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The relationship between masking and short-term consolidation during recall from visual working memory

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The presentation of a similar but irrelevant stimulus immediately following presentation of a memory item is called *masking*. Masking is known to reduce performance on working memory tests. This is the type of memory used to hold information in mind for brief periods of time for use in ongoing cognition. Two approaches to understanding masking effects have been proposed in different literatures. Working memory researchers often assume that the reduction in working memory performance after masking is because masking interferes with a transient sensory representation that is needed to complete consolidation into a working memory state. Researchers focused on the attentional blink, a finding that attention cannot be directed to new stimuli during working memory consolidation, have an alternative theory. Attentional blink researchers assume that masking slows the short-term consolidation process, thereby extending the length of the attentional blink. In two experiments, we contrast these two approaches to explaining masking effects and investigate the validity of both hypotheses. Some aspects of both approaches are validated, but neither theoretical perspective alone sufficiently explains the entire pattern of results.

Keywords: working memory; short-term memory; visual memory; consolidation; masking; interference

Introduction

Short-term consolidation is the process of creating a robust working memory trace. Consolidated working memory traces can be maintained for brief periods of time for immediate access and use in ongoing cognition. Working memory has a central role in a variety of higher order tasks, such as reading,[1] arithmetic,[2] and reasoning,[3] making understanding of the short-term consolidation process important for understanding human cognition.

Short-term consolidation is a quick process, taking no more than a second or two at most.[4–7] Initiation of short-term consolidation appears to occupy or suppress attention, preventing the execution of other cognitive processes that require attention during its completion.[6,8–10] This brief period when attention is unavailable is often referred to as the attentional blink,[4,7,11,12] and has been extensively studied using the Rapid Serial Visual Presentation (RSVP) paradigm. In this paradigm, a stream of stimuli is presented in rapid succession, often in the range of 10 stimuli per second, and the observer must identify some stimulus or stimuli matching certain characteristics for report at the end of the trial. When the second stimulus occurs in close temporal proximity to the first stimuli, generally within 200–700 ms, the second stimulus shows a sharp deficit in identification performance. This deficit in performance is hypothesized to occur because the first stimulus is being consolidated into working memory, preventing attention from being redirected toward the processing of the second stimulus.[7,11]

Short-term consolidation is also thought to play a role in working memory tasks.[5,8,9,13] Working memory tasks differ from the typical RSVP task in that larger numbers of items may need to be maintained, the memory items are generally presented at a much slower pace, and distracting stimuli are generally fewer and presented at a slower pace. Researchers working within the working memory tradition often

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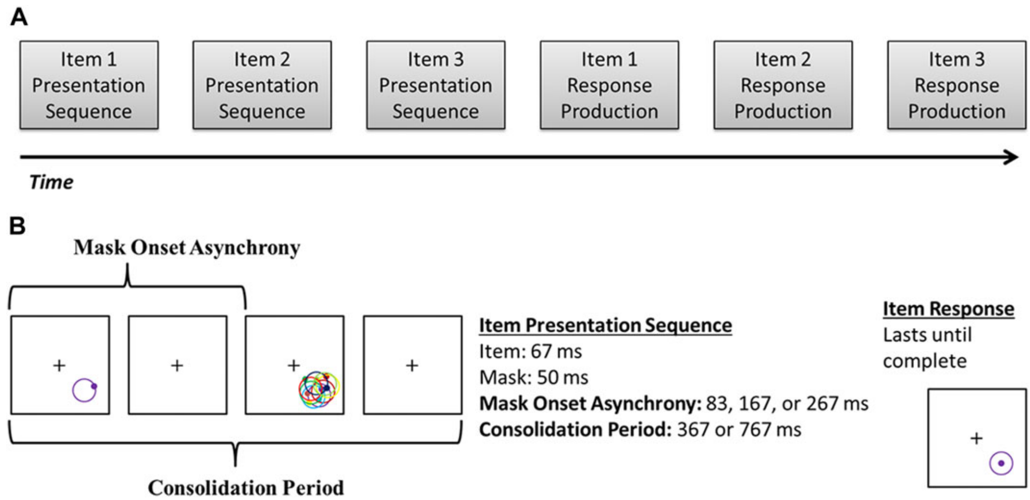

Figure 1. An example of a single experimental trial. Panel A details the sequence of events for the entire trial. Panel B shows a single presentation sequence and a single response production for the same memory item.

