, then the slopes of the consolidation functions would be expected to be equivalent in the consolidation-baseline and consolidation-during-maintenance conditions. However, if maintenance and consolidation use common control mechanisms, then consolidation would be expected to be less efficient during maintenance than in the baseline condition.

GENERAL METHOD

Subjects

A different group of 14 Vanderbilt University undergraduates participated in each experiment in exchange for course credit after providing informed consent.

Stimuli and Procedure

Stimuli, which were viewed at a distance of approximately 57 cm, were presented on a gray background (40.6 cd/m^2) with a central black fixation point (0.04 cd/m^2, 0.2° × 0.2°). The to-be-remembered stimuli for Experiments 1, 2, and 5 were black (0.04 cd/m^2) rectangular bars that subtended 2.0° × 0.4° and varied in orientation (vertical, horizontal, or tilted −45° or +45° from vertical). In Experiments 3 and 4, the memory stimuli were black geometric shapes (i.e., a circle, square, triangle, diamond, rhombus, and symmetric cross) that were approximately 2.0° × 2.0°. The mask arrays were composed of randomly generated checkerboard masks in Experiments 1a and 2 through 5. One mask was centered on the location of each masked-sample stimulus. Each mask was generated by randomly choosing half of the cells (each 0.6° × 0.6°) of a 4 × 4 matrix to be black (0.04 cd/m^2) and the other half to be white (92.6 cd/m^2). In Experiment 1b, each mask was a composite of the four possible oriented bars.

In the consolidation-baseline condition, the masked-sample arrays were composed of two (Experiments 2 and 4) or three (Experiments 1, 3, and 5) to-be-remembered stimuli. Each was centered 7.2° from fixation at one of 12 possible locations (randomly selected, without replacement). The orientation or shape of each stimulus was randomly sampled from the set of four possible orientations (without replacement within sample array) or six possible geometric shapes (without replacement across arrays). The masked-test array was identical to the masked-sample array on half of the trials; on the other half of the trials, one of the items in the masked-test array changed to an orientation or shape not seen in the masked-sample array.

Each consolidation-baseline trial began 500 ms after the onset of the fixation point with a 23-ms presentation of the masked-sample array. Next, there was a variable-duration ISI followed by the 500-ms presentation of the mask array. The stimulus-onset asynchrony (SOA) between the onset of the sample array and the test array was fixed at 1,500 ms, regardless of the sample-to-mask ISI, by concurrently varying the time between the sample array and the mask array and between the mask and the test array. Finally, the test array was presented for 5,000 ms or until response. Observers pressed the "x" on the keyboard to indicate that they thought the test array was identical to the sample array or the "z" key to indicate that the test array was different from the sample array. Responses were unspeeded, and accuracy was emphasized.

In the consolidation-during-maintenance condition, the masked-sample, masked-test, and mask arrays were generated in the same way as in the consolidation-baseline condition. In addition, unmasked-sample and unmasked-test arrays were constructed for this condition. In Experiments 1, 3, and 5, the unmasked-sample array was created by randomly selecting two oriented bars or shapes and placing one to the right of fixation and the other to the left (both centered 4.2° from fixation); in Experiments 2 and 4, a single randomly selected item was presented either to the left or right of fixation. Finally, on each trial in this condition, either the unmasked-test array or the masked-test array was presented. The two kinds of test arrays were equally probable and randomly interleaved. On half the trials with unmasked-test arrays, the test array was identical to the unmasked-sample array, and on the other half, the test array differed in that an item not shown in the unmasked-sample array replaced one of the stimuli (in the case of Experiments 2 and 4, this was the only stimulus).

Each trial in the consolidation-during-maintenance condition began 500 ms after the onset of the fixation point with a 500-ms presentation of the unmasked-sample array. Following a 500-ms blank interval, the masked-sample array was presented for 23 ms. The mask array was presented for 500 ms at a variable ISI after the offset of the masked-sample array. The mask array was followed by another blank interval, which had a variable duration such that the SOA between the masked-sample array and test array was always 1,500 ms. The test array was presented for 5,000 ms or until the keyboard response.

