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Beyond a Mask and Against the Bottleneck: Retroactive Dual-Task Interference During Working Memory Consolidation of a Masked Visual Target

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While studies on visual memory commonly assume that the consolidation of a visual stimulus into working memory is interrupted by a trailing mask, studies on dual-task interference suggest that the consolidation of a stimulus can continue for several hundred milliseconds after a mask. As a result, estimates of the time course of working memory consolidation differ more than an order of magnitude. Here, we contrasted these opposing views by examining if and for how long the processing of a masked display of visual stimuli can be disturbed by a trailing 2-alternative forced choice task (2-AFC; a color discrimination task or a visual or auditory parity judgment task). The results showed that the presence of the 2-AFC task produced a pronounced retroactive interference effect that dissipated across stimulus onset asynchronies of 250–1,000 ms, indicating that the processing elicited by the 2-AFC task interfered with the gradual consolidation of the earlier shown stimuli. Furthermore, this interference effect occurred regardless of whether the to-be-remembered stimuli comprised a string of letters or an unfamiliar complex visual shape, and it occurred regardless of whether these stimuli were masked. Conversely, the interference effect was reduced when the memory load for the 1st task was reduced, or when the 2nd task was a color detection task that did not require decision making. Taken together, these findings show that the formation of a durable and consciously accessible working memory trace for a briefly shown visual stimulus can be disturbed by a trailing 2-AFC task for up to several hundred milliseconds after the stimulus has been masked. By implication, the current findings challenge the common view that working memory consolidation involves an immutable central processing bottleneck, and they also make clear that consolidation does not stop when a stimulus is masked.

Keywords: working-memory consolidation, backward masking, attentional blink, psychological refractory period, retroactive dual-task interference

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In dealing with a rapid and ever-changing stream of visual sensory input, the storage of information in working memory forms a central requirement for many perceptual and cognitive tasks. While considerable insight has been gained into the quality and quantity of information that can be stored in working memory (e.g., Prinzmetal, Amiri, Allen, & Edwards, 1998; Wilken & Ma, 2004; Zhang & Luck, 2008), the mechanisms that mediate the initial transfer and consolidation of visual information into working memory remain poorly understood. As a case in point, consider the basic but important questions of how long it might take to consolidate a familiar visual stimulus such as a letter, and how this process might be affected when the letter is masked—a common procedure in studies on visual perception, attention, and memory. According to one influential perspective, the appearance of a mask would interrupt consolidation, and therefore the finding that people can recall about four letters from a 100-ms masked display entails that it takes only 100 ms to consolidate four letters in working memory (Gegenfurtner & Sperling, 1993; Vogel, Woodman, & Luck, 2006). In contrast, another widely influential perspective proposes that the consolidation of a single letter can continue for several hundred milliseconds even after a mask (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998). Evidently, one of these perspectives must be incorrect, and resolving this matter is of broad theoretical importance because our understanding of many phenomena in research on perception, attention, and working memory relies on assumptions about the dynamics and limits of working memory consolidation (WMC). In the current study, we set out to meet this demand by examining the origins of the opposing views and by conducting a series of experiments that aimed to adjudicate between them.

In characterizing the role of WMC in human information processing, most accounts agree in assuming a distinction between

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two stages of processing. During the first of these two stages, visual stimuli such as letters, words, and even pictures of unfamiliar scenes are rapidly represented and categorized by means of the activation of neurons along the ventral processing stream (e.g., Keysers, Xiao, Foldiak, & Perrett, 2001; Thorpe, Fizet, & Marlot, 1996; see also Grill-Spector & Kanwisher, 2005; Potter, 1975). While this first stage of visual representation and categorization may take only 100 ms, the resulting information is highly volatile as it is rapidly lost due to decay and interference from cotemporaneous stimuli, which act as a mask (e.g., Averbach & Coriel, 1961; Breitmeyer & Ogmen, 2000; Enns & Di Lollo, 2000; Kahneman, 1968; Kovács, Vogels, & Orban, 1995; Potter, 1976; Rolls, Tovée, & Panzeri, 1999). Hence, the ability to report or judge a stimulus after it has been masked is generally thought to require that the stimulus undergoes a second stage of processing wherein it is consolidated in working memory. Once this consolidation process has been completed, the stimulus is said to be "stored" in working memory where it can persist in the face of newly presented stimuli for a period of several seconds (Baddeley, 2012; see also Miller, Erickson, & Desimone, 1996; Oberauer, 2009).