assert that masking effects can be used to index the time course of consolidation.[14–17] Masking is the presentation of an irrelevant stimulus immediately following the target stimulus to disrupt any residual sensory trace left by the original target.[18,19] It is commonly assumed that only information about the target stimulus held within central working memory resources should remain after masking.[17,20,21]

An example of masking to end consolidation comes from Vogel *et al.*[15] These researchers briefly presented a visual array of colored squares to-be-remembered and then varied the time until a masking stimulus was presented. The deficit in performance caused by the mask was tied to its temporal proximity to the memory item. Longer delays before presentation of the mask resulted in better performance. When more items were presented in the memory array, the mask also affected performance for a longer period after array presentation. Vogel *et al.* argued that consolidation of each item took some time and must be complete if presenting a masking stimulus no longer disrupted memory performance. This interpretation suggests that masks disrupt memory performance by either interfering with the memory trace representation or by ending the consolidation process. Several studies have demonstrated that consolidation continues after masking, ruling out the second possibility.[5,8,9,13]

In contrast to the idea that masking directly interferes with the memory trace, theories from the RSVP literature on short-term consolidation account for masking effects by assuming that masks slow the rate of consolidation.[4,7] This approach can explain the time-dependent masking effects observed in the working memory literature by arguing that masks presented with a shorter onset delay result in a greater slowing of short-term consolidation. Slower consolidation can result in either a longer attentional blink or a lower probability of successful consolidation into working memory. In either case, fewer memory items would be successfully stored in working memory with quicker mask-onset times, in line with past findings in the working memory field.[14–17]

Here, we sequentially present visual memory items and require recall immediately after the entire list is presented (Fig. 1). After each individual item is presented, we vary both the delay before a masking stimulus is presented and the total amount of time available for consolidation before presenting the next item to evaluate the following competing hypotheses. If masking effects arise from slowed consolidation, then we should observe an interaction between mask-onset time and consolidation time, with faster masking resulting in a longer consolidation time course.[a] If masking

[a]We do not mean to imply that masking is the only factor influencing the time to complete consolidation. Factors such as viewing conditions, temporal or spatial uncertainty in target onset, as well as many others should influence the time course of consolidation as well.

effects arise from interference with the memory representation but do not affect the rate of consolidation, then we should *not* observe an interaction between mask-onset time and consolidation time, instead the consolidation time course should be the same length in all masking conditions.

Experiment 1

In this experiment, we test the relationship between masking and short-term consolidation by varying the mask-onset (83, 167, or 267 ms) and the consolidation time (367 or 767 ms) on each trial. Conditions are labeled in reference to the time of memory item onset. Within each trial, all of the mask-onset and consolidation times are the same for all items presented.

Materials and method

A schematic of a single trial is presented in Figure 1. Once initiating a trial with a button-press, participants ($n = 54$) were presented with a fixation cross for 500 milliseconds. After the fixation cross, three memory items were presented, each one at a time, with a brief period between item presentations during which participants could consolidate the previous memory item. Memory items were each presented at one of eight locations equidistant from fixation and evenly spaced from one another. Each memory item was a different colored ring with a matching colored dot located somewhere along the edge of the ring (see Fig. 1B for an example). Participants were asked to remember the location of the dot on each ring. During the recall phase of the trial, following item presentation, each of the colored rings was again presented one at a time in its original sequential order. No colors were repeated within a single trial. This time the dot was located at the center of each ring and participants were instructed to position the dots into their original locations by using the mouse and clicking the left mouse button to enter their response. Once all item responses were recorded, participants received feedback showing their responses as well as the correct dot locations. This was repeated for a total of 210 trials.

Memory items were presented for 67 ms each. A blank screen followed each memory item and lasted for either 300 or 700 ms in duration. During the blank screen period following each memory item, a mask was presented 17, 100, or 200 ms after memory item offset. The masking stimulus was composed of eight randomly positioned circles and dots presented in the same location as the memory item, each with a small displacement in location (see Fig. 1B for an example). The masking stimulus was presented for 50 milliseconds. The consolidation and masking conditions on each trial were randomly determined and were the same for all items within a trial.

Data analysis

To determine how well participants remembered each memory item, we computed the absolute value of the response error, in circular degrees, for each response. We then computed the mean response error for each condition and serial position. In our statistical analysis, we use Bayes factors for ANOVA effects[22] as our measure of inference. Bayes factors in this context give the probability of the presence of an effect (i.e., the alternative hypothesis) relative to the probability of the absence of an effect (i.e., the null hypothesis). A Bayes factor of 12 in favor of an effect means that the alternative is 12 times more likely than the null, given the data. We compute all Bayes factors with the BayesFactor package v0.9.12-2[23] for the R statistical computing language.[24] We set the standard deviation of the alternative to $\sqrt{2}/2$ and use the default settings for all other parameters.