Subjects alternated between blocks of trials in the consolidation-baseline and the consolidation-during-maintenance conditions, with beginning condition counterbalanced across subjects. Each of the six blocks in each condition contained 24 trials. Each block began with the presentation of articulatory suppression stimuli that the subjects repeated aloud during each trial of that block. These stimuli were strings of four white characters (92.6 cd/m^2), each approximately 1° × 1.4°, shown for 1,500 ms, beginning 3,000 ms before the first trial. Subjects saw either "ABCD," "WXYZ," "1234," or "6789" and repeated these at a rate of three to four characters per second. Which set each subject began with was randomized, and across blocks, subjects cycled through each of the four sets three times.

We conducted a pilot experiment to determine which ISIs would likely yield data from the increasing portion of the consolidation function. A separate group of 10 participants performed only the consolidation-baseline condition of Experiment 1a while we sampled from a large set of sample-to-mask ISIs (12, 35, 59, 105, 152, 211, and 246 ms). On the basis of these findings, we selected ISIs of 35, 105, and 211 ms for Experiments 1 through 4 and 105, 176, 246, and 316 ms for Experiment 5.

Data Analysis

Change-detection performance was converted from hit rate and false alarm rate to *K*, an estimate of the number of object representations retained in memory. Specifically, we used Cowan's (2001) modification of Pashler's (1988) equation: $K = \{[SS * (HR - FAR)]/(1 - FAR)\} * 1 - FAR$, where SS is the set size, and HR and FAR are the hit and false alarm rates, respectively. Although *K* was originally conceived as a measure of the number of complete, all-or-none representations stored in memory, as in previous studies we used it as a metric of the number of object's worth of information stored (Vogel et al., 2001; Woodman, Vogel, & Luck, 2001). In addition, in a previous study, we found that *K* was linearly related to the amount of information consolidated per unit time (Vogel et al., in press).

The *K* values were entered into analyses of variance (ANOVAs) with factors of consolidation condition (baseline, during maintenance) and ISI (35, 105, and 211 ms for Experiments 1–4, and 105, 176, 246, and 316 ms for Experiment 5).

RESULTS AND DISCUSSION

In Experiment 1a, we found that the rate of consolidation was essentially identical whether or not other information was being maintained. This can be seen in Figure 2, which also shows performance from trials in which the unmasked information was tested. Although the slopes of the consolidation functions did not differ, we did find a difference in the *y*-intercept because subjects were more accurate in the consolidation-baseline condition by a constant amount across ISIs. This finding indicates that less information was consolidated during maintenance regardless of the sample-to-mask ISI. These observations were supported by the significant effects of condition, $F(1, 26) = 41.90$, $p < .0001$, $\eta^2 = .14$, and ISI, $F(2, 26) = 57.32$, $p < .0001$, $\eta^2 = .39$; the interaction did not approach significance, $F < 1$.