The opposing views on the time-course of WMC derive from the fact that this matter has been addressed with different paradigms and assumptions, in different lines of research. The first perspective derives from studies on visual masking, which commonly assume that if a stimulus can still be recalled after it has been masked, then the consolidation of that stimulus must have been completed before the appearance of the mask (Gegenfurtner & Sperling, 1993; Vogel et al., 2006; see also Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011; Bundesen, 1990; Fuller, Luck, McMahon, & Gold, 2005; Saults & Cowan, 2007; Shibuya & Bundesen, 1988; Sun, Zimmer, & Fu, 2011; Todd, Han, Harrison, & Marois, 2011; Woodman & Vogel, 2005; Wutz & Melcher, 2013; Zhang & Luck, 2008). Thus, according to this view, the finding that observers can recall about four letters from a masked, 100-ms display entails that it takes only 100 ms of processing time to consolidate four letters in working memory (Gegenfurtner & Sperling, 1993; Vogel et al., 2006). The rationale underlying this interpretation is that the consolidation of the letters can only continue for as long as the representations of these letters are available in sensory memory. Since these representations would be rapidly overwritten by a trailing mask (e.g., Breitmeyer & Ogmen, 2000; see also Kovács et al., 1995; Rolls et al., 1999), it follows that the mask would interrupt the consolidation of the letters in working memory. By implication, any letters that can be recalled after a mask would be assumed to have been consolidated in working memory prior to the appearance of the mask.

A markedly different perspective on the temporal dynamics and vulnerability of WMC can be found in research on dual-task interference effects such as the attentional blink (Raymond, Shapiro, & Arnell, 1992)—the phenomenon that observers frequently fail to encode the second of two target stimuli in memory if it appears within less than half a second from the first. Importantly, this effect has been shown to occur regardless of whether the first target is masked (e.g., Nieuwenstein, Potter, & Theeuwes, 2009) but only if the first target can be recalled (Nieuwenstein, Van der Burg, Theeuwes, Wyble, & Potter, 2009), and it has also been found that the magnitude of the attentional blink is stronger when the amount of to-be-consolidated information is increased for the first target (Olson, Chun, & Anderson, 2001; Ouimet & Jolicœur, 2007; see also Tombu et al., 2011). Accordingly, theories of the attentional blink generally assume that this effect reflects a consequence of consolidating the first target in memory, thus suggesting that the consolidation of a visual stimulus continues for several hundred milliseconds even after it has been masked (Bowman & Wyble, 2007; Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Shih, 2008; Taatgen, Juvina, Schippers, Borst, & Martens, 2009; Wyble, Bowman, & Nieuwenstein, 2009; Wyble, Potter, Bowman, & Nieuwenstein, 2011; see also Lagroix, Spalek, Wyble, Jannati, & Di Lollo, 2012). In explaining how this might occur, theories of the attentional blink generally converge in assuming that the effect of a visual mask is confined to disrupting the processing of stimuli prior to selection for consolidation, that is, during the first stage of processing. Once selected for consolidation, however, the representation of a stimulus is thought to undergo a strengthening (Shih, 2008) or binding process (Bowman & Wyble, 2007; Wyble et al., 2009, 2011) that allows this representation to be sustained even in the face of a trailing mask, until consolidation is completed.