Results

Mean response error for each condition and serial position is presented in Figure 2. The key theoretical question is whether an interaction is present between the masking and consolidation conditions. Visual inspection of the means suggests that there is a main effect of mask-onset with the shortest mask onset leading to particularly impaired performance relative to the other conditions. An effect of consolidation time is also clear, with shorter consolidation time resulting in lower levels of performance, but this effect does not appear to change under different mask-onset conditions.

Note that serial position 1 does not show a consolidation effect in these data. This was expected a priori following the same finding by Ricker and Hardman,[5] who replicated this invariance to consolidation manipulations at serial position 1 across multiple experiments. As the data from serial position 1 do not inform our theoretical question, we exclude it from our statistical analysis.

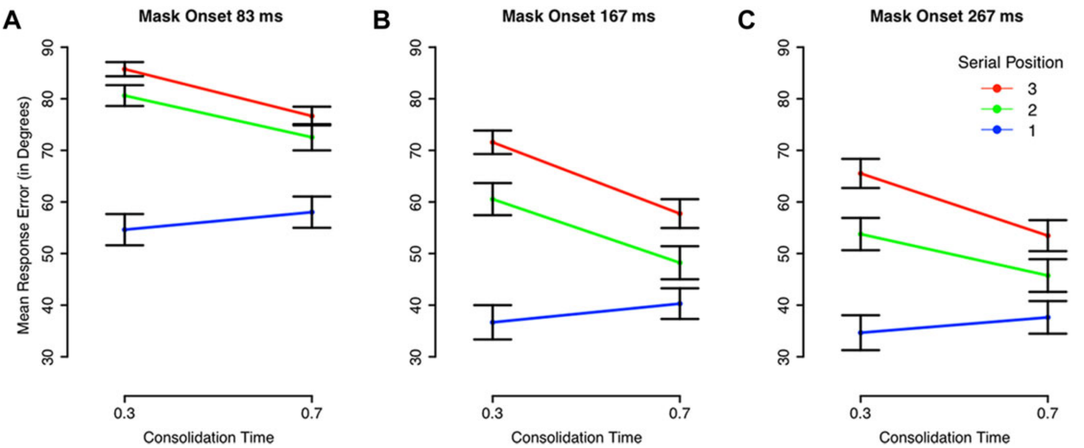

Figure 2. Mean response error for each condition and serial position in experiment 1. For ease of display, the consolidation time listed on the *x*-axis does not include the 67 ms of presentation time during which the memory item was on screen. For example, 0.3 corresponds to the 367 ms consolidation time condition. Panel A shows the 83 ms mask-onset condition, panel B shows the 167 ms mask-onset condition, and panel C shows the 267 ms mask-onset condition. Error bars represent standard error of the mean.

To statistically confirm the presence of these main effects and the absence of an interaction between mask-onset and consolidation time, a 3 (mask-onset: 83, 167, or 267 ms) × 2 (consolidation time: 367 or 767 ms) × 2 (serial position: 2 or 3) repeated measures BANOVA of mean response error was performed and Bayes factors were calculated. There was a main effect of mask-onset, $F(2,106) = 136.50$, $\eta_p^2 = 0.72$, Bayes factor $= 1.00 \times 10^{80}$ in favor of an effect (means: 83 ms = 78.89, 167 ms = 59.52, 267 ms = 54.63), a main effect of consolidation time, $F(1,53) = 92.75$, $\eta_p^2 = 0.64$, Bayes factor $= 1.69 \times 10^{25}$ in favor of an effect (means: 367 ms = 69.63, 767 ms = 59.06), and a main effect of serial position, $F(1,53) = 80.49$, $\eta_p^2 = 0.60$, Bayes factor $= 2.33 \times 10^{15}$ in favor of an effect (means: serial position 2 = 60.24, serial position 3 = 68.45). There was evidence against the presence of any interactions, all Bayes factors < 1.0 (in the form of alternative/null). In particular, there was evidence against the key interaction of mask-onset and consolidation time, $F(2,106) = 2.78$, $\eta_p^2 = 0.05$, Bayes factor = 7.97 in favor of the null.