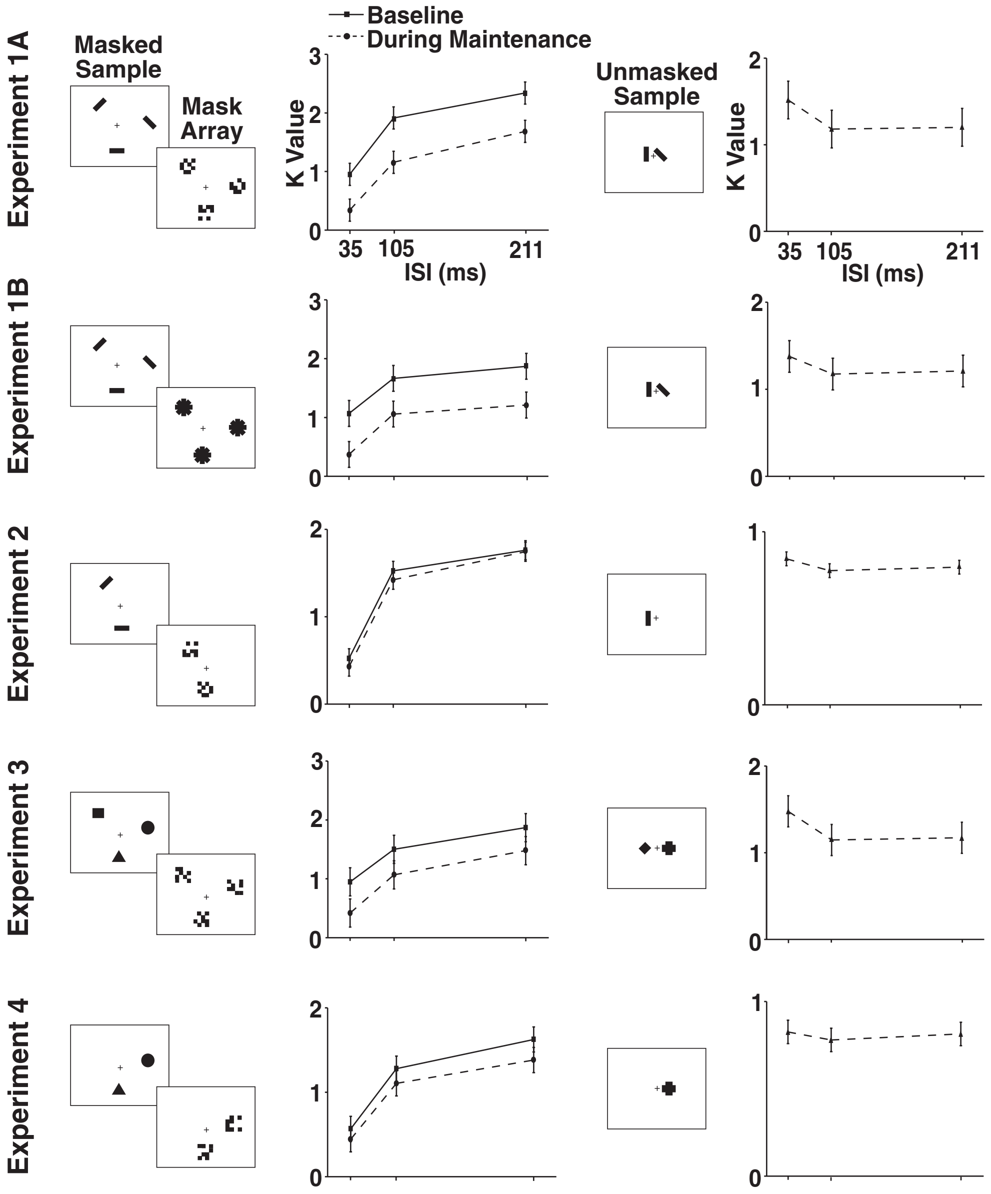

Fig. 2. Example stimuli and results from Experiments 1 through 4. Each experiment is represented in a separate row, showing (from left to right) examples of masked-sample and mask arrays, the consolidation functions obtained in the consolidation-baseline and consolidation-during-maintenance conditions, an example of an unmasked-sample array, and the results from the trials in which subjects' memory for unmasked samples was tested. In the graphs, change-detection accuracy is shown in terms of the number of objects remembered (*K*) as a function of the interstimulus interval (ISI) between the offset of the masked-sample array and the onset of the mask array. Error bars are 95% within-subjects confidence intervals (see Loftus & Masson, 1994).

These findings suggest that the accrual of information in VWM is not slowed by concurrent maintenance, but that maintenance does limit the amount of information that can be encoded simply because of limited VWM capacity.