The Present Study

Evidently, the available perspectives on the time course of consolidating information in working memory are extremely divergent, and resolving this matter is of both practical and theoretical importance. After all, if it were true that consolidation is interrupted by a mask and that the consolidation of a single letter takes only 25 ms, then this would entail that a variety of theories of the attentional blink are incorrect in assuming that this effect reflects the time course of WMC.[1] Conversely, if it were true that WMC can continue for several hundred milliseconds after a mask, then this would entail that researchers can no longer assume that backward masking can be used as a means to assess or restrict the duration of consolidation, as has been done in many previous empirical and theoretical studies (e.g., Bays et al., 2011; Bundesen, 1990; Fuller et al., 2005; Gegenfurtner & Sperling, 1993; Saults & Cowan, 2007; Shibuya & Bundesen, 1988; Sun et al., 2011; Todd et al., 2011; Vogel et al., 2006; Woodman & Vogel, 2005; Wutz & Melcher, 2013; Zhang & Luck, 2008).[2]

The goal of the current study was to adjudicate between the opposing perspectives on the dynamics of WMC. To this end, we examined if and for how long the processing of a masked display of to-be-remembered stimuli can be disrupted by a trailing 2-alternative forced choice (2-AFC) task. The rationale underlying this approach resembles that underlying the interruption-by-masking approach (e.g., Gegenfurtner & Sperling, 1993; Vogel et al., 2006) in that it aimed to characterize the time course of WMC

[1] It is worth noting that the implications of such a rapid consolidation process reach beyond theories of the attentional blink, as the assumption that WMC involves a relatively slow process also features in other theories, including the theory of short-term memory proposed by Jonides et al. (2008) and Oberauer and colleagues' theory of performance in the complex span task (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012).

[2] It is worth mentioning that proponents on both sides of this debate have argued against each other's proposals, such that Vogel et al. (2006) argued that "the attentional blink paradigm does not provide a good means of estimating the time course of WM consolidation" (p. 1437), whereas researchers working on the attentional blink have argued that "the manipulation of memory-mask stimulus onset asynchrony" used by Vogel et al. does not affect "consolidation duration" (p. 224; Shih, 2008) and therefore should not be taken as a proper means for estimating the time course of WMC.

by means of examining for how long this process can be disturbed, but it differed from the interruption-by-masking approach in that we used a 2-AFC task instead of a task-irrelevant mask to disrupt WMC. Our choice for using this type of task was based on the assumption that the processing required for a 2-AFC task may interfere with WMC because it relies on the same processing mechanisms as those involved in WMC. To be precise, there are several neuroimaging studies that show that WMC relies on a network of frontal and parietal brain areas that are also activated in tasks that require participants to decide upon and select an appropriate response for a stimulus (Marti, Sigman, & Dehaene, 2012; Tombu et al., 2011; see also Marois & Ivanoff, 2005; Zylberberg, Slezak, Roelfsema, Dehaene, & Sigman, 2010). Furthermore, there are several behavioral studies that suggest that these two types of tasks produce interference when they need to be performed for two targets shown in close temporal succession (e.g., Arnell & Duncan, 2002; Arnell, Helion, Hurdelbrink, & Pasieka, 2004; De Jong & Sweet, 1994; Jolicœur & Dell'Acqua, 1998, 1999; Koch & Rumiati, 2006; Ruthruff & Pashler, 2001; Stevanovski & Jolicœur, 2007, 2011; see also Wong, 2002). Accordingly, we reasoned that if the consolidation of a visual stimulus continues after a mask, then it might still suffer interference from a trailing 2-AFC task because the execution of this task would call upon the same central processing resources that mediate the ongoing consolidation of the earlier shown stimuli.