Discussion

In this experiment, we varied mask-onset time and consolidation time for each memory item. We observed greater errors with shorter mask-onset times and shorter consolidation periods. This replicates past results measuring the effect of mask-onset time[15–17,25] and the effect of consolidation time[5,9,13,26] on performance. We did not observe a change in the rate of consolidation when the mask was presented with a shorter onset time. This is in agreement with the interference explanation of masking effects, which predicts that masking does not change the length of consolidation and in opposition to a slowed consolidation approach that argues that masking effects arise from a longer consolidation process.

Although slowed consolidation did not account for the differential effects of masks presented at differing onset times, masking may still slow the rate of consolidation. Specifically, it may be that the mere presence of a mask slows consolidation compared with when no mask is presented. In the episodic simultaneous type/serial token (eSTST) mathematical model of the attentional blink,[7] there is a brief delay immediately after target item presentation during which consolidation begins but before the attentional blink occurs. According to the model, if a mask is presented during this delay, it will disrupt the sensory representation, but not the working memory representation being consolidated, resulting in slower consolidation. As long as the mask is presented during this delay, it will have the same slowing effect no matter how long the delay was between target-item onset and mask-onset. In the present context, the model predicts that masking will slow the consolidation process relative to no mask being present, but that the exact onset time of

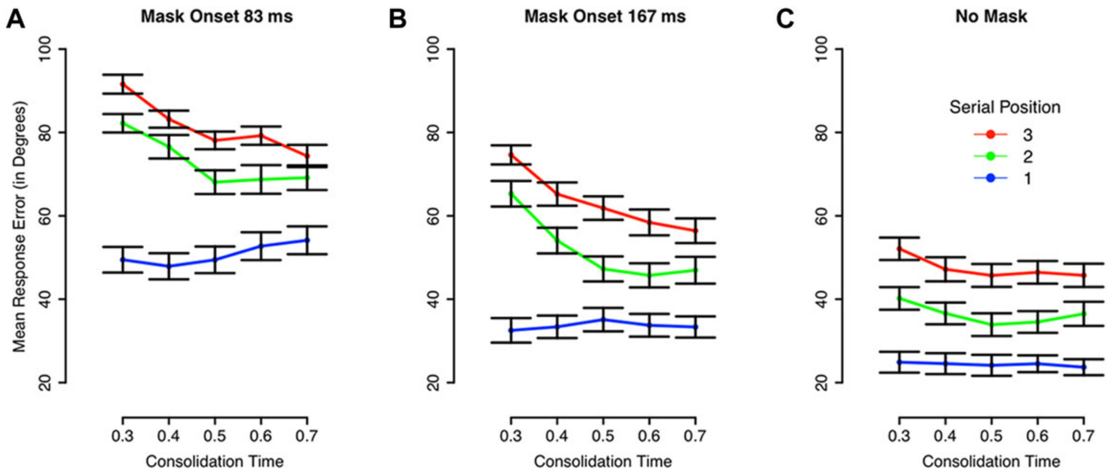

Figure 3. Mean response error for each condition and serial position in experiment 2. For ease of display, the consolidation time listed on the *x*-axis does not include the 67 ms of presentation time during which the memory item was on screen. For example, 0.3 corresponds to the 367 ms consolidation time condition. Panel A shows the 83 ms onset mask condition, panel B shows the 167 ms onset mask condition, and panel C shows the no mask condition. Error bars represent standard error of the mean.

the mask should not matter as long as it is within the critical post-target window.

Although this approach does not explain why mask-onset time is important for understanding the size of the masking effect, it does suggest that masks may affect memory performance in two different ways. First, experiment 1 supports a view that masks cause interference that disrupts the memory representation.[21,25,27] Second, the mere existence of a mask may slow the consolidation process relative to no mask being present.[4,7] This second hypothesis is explored in the next experiment.

Experiment 2

In this experiment, we test the relationship between masking and short-term consolidation by varying the mask condition (83, 167 ms, or no mask) and the consolidation time (367, 467, 567, 676, or 767 ms). Conditions are labeled in reference to the time of memory item onset. Within each trial, all mask-onset and consolidation times are the same for all items presented.

Materials and methods

All materials and methods were the same as in experiment 1, except for the following differences. In experiment 2, the mask was only presented on two-thirds of the trials. When the mask was present, it appeared 17 or 100 ms after memory item offset. The blank screen between item presentations lasted 300, 400, 500, 600, or 700 milliseconds. There were a similar number of participants in experiment 2 ($n = 53$) as compared with the previous experiment.

Results

Mean response error for each condition and serial position is presented in Figure 3. The key theoretical question is whether an interaction is present between the masking and consolidation conditions. Specifically, we should see that both masking conditions show similar rates of consolidation, while the no mask condition shows faster consolidation. This faster consolidation would be evident in that the no mask condition should reach near asymptotic levels of performance across consolidation conditions faster than in the masking conditions.