To determine whether the findings of Experiment 1a were due to the specific type of masks used, we recruited a new group of subjects to participate in Experiment 1b, which was nearly identical to Experiment 1a except that the masks were composites of the four possible to-be-remembered rectangular bars. As shown in Figure 2, the same pattern of effects was obtained as in Experiment 1a. Specifically, we found significant main effects of condition, $F(1, 26) = 34.48$, $p < .0001$, $\eta^2 = .12$, and ISI, $F(2, 26) = 22.10$, $p < .0001$, $\eta^2 = .18$, although the interaction was not significant, $F < 1$. Thus, these results are not specific to checkerboard masks, and the findings again demonstrate the similarity of the rate of consolidation in the baseline and maintenance conditions.

The *y*-intercept effects observed in Experiment 1 support our assumption that information from the unmasked-sample array and information from the masked-sample array were consolidated into the same limited-capacity store. Moreover, these findings suggest that encoding into VWM may involve a two-step process of partitioning remaining VWM capacity and then consolidating new information. According to this account, in the first step, representational space in VWM is partitioned. This step would involve determining the space available for new incoming objects so that VWM capacity is not exceeded and parceling that space to accommodate some or all of the new object representations. In the consolidation-during-maintenance condition, the remaining space in VWM was sufficient for only a subset of the masked objects to have space dedicated to their representation; in contrast, in the baseline condition, VWM could be partitioned to accommodate all three new items. This account posits that after VWM is partitioned, the new object representations are consolidated, or formed, at a rate that is not slowed by concurrent maintenance (i.e., as evidenced by the similar slopes of the consolidation functions). Thus, when the information in the unmasked- and masked-sample arrays exceeded VWM capacity, less information from the masked-sample array was encoded during maintenance regardless of the sample-to-mask ISI. This is because information from the unmasked-sample array occupied a significant proportion of VWM capacity when the remaining representational space was partitioned. We conducted Experiment 2 to test this account of the *y*-intercept effects from Experiment 1.

Experiment 2 was identical to Experiment 1a with the exception that observers were shown two masked items in both conditions and required to maintain a single unmasked item in the consolidation-during-maintenance condition. Thus, in Experiment 2, subjects needed to remember a subcapacity amount of information (i.e., fewer than three simple objects) in both conditions. We expected that the consolidation functions would be similar in the two conditions, just as in Experiment 1, but that the *y*-intercept effect observed previously would be eliminated because the number of objects subjects needed to store was within the capacity of VWM. As shown in the third row of Figure 2, these predictions were confirmed by essentially identical consolidation functions; only ISI had a significant effect, $F(2, 26) = 133.61$, $p < .0001$, $\eta^2 = .69$. These results further support the hypothesis that the rate of VWM consolidation is unaffected by maintenance and demonstrate how the process of maintenance influences encoding only when the limited capacity of VWM would be exceeded (as in Experiment 1).

In Experiments 3 and 4, we required observers to encode and maintain simple geometric shapes. We sought to generalize the effects observed with oriented rectangles to a different stimulus set. Experiments 3 and 4 were identical to Experiments 1a and 2, respectively, except that the to-be-remembered stimuli were geometric shapes (e.g., a circle, square, triangle). As illustrated in the lower rows of Figure 2, we found strikingly similar consolidation rates in the baseline condition and during-maintenance condition in Experiments 3 and 4. Accordingly, neither condition-by-ISI interaction approached significance, *F*s < 1. When the total number of shapes to be remembered surpassed existing capacity estimates of VWM (in Experiment 3), condition had a significant effect on the *y*-intercept, $F(1, 26) = 10.60$, $p < .01$, $\eta^2 = .08$ (vs. $F < 1$ in Experiment 4). Although the effect of condition was not significant in Experiment 4, it was slightly larger than in Experiment 2, a finding consistent with previous observations that objects with more complex shapes occupy more working memory capacity than simple colored squares or rectangles (Woodman et al., 2001).