While the aforementioned considerations suggest that it is plausible that the consolidation of a visual stimulus can be disrupted by means of a trailing 2-AFC task, it is important to note that this type of retroactive interference effect has thus far not been observed in studies that combined a memory encoding task with a trailing 2-AFC task (Arnell & Duncan, 2002; Arnell et al., 2004; Jolicœur & Dell'Acqua, 1998; Koch & Rumiati, 2006; Ruthruff & Pashler, 2001; Stevanovski & Jolicœur, 2007, 2011; Tombu et al., 2011). To be precise, these studies all found that performance on the 2-AFC task suffers a pronounced proactive interference effect in the form of a psychological refractory period effect (i.e., a decrease in response times with increasing stimulus onset asynchrony [SOA]; Welford, 1952; see also Pashler, 1994), whereas performance on the memory task showed little to no evidence for a concomitant retroactive interference effect. Accordingly, accounts of performance in these types of tasks generally agree in assuming that WMC imposes an immutable, central information-processing bottleneck, the idea being that response selection for the second task is postponed until the consolidation of information for the first task is completed (e.g., Jolicœur & Dell'Acqua, 1998; Marois & Ivanoff, 2005; Tombu et al., 2011; Zylberberg, Dehaene, Roelfsema, & Sigman, 2011). Importantly, however, closer scrutiny of the methods and results of the experiments at stake shows that the lack of retroactive interference may be more apparent than real. To wit, most of these studies used a memory task for which performance was close to ceiling, but the few studies that used a relatively difficult memory task do seem to show some degree of improvement in first-target performance across SOA (e.g., Experiment 2 in Arnell & Duncan, 2002; the conditions with a memory set of three symbols in Experiments 3 and 5 by Jolicœur & Dell'Acqua, 1998; Experiment 3 in Stevanovski & Jolicœur, 2007). Indeed, the current study shows that the consolidation of a masked visual stimulus can suffer pronounced retroactive interference from a trailing 2-AFC task, but the magnitude of this effect depends on the difficulty of both tasks.

Experiments 1 and 2: The Demonstration of Retroactive Dual-Task Interference

To examine whether the consolidation of a visual stimulus can be disrupted after a mask, by means of a trailing 2-AFC task, we conducted two experiments that differed in terms of whether the to-be-remembered stimuli comprised verbal or nonverbal visual stimuli (see Figure 1). Specifically, in Experiment 1, participants were asked to encode a string of four letters in memory for a delayed free recall test, while in Experiment 2 participants were asked to encode an unfamiliar, complex shape (i.e., a Kanji character) for a delayed recognition test. In both experiments, the to-be-remembered stimulus was shown for about 100 ms and followed by a mask in half the trials. The presence versus absence of the mask was crossed with the presence versus absence of a visual parity judgment task that required a speeded odd-even judgment of a digit that could appear at an SOA of 250; 500; or 1,000 ms (Experiment 1), or 247; 494; 1,000; or 1,494 ms (Experiment 2) from the earlier shown targets for the memory task.

In accordance with theories of the attentional blink (e.g., Wyble et al., 2009, 2011), we hypothesized that the consolidation of both the letters and the Kanji character would continue after the mask, and we further hypothesized that this still ongoing consolidation process would be disrupted by the trailing 2-AFC task. Based on these hypotheses, we predicted that, regardless of the presence of a mask, the 2-AFC task would lead to an impairment in memory for the preceding stimuli, and we predicted that the magnitude of this impairment would dissipate with increasing SOA, thus reflecting the increasing likelihood that consolidation could be completed prior to the disruptive second task. In contrast, if the consolidation of the stimuli would already be completed—or terminated—upon the appearance of a mask (e.g., Gegenfurtner & Sperling, 1993; Vogel et al., 2006), then the presence of the second task could no longer interfere with the consolidation of these stimuli though it might still interfere with their retention in working memory (e.g., Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012; Ricker & Cowan, 2010). If so, then one would not expect the interference effect to dissipate as a function of SOA as previous studies examining dual-task interference during the retention interval of a working memory task have found that such interference effects tend to increase—not decrease—as a function of SOA (Ricker & Cowan, 2010).

Method

Participants. Experiment 1 was conducted at the University of Groningen and Experiment 2 was conducted at Penn State University. For both experiments, the participants were 16 undergraduate psychology students who volunteered to participate in return for course credit.

Materials. In both experiments, the presentation of stimuli and the registration of responses was controlled using Eprime 1.2. In Experiment 1, the stimuli were displayed on a monitor set to $1{,}024 \times 768$ pixels, with a refresh rate of 100 Hz. In Experiment 2, the monitor was set to the same resolution, with a 85-Hz refresh rate.