Visual inspection of mean performance across conditions again suggests that there is a main effect of mask condition, with the worst performance observed during the short mask-onset delay and the best performance during the no mask condition. An effect of consolidation time is also evident, with shorter consolidation time resulting in larger errors. The effect of consolidation time is clearly different in the no mask condition than it is in the conditions with masks. The no mask condition generates near asymptotic performance levels evident at even the shortest consolidation times. These conclusions are confirmed through two statistical analyses detailed below.

First, we examined whether the two conditions with the mask present demonstrated the same rate of consolidation. This would be evident in the absence of an interaction between the masking and consolidation manipulations. A 2 (mask condition: 83 or 167 ms) × 5 (consolidation time: 367, 467, 567, 676, or 767 ms) × 2 (serial position: 2 or 3) repeated measures BANOVA of mean response error was performed and Bayes factors were calculated. There was a main effect of mask-onset, $F(1,52) = 214.9$, $\eta^2_p = 0.81$, Bayes factor = 3.05×10^{79} in favor of an effect (means: 83 ms = 77.11, 167 ms = 57.58), a main effect of consolidation time, $F(4,208) = 40.72$, $\eta^2_p = 0.44$, Bayes factor = 4.26×10^{31} in favor of an effect (means: 367 ms = 78.42, 467 ms = 69.76, 567 ms = 63.82, 676 ms = 63.02, 767 ms = 61.71), and a main effect of serial position, $F(1,52) = 66.16$, $\eta^2 p = 0.56$, Bayes factor = 2.56×10^{22} in favor of an effect (means: serial position 2 = 62.40, serial position 3 = 72.29). There was strong evidence against the presence of the key interaction of mask-onset and consolidation time, $F(4,208) = 0.92$, $\eta^2_p = 0.02$, Bayes factor = 241.59 in favor of the null. There was evidence against the presence of any other interactions, all Bayes factors < 1.0 (in the form of alternative/null).

Given that there was no difference between the rates of consolidation in the two mask-onset conditions, a finding that replicates the results of experiment 1, we combined the data from both mask-onset conditions in experiment 2 into a single mask present condition to test whether the mere presence of a mask affects the speed of consolidation. We then performed a 2 (mask: present or absent) × 5 (consolidation time: 367, 467, 567, 676, or 767 ms) × 2 (serial position: 2 or 3) repeated measures BANOVA of mean response error and calculated the corresponding Bayes factors. There was a main effect of mask, $F(1,52) = 273.6$, $\eta^2_p = 0.84$, Bayes factor = 7.74×10^{158} in favor of an effect (means: present = 67.28, absent = 41.88), a main effect of consolidation time, $F(4,208) = 30.5$, $\eta^2_p = 0.37$, Bayes factor = 6.78×10^{21} in favor of an effect (means: 367 ms = 62.21, 467 ms = 55.76, 567 ms = 51.86, 676 ms = 51.87, or 767 ms = 51.22), and a main effect of serial position, $F(1,52) = 128$, $\eta^2_p = 0.71$, Bayes factor = 6.61×10^{37} in favor of an effect (means: serial position 2 = 49.32, serial position 3 = 59.84). There was evidence in favor of the key interaction of mask and consolidation time, $F(4,208) = 8.10$, $\eta^2_p = 0.13$, Bayes factor = 689.62 in favor of an effect. There was evidence against the presence of any other interactions, all other interaction Bayes factors < 1.0 (in the form of alternative/null).

Discussion

Experiment 2 confirms the prediction of the eSTST attentional-blink model[7] that masking target stimuli slow their consolidation. Although onset time of the mask does not change the consolidation function, the presence of a mask changes the function dramatically relative to no mask being present. In this experiment, consolidation was nearly complete in the no mask condition even at the shortest consolidation times. In contrast, when a mask was presented, significant consolidation was still clearly present at short consolidation delays.

General discussion

The present work demonstrates that masking a memory stimulus results in two effects. Masking stimuli produce interference based upon the temporal proximity to the memory item, with closer temporal proximity resulting in greater interference. This is observed in experiments 1 and 2 as lower performance with shorter mask onset times. Masking stimuli also slow the rate of consolidation, but this effect is not related to the temporal proximity of the mask itself. This is observed in experiment 2 as an interaction between mask present and mask absent conditions. In the mask present conditions, there is considerable improvement in performance as consolidation time increases. In the mask absent condition, there is little to no improvement in performance as consolidation time increases, indicating that consolidation is nearly complete at even the shortest consolidation times. The production of two effects following from the presentation of a mask supports the differing approaches to understanding masking that come from both the working memory[21,25,27] and the attentional blink[4,7] literatures.