Finally, we wondered if the consolidation of the masked information might simply be delayed during maintenance. According to this explanation of the previous findings, change-detection performance would asymptote at the same level in the during-maintenance condition as in the baseline condition if enough time were given before the masks were presented. We tested this hypothesis in Experiment 5, which was identical to Experiment 1a except that we sampled from a larger set of sample-to-mask ISIs. Of interest was performance in the two conditions at the longest ISIs, when the consolidation functions had reached asymptote (see Fig. 3). We found that the difference between conditions was essentially constant across ISI even after both functions had reached asymptote. This observation was supported by the significant effects of condition, $F(1, 27) = 5.96$, $p < .05$, $\eta^2 = .06$, and ISI, $F(3, 27) = 8.34$, $p < .001$, $\eta^2 = .16$, and the absence of a significant interaction, $F < 1$. These results rule out the delayed-consolidation explanation of the findings of Experiments 1 through 4 and support the position that maintenance of information from the unmasked-sample array prevented storage of all of the masked-sample information in VWM regardless of the time given for consolidation (see the unmasked-sample graph in Fig. 3).

As an additional way to quantify the results of these experiments, we calculated the slope of the consolidation functions

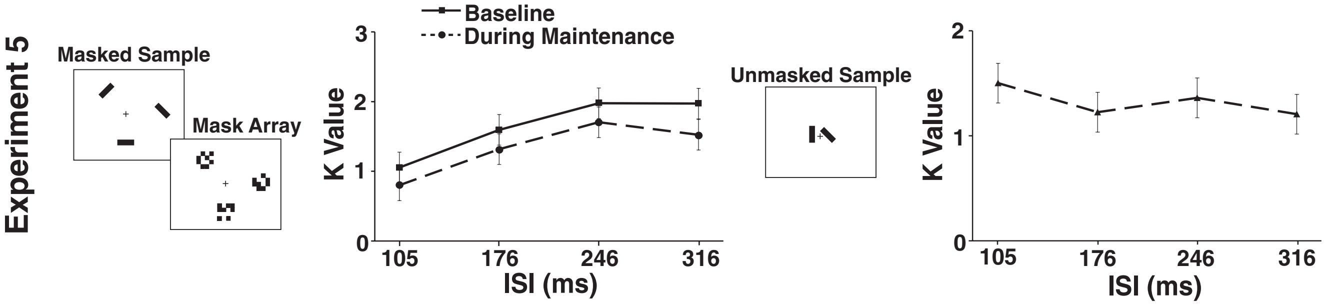

Fig. 3. Example stimuli and results from Experiment 5. See Figure 2 for an explanation of the illustrations and graphs.

(i.e., milliseconds needed to consolidate an object).[1] In Experiment 1a, the mean slope of the consolidation function was 85.5 ms/object in the baseline condition and 72.6 ms/object in the consolidation-during-maintenance condition, $F < 1.0$. Indeed, none of the differences between the slopes of the consolidation functions were significantly different (in the consolidation-baseline and consolidation-during-maintenance conditions, respectively, slopes were as follows: Experiment 1b, 117.7 ms/item vs. 102.3 ms/item; Experiment 2, 69.7 ms/item vs. 70.3 ms/item; Experiment 3, 126.5 ms/item vs. 107.9 ms/item; Experiment 4, 98.3 ms/item vs. 105.9 ms/item; Experiment 5, 129.8 ms/item vs. 135.1 ms/item; all Fs < 1.0).[2] Thus, this alternative measure also suggests that VWM consolidation is unaffected by concurrent maintenance of information in the visual store.

CONCLUSIONS

The findings of the present study indicate that the efficiency of VWM consolidation is not influenced by concurrent maintenance. Specifically, we consistently found that the slopes of functions relating change-detection performance to sample-to-mask ISI were essentially identical in the baseline and during-maintenance conditions.[3] However, we found that less information from the masked array could be stored regardless of ISI when capacity was exceeded. This finding suggests that the limited work space of VWM is first allocated to new object representations that are then consolidated, and made resistant to masking by subsequent stimuli, at a constant rate. Thus, consolidation and maintenance appear to be essentially independent processes, although they operate in the same limited-capacity store.