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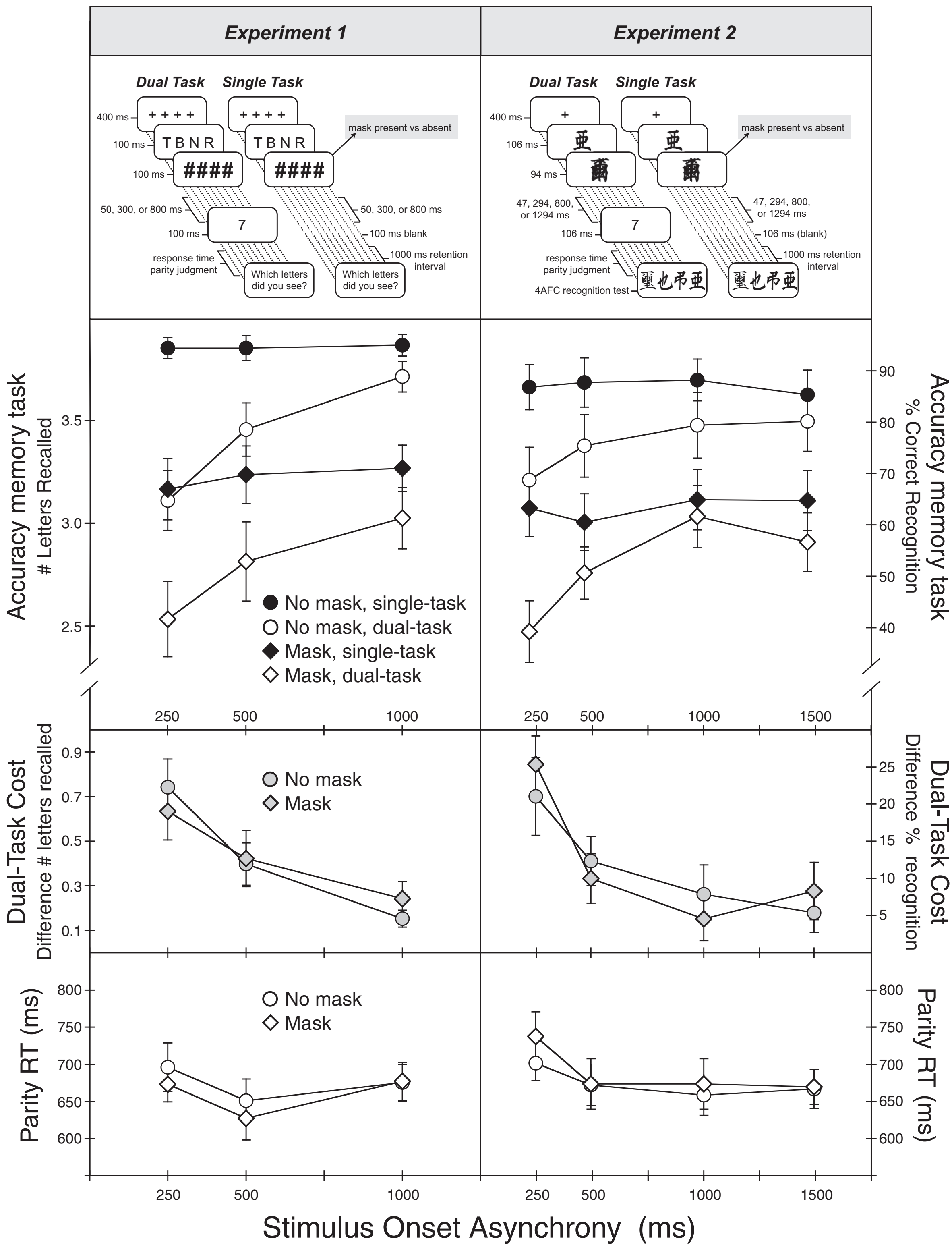

Figure 1. Design and results of Experiments 1 and 2. The upper panel shows the design of the two experiments, and the lower panels show the results. From top to bottom, the panels show the average performance in the memory task, the dual-task cost defined as the difference in performance between the single and the dual task condition, and the average response times (RT) for the parity judgment task. Error bars show the *SE* of the mean. 4AFC = four-alternative forced choice task.