A brief account of the slowing effect

The attentional blink approach to understanding masking championed by the eSTST model[7] argues that a single consolidation episode is not necessarily composed of only a single target item. Instead, each consolidation episode includes representations of all target items presented during the episode, which lasts so long as attention is available to boost the sensory memory representations of the targets. Attended sensory memory traces lead to the activation of abstract identity information, in eSTST this is called the *type representation*, that is then consolidated as part of the working memory trace. All target items that are attended are consolidated within an episode. Crucially, the availability of attention is maintained by the detection of target stimuli and partially suppressed by the ongoing consolidation of already detected stimuli. This competitive interaction means that when new targets are no longer detected, the degree of suppression passes a threshold value, ending the consolidation episode and initiating full suppression of attention manifested as the attentional blink.

When a masking stimulus is presented before the attentional blink is initiated, it will be briefly attended in order to identify it as a nontarget item. As a result, the mask disrupts the sensory trace for the preceding stimulus. Loss of the sensory representation decreases the strength of the corresponding type (abstract identity) representation being consolidated. Within eSTST, weaker type representations result in slower consolidation. In this way, the mask is either presented during the consolidation episode when attention is available and the mask is attended, slowing consolidation, or the mask is presented after the consolidation episode has ended and attention is fully suppressed, preventing it from being attended and resulting in no slowing of consolidation.

The finding that masking slows the consolidation process has been observed within the RSVP paradigm, but has not been previously investigated within a working memory paradigm. Nieuwenstein *et al.*[4] demonstrated that when the first target in an RSVP task is not masked, an attentional blink still exists, but that it is much shorter than the blink that occurs when a mask is present. If the attentional blink occurs as a byproduct of ongoing short-term consolidation, then Nieuwenstein *et al.*'s[4] findings show strong evidence that unmasked targets can be consolidated faster than masked targets. We find the same shortened consolidation period in our present work using a visual working memory paradigm rather than an RSVP task. This shared pattern of findings provides further evidence that short-term consolidation during working memory tasks induces an attentional blink.[5]

A brief account of the interference effect

The interference approach to understanding masking effects found in the working memory literature follows from a very different set of findings related to masking than those found in the RSVP literature. In the working memory tradition, a memory set is presented and followed by a masking stimulus. The onset of this masking stimulus is variable. Longer onset delays lead to better performance.[15–17,25] At some point, asymptotic performance is reached and further delays in mask presentation do not improve performance. Explanations of this temporally sensitive masking effect come in several flavors but all assume that the mask impairs performance directly by interfering with the memory representation,[21,25,27] not by changing the speed of consolidation.

One prominent approach to explaining masking effects in the working memory literature proposes that the presentation of a mask disrupts any unconsolidated trace and prevents it from being consolidated.[14–17] This view is problematic in that a series of other studies have shown that consolidation continues even after masking stimuli are presented.[5,8,9,13] Others have argued that the masking stimulus disrupts only the iconic/sensory memory trace, preventing its use, but does not disrupt consolidation of any not-yet consolidated working memory representation.[8,13,27]

The interference effect observed in our present results could be seen as consistent with this second explanation. Sensory memory may initially be relied upon while a working memory representation is created, a process we call encoding. Encoding here is the transformation of a sensory memory into a working memory state, thereby creating the working memory trace. In this conceptualization, the presentation of a mask overwrites a sensory memory representation but not a working memory representation. Without the presence of a sensory memory, a working memory state cannot be encoded. Faster masking results in lower memory performance because there is a higher probability that the sensory memory has not been encoded into a working memory state at the time of the mask, preventing creation of a working memory trace. In this approach, working memory creation and working memory consolidation are separate processes, with masking interference affecting memory creation (encoding) and the mask-related slowing affecting memory consolidation.

The present data can be seen as consistent with this approach in that the interference effect would exist because masking eliminates the sensory memory trace, preventing the creation of a working memory trace unless it exists before mask presentation. With no working memory trace to rely on, participants must respond by guessing on the memory test. Guesses would produce higher error rates than memory-based responses, reducing performance. When masking occurs faster, it is less likely that a working memory trace has been encoded at the time of the mask and guessing rates will be higher. The presence of fewer encoded working memories would not alter the speed of consolidation.