The findings of this study are relevant for a number of paradigms used in behavioral and neurophysiological studies of attentional selection and working memory functions. In addition to change-detection and attentional-blink paradigms (e.g., Chun & Potter, 1995; Simons & Levin, 1997), *N*-back tasks (e.g., Cohen et al., 1997), memory-span tasks (e.g., Schweickert, Guentert, & Hersberger, 1990), and clinical assessments such as continuous performance tests (Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956) are among a large class of paradigms in which information must be encoded into working memory while previously presented information is maintained. Furthermore, several theories of attention propose that visual search requires the maintenance of a target template while candidate target objects are encoded into VWM to be compared with that template (Bundesen, 1990; Duncan & Humphreys, 1989). The present findings indicate that efficient consolidation of new information can be expected even when paradigms require the temporary retention of existing information. Moreover, our findings suggest a two-step model of encoding into VWM such that consolidation is not a continuous process but instead has stagelike components.

At least two competing explanations are consistent with the existing literature and the findings reported here. First, the control processes of consolidation and maintenance may be performed by different mechanisms. This would be consistent with the view that the control processes that operate on the representations in VWM are best conceptualized as a loose collection of independent processes rather than a unitary mechanism or resource (Baddeley, 1986). For example, it may be advantageous for the working memory system to efficiently encode new information even when modality-specific stores are partially filled (e.g., if a looming truck appears in your rearview mirror when you are surrounded by several other vehicles in traffic).

The second alternative account of our results is that maintenance of information in VWM does not require top-down

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[1] We calculated the slope of the line connecting the first two ISIs we sampled because this is where the function is steeply increasing, and Experiment 5 suggests the final ISI sampled in Experiments 1 through 4 approached asymptotic levels of change-detection performance.

[2] We recognize that there are differences in the mean slopes between experiments. We believe these to be due to individual differences in consolidation rates between the subjects sampled across experiments. The existence of between-subjects variability does not affect our conclusion that maintenance did not slow consolidation relative to the within-subjects baseline.

[3] Previous studies have demonstrated that substantial semantic and affective evaluation of unreportable masked stimuli can occur (e.g., Marcel, 1983; Öhman & Soares, 1993; Vogel et al., 1998). However, we do not believe that implicit semantic or affective processing aided explicit change-detection performance in this study because the stimuli were simple oriented bars and shapes, which are typically not associated with specific emotional states or meanings. Moreover, to the degree that such processing occurred, it should have had similar effects in the two experimental conditions.

input. Accordingly, the process of consolidation demands top-down control while existing information in VWM is maintained through a self-sustaining process (e.g., via recurrent self-excitation of cell assemblies representing the to-be-remembered objects). This idea is similar to Hebb's (1949) proposal that temporary memory is due to the reverberation of cell assemblies representing memory items and underlies a subset of recent neurocomputational models of working memory (Durstewitz, Seamans, & Sejnowski, 2000). Models proposing that maintenance does not require top-down control are supported by experiments with humans and monkeys that found no influence of maintenance of information in VWM on secondary-task performance (Washburn & Astur, 1998). Regardless of the nature of the underlying processes, the findings of this study demonstrate that consolidation and maintenance operate independently in VWM and serve to further constrain models of working memory and executive functions.

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REFERENCES

Baddeley, A.D. (1986). *Working memory.* Oxford, England: Clarendon.

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

Blankenship, A.B. (1938). Memory span: A review of the literature. *Psychological Bulletin*, *35*, 1–25.

Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, *97*, 523–547.

Chun, M.M., & Potter, M.C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 109–127.