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The memory task in Experiment 1 required recall of a string of four letters that were selected randomly without replacement from the alphabet (excluding M, W, and all vowels). The mask consisted of a string four "#" symbols and the digit used for the parity judgment task was randomly selected from the set {2–9}. Letters and digits were drawn in a black, 20-point Helvetica font and shown on a white background. The mask was drawn in a boldfaced 24-point Helvetica font. The reason for using a boldfaced and larger font for the mask was to ensure that the line elements comprising the mask overlapped with most of the line elements of the letters.

In Experiment 2, participants had to memorize a Kanji character[3] that matched the identity of a randomly selected letter of the Roman alphabet. The mask for the Kanji character consisted of three other Kanji characters that were displayed on top of each other to create a dense mask that included most of the line elements also present in the to-be-remembered Kanji (see Figure 1). To test participants' memory for the Kanji character, we used a four-alternative forced-choice recognition test in which the to-remembered Kanji character had to be selected from a set of four Kanji characters. The foils in this recognition test were selected at random from the set of Kanji characters, excluding the characters that were used for the mask. The Kanji target, mask, and digit were all drawn in a 48-point font.

Design and procedure. Both experiments used a within-subject design with three factors, namely the presence of a mask, the presence of a parity judgment task, and the SOA separating the to-be-remembered stimuli from the parity judgment task. In Experiment 1, the SOA separating the letter string from the target for the parity judgment task was 250; 500; or 1,000 ms. In Experiment 2, the SOA was 247; 494; 1,000; or 1,494 ms. In both experiments, the different trial types were randomly intermixed. Experiment 1 included a total of 240 trials (20 replications per condition), while Experiment 2 included a total of 384 trials (24 replications per condition).

Due to the use of monitors with different refresh rates, there were some minor differences in the timing of the stimuli between the two experiments. We here describe the main features of the trial procedure, and we refer to Figure 1 for information about the exact timing of the stimuli. In both experiments, a trial began with a fixation cross in the center of the screen. The participants could then initiate the trial by pressing the spacebar using their left hand. The fixation display then remained in view for 400 ms before the to-be-remembered stimulus was shown (~100 ms). This stimulus was followed either by a mask or by a blank interval that matched the duration of the mask (~100 ms). Subsequently, there was a blank interval of varying duration to create SOAs of varying duration. In the dual-task condition, this blank interval was followed by the presentation of a digit (~100 ms) for which participants had to indicate as quickly as possible whether it was odd or even, by pressing one of two designated keys using the index and middle fingers of their right hand. The memory test (a probe to report the four letters, or the recognition test for the Kanji character) followed immediately after this response was recorded. In the single-task condition, the digit was replaced by a blank interval, and there was a 1-s retention interval before the memory test was presented. By including this 1-s retention interval, we aimed to equate the retention intervals in the dual and single-task conditions.

Data-analysis. Trials on which response times (RT) for the parity judgment were shorter than 200 ms or longer than the participant's mean response time plus 2.5 *SD* were excluded as outliers. The analyses of accuracy in the memory task and RTs in the parity judgment task only included trials on which the parity judgment was correct.

Results

Experiment 1: The memory task. The total number of correctly recalled letters was examined with a repeated-measures analysis of variance (ANOVA) that included SOA, the presence of a pattern mask, and the presence of the parity judgment task as factors. The analysis revealed significant main effects of all three factors (all ps $< .001$, all h_p^2s $> .65$) and a significant interaction of SOA and the presence of a second task, $F(2, 30) = 15.2$, $p < .001$, $h_p^2 = .50$. As can be seen in Figure 1, this dual-task cost dissipated as SOA increased from 250–1,000 ms, and its magnitude was not affected by whether the letters were masked. Comparisons of performance at each SOA showed that the detrimental effect of the second task was significant at all SOAs, regardless of the presence of a mask (all ps $< .007$).