A final approach to understanding masking within the working memory literature is to assume that the masking stimulus interferes with the memory representation through graded interference. In this approach, interference does not stop the consolidation or encoding processes, but instead disrupts the quality of the memory representation.[28,29] Interference theories can explain the larger effect of masking stimuli at shorter mask-onset times observed here by assuming that consolidation protects the memory representation against interference.[15–17,27,30] When masking stimuli are presented at later delays, the memory trace is less vulnerable to interference, resulting in smaller masking interference. Again, this interference needs not alter the rate of consolidation but would simply lower the precision of the memory representation.

In these last two approaches, masking effects do not reflect the full time course of consolidation and masks do not directly affect the consolidation process. Despite this, the masking effect itself is related to the consolidation process. The time-course of masking interference seems to reflect a period when the memory trace is undergoing encoding or consolidation, but is still vulnerable to perceptual disruption. The discrepancy between this time course and the full time course of consolidation suggests that consolidation is a gradual time-dependent process of memory transformation in which resistance to perceptual disruption occurs before full consolidation is achieved.

Reconciling working memory and attentional blink approaches to consolidation

Despite differences in terminology, the attentional blink and working memory approaches to working memory consolidation can be seen as complementary. In order to see the similarities in both approaches, one must first see how masking can be related to the consolidation process without terminating consolidation. Resistance to this point of view largely stems from terminology differences across fields of study, so some explicit evidence of experimental effects is helpful in demonstrating this point.

Evidence that masking does not end consolidation comes from several studies that keep mask onset time constant relative to memory item presentation while varying the time for consolidation available after the mask. In all of these studies, consolidation time is determined by calculating the time between memory item onset and the onset of another attention-demanding task. Jolicœur and Dell'Acqua[8] presented one or three memory items, either letters or symbols, masked them, and then varied the amount of time before a onset of a secondary task. Secondary task reaction times were faster when more time was given between memory item presentation and secondary task onset. The same was not true when participants were told they could ignore the memory items because they would not be tested later, indicating that intentional storage of a memory was necessary to observe secondary task slowing.

More recently, several studies have shown that more time for consolidation improves memory performance even when mask onset is held constant. Nieuwenstein and Wyble[9] presented several memory items, four letters or one complex symbol, masked them, and then asked participants to perform a secondary task after a variable delay for memory consolidation. Each trial concluded with a recognition test. When more time was given for consolidation of the memory items, performance on the memory test improved. Ricker and Cowan[13] held the time between item presentation and mask onset constant across several conditions using both sequential and simultaneous presentation of a memory set of three unfamiliar symbols. Here, consolidation time was varied by manipulating the time between memory items in the case of sequential presentation or by presenting the array multiple times with varying amounts of time between array presentations in the case of simultaneous presentation. Recognition performance improved with increasing time for consolidation. Similar results were found by Ricker and Hardman[5] who presented a sequence of four orientations, using the same stimuli as the present study, with a constant mask onset time after each memory item. Increasing the time for consolidation between items improved memory performance. Finally, De Schrijver and Barrouillet[31] presented a sequence of letters and observed improved memory recall with more time for consolidation. Each letter was presented, masked after a constant delay, and then a secondary task was performed. Consolidation was manipulated by varying the time between memory item presentation and secondary task onset. Across a variety of paradigms, with visual or verbal memory items, sequential or simultaneous presentation, or with recognition or recall responses, consolidation time improved performance, even after memory items were masked.

Although masking does not end consolidation, it does not mean that it is unrelated to the consolidation process. Indeed, our data show that the presence of a mask does alter the consolidation process. We show that masking slows the consolidation process, as predicted by the eSTST model. Using the eSTST framework, with some additional assumptions and terminology translations, we can include the interference predictions of the working memory approach and slowing predictions of the attentional blink approach in a common model.

The first step in forming this common model is to equate the concept of an unconsolidated working memory representation with the concept of type representations in eSTST. If one thinks of a working memory representation as an abstract concept of the memory item, then this is a straightforward translation. Next, we should see that both approaches incorporate a concept of sensory memory that is equivalent. While eSTST stipulates that masks eliminate the sensory memory trace of a stimulus, it does not stipulate that this has an effect on the type representation beyond lowering its activation level. If instead we assume that masking does influence the working-memory/type representation beyond activation level, then we could view the interference effect observed in the present study as either a reduction in the probability that a working-memory/type representation will be activated/created or as degrading the information contained in the type representation. Faster masking would result in a greater interference effect if the activation/creation of the type representation reflects the time-course of masking interference. In this way, both the slowing effect, already present in the eSTST model, and the temporal-interference effect of masking could be incorporated in a common framework without altering assumptions about the processes in the attentional blink or working memory literatures, beyond language and terminology use.