Cohen, J.D., Perlstein, W.M., Braver, T.S., Nystrom, L.E., Noll, D.C., Jonides, J., & Smith, E.E. (1997). Temporal dynamics of brain activation during a working memory task. *Nature*, *386*, 604–608.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*, 87–185.

Duncan, J., & Humphreys, G.W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*, 433–458.

Durstewitz, D., Seamans, J.K., & Sejnowski, T.J. (2000). Neurocomputational models of working memory. *Nature Neuroscience*, *3*(Suppl.), 1184–1191.

Gegenfurtner, K.R., & Sperling, G. (1993). Information transfer in iconic memory experiments. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 845–866.

Hebb, D.O. (1949). *Organization of behavior: A neuropsychological theory.* New York: Wiley.

Irwin, D.E. (1996). Integrating information across saccadic eye movements. *Current Directions in Psychological Science*, *5*, 94–100.

Jolicoeur, P., & Dell' Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology*, *36*, 138–202.

Loftus, G.R., & Masson, M.E.J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review*, *1*, 476–490.

Logie, R.H. (1995). *Visuo-spatial working memory.* Hove, England: Erlbaum.

Luck, S.J., & Vogel, E.K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281.

Marcel, A.J. (1983). Conscious and unconscious perception: Experiments on visual masking and word recognition. *Cognitive Psychology*, *15*, 197–237.

Morris, N. (1987). Exploring the visuo-spatial scratch pad. *Quarterly Journal of Experimental Psychology*, *39A*, 409–430.

Öhman, A., & Soares, J.J.F. (1993). On the automatic nature of fear: Conditioned electrodermal responses to masked fear-relevant stimuli. *Journal of Abnormal Psychology*, *102*, 121–132.

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

Pessoa, L., Gutierrez, E., Bandettini, P.A., & Ungerleider, L.G. (2002). Neural correlates of visual working memory: fMRI amplitude predicts task performance. *Neuron*, *35*, 975–987.

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

Phillips, W.A., & Christie, D.F. (1977). Interference with visualization. *Quarterly Journal of Experimental Psychology*, *29*, 637–650.

Potter, M.C. (1976). Short-term conceptual memory for pictures. *Journal of Experimental Psychology: Human Learning and Memory*, *2*, 509–522.

Quinn, J.G. (1988). Interference effects in the visuo-spatial sketchpad. In M. Denis, J. Engelkamp, & J.T.E. Richardson (Eds.), *Cognitive and neuropsychological approaches to mental imagery* (pp. 181–189). Dordrecht, The Netherlands: Martinus Nijhoff.

Rosvold, H.D., Mirsky, A.F., Sarason, I., Bransome, E.D., & Beck, L.H. (1956). A continuous performance test of brain damage. *Journal of Consulting Psychology*, *20*, 343–350.

Schweickert, R., Guentert, L., & Hersberger, L. (1990). Phonological similarity, pronunciation rate, and memory span. *Psychological Science*, *1*, 74–77.

Shibuya, H., & Bundesen, C. (1988). Visual selection from multielement displays: Measuring and modeling effects of exposure duration. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 591–600.

Simons, D.J. (1996). In sight, out of mind: When object representations fail. *Psychological Science*, *7*, 301–305.

Simons, D.J., & Levin, D.T. (1997). Change blindness. *Trends in Cognitive Sciences*, *1*, 261–267.

Smith, E.E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology*, *33*, 5–42.

Vogel, E.K., Luck, S.J., & Shapiro, K.L. (1998). Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1656–1674.

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.

Vogel, E.K., Woodman, G.F., & Luck, S.J. (in press). The time course of consolidation in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*.

Washburn, D.A., & Astur, R.S. (1998). Nonverbal working memory of humans and monkeys: Rehearsal in the sketchpad? *Memory & Cognition*, *26*, 277–286.

Woodman, G.F., Vogel, E.K., & Luck, S.J. (2001). Visual search remains efficient when visual working memory is full. *Psychological Science*, *12*, 219–224.

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