Using sequential presentation in a visual working memory task

In the present study, we use sequential presentation of visual materials to examine masking and consolidation effects rather than simultaneous presentation of visual working memory tasks for several reasons. First, past work using the present stimuli has examined the consolidation process in detail.[5] From this work, we know the rough time course of consolidation that we should expect and we have verified that any observed effects following from manipulations of consolidation time are not due to changes in temporal distinctiveness.[5] Second, sequential and simultaneous presentation in visual working memory tasks with a small number of items have demonstrated similar performance levels and similar changes in accuracy in responses to changes in consolidation time, so long as all overall presentation times and mask-onset times are equated.[13] Third, the present work also tests predictions from a mathematical model of the attentional blink[7] that was developed to explain consolidation effects within a sequential presentation paradigm.

More importantly, manipulating the time available for consolidation with sequential presentation allows us to use a single-task structure in our procedure. When manipulating the time available for consolidation with simultaneous presentation techniques, an attention-demanding secondary task is required to remove attention from the to-be-remembered stimulus. In these tasks, the memory set is presented and then after a variable delay, to allow for consolidation, the secondary task is presented. In this paradigm, consolidation effects are often observed as delayed reaction times to the secondary task.[6,8,10] However, in addition to manipulating consolidation time, in the present work, we also manipulate mask onset time. Unlike the consolidation effect, under dual-task conditions, we still expect that the main effect of mask-onset time will manifest as a change in the primary memory task error rates. In order to ensure we observe the effects of both of our task manipulations within the same dependent variable, we used a single-task sequential presentation procedure.

We also had concerns about participant strategies leading to dual-task performance tradeoffs across conditions in a dual-task paradigm. For example, faster masking may encourage more attention toward the secondary task at the expense of the memory task. Similarly, limited time for consolidation may encourage more attention toward the memory task at the expense of secondary task performance. This style of tradeoff would be hard to predict or verify and would introduce serious complications in interpreting the results. Interpretations of the present results are clearer under single-task conditions that require sequential presentation.

The default method of studying the time course of masking in the visual working memory literature has been to use simultaneous presentation, and not sequential presentation.[15–17,25] It is possible that our use of sequential presentation resulted in fundamentally different cognitive processing of the stimuli than under simultaneous presentation and perhaps our results would not generalize to the simultaneous-presentation case. For example, the consolidation effects we observed, above and beyond the masking effects, could be due to higher order strategies such as verbal recoding and rehearsal applied during sequential presentation and not due to ongoing consolidation. In this case, our results would lead to quite different conclusions from those argued above.

While it is always possible that methodological choices bias ones results in a particular direction, it is unlikely that the choice of sequential presentation alone resulted in our observed consolidation effects. First, sequential and simultaneous presentation show similar consolidation effects in visual working memory change detection.[13] Second, at least two studies manipulating the availability of articulation during the consolidation period have ruled out verbal rehearsal as being responsible for the consolidation effect in sequential[26] and simultaneous[6] presentation procedures. Finally, our sequential presentation technique replicates existing findings in the literature on masking and consolidation across item presentation methodologies. For example, here, we show that masking effects are sensitive to mask onset time, as they are under simultaneous presentation.[15–17,25] We also replicate consolidation effects that have been demonstrated under both sequential and simultaneous presentation conditions using both verbal and nonverbal materials.[4–10,13,26,31] Altogether, this is strong evidence that our findings are not particular to sequential presentation of memory items. Nonetheless, future work should verify these findings under simultaneous presentation conditions to test for boundary conditions.

Concluding remarks

The present work shows that the relationship between masking and consolidation is complex. Masks appear to influence working memory performance through at least two distinct mechanisms, both related to consolidation in differing ways. While masks slow the consolidation process, they also directly interfere with the representation being consolidated. The magnitude of this disruption is dependent on the progress of the consolidation process. Further work will be needed to understand the exact mechanism through which masking interference disrupts the memory representation. For example, future experiments should use mathematical modeling techniques to determine whether masking interference leads to complete loss of the working-memory/type representation or if it leads to degradation of the information contained in the working-memory/type representation. While there is still much to learn, the preceding experiments advance our knowledge of masking effects by demonstrating that approaches to understanding masking in the working memory and RSVP literatures are complementary rather than competing explanations.

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Competing interests

The authors declare no competing interests.

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