Experiment 1: The parity judgment task. The analysis of response accuracy for the parity judgment task showed no significant effects of the presence of a pattern mask, or of SOA (all ps $>$ .14), with the average performance being 87.8% correct. A similar analysis of the response times revealed a significant effect of SOA, $F(2, 30) = 8.7$, $p = .001$, $h_p^2 = .37$, with response times being slightly faster at the 500-ms SOA than at the the 250- and 1,000-ms SOAs (both ps $< .037$; see Figure 1).

Aside from examining the effects of SOA on response times, we also examined if these response times depended on the number of letters that could be recalled for the memory task. To this end, we used the data from trials with a 250-ms SOA, and we compared the average response times for the parity judgment task for trials on which 0–2 or 3–4 letters could be correctly recalled. The results[4] showed that responses for the parity judgment task were not affected by the number of letters that could be recalled for the memory task, with the mean response times being 588 and 581 ms, respectively, for trials in which 0–2 or 3–4 letters could be recalled ($F < 1$).

Experiment 2: The memory task. As can be seen in Figure 1, the results for Experiment 2 closely resembled those of Experiment 1. Performance on the recognition test showed significant main effects of the presence of a mask, the presence of the parity judgment task, and SOA (all Fs > 14.24, all ps $< .001$, all h_p^2s $>$ .49). The only other effect to reach significance was the interaction between SOA and the presence of the parity judgment task, $F(3, 45) = 16.36$, $p < .001$, $h_p^2 = .52$ (all other ps $> .26$). Pair-wise comparisons of performance at each SOA showed that the parity judgment produced a significant interference effect at SOAs of 250

[3] Font set retrieved from http://web.archive.org/web/19990429083728/http://www.west.net/~kurrasch/kanji.htm

[4] This analysis was based on the data for 15 participants, as one participant always recalled three to four letters. These 15 participants each had at least one observation in each cell of the design, and the results did not change when we only considered the data for 12 participants who had at least five observations in each cell ($RT_{0-2} = 598$ vs. $RT_{3-4} = 606$ ms; $F < 1$).

and 500 ms, regardless of whether the Kanji character was masked (all $ps < .009$). At SOAs of 1,000 and 1,500 ms, there was still a suggestion of some interference, but this effect only reached significance for the 1,494-ms SOA in the masked condition ($p = .048$). The other comparisons showed a trend in the same direction (all $ps > .056$).

Experiment 2: The parity judgment task. Accuracy in the parity judgment task showed a significant effect of SOA, $F(3, 45) = 5.85$, $p = .002$, $h_p^2 = .28$, with responses being accurate on 93.8, 90.6, 92.8, and 95.4% of the trials for SOAs of 247; 494; 1,000; and 1,494 ms, respectively. Accuracy was not influenced by the presence of a mask (all $ps > .10$). For the analysis of response times, the only effect to reach significance was the main effect of SOA, $F(2.1, 31.0) = 4.04$, $p = .026$, $h_p^2 = .21$ (all other $ps > .12$). Post-hoc comparisons showed that the average response time was significantly slower at the 250-ms SOA than at the 1,000-ms SOA ($p = .006$). None of the other comparisons between SOAs reached significance (all $ps > .072$). As in Experiment 1, we again examined if the response times for the 250-ms SOA condition depended on accuracy for the memory task and found that there was no such relationship. Indeed, if anything the response times were slightly faster on trials in which the response for the recognition test was correct ($M = 597$ ms) than on trials in which this response was incorrect ($M = 629$ ms), $F(1, 15) = 3.31$, $p = .089$, $h_p^2 = .18$.

Discussion

The results of Experiments 1 and 2 show that memory for two different types of visual stimuli (i.e., a string of letters or a complex, unfamiliar shape) is significantly impaired if the stimuli are followed closely in time by the target for a visual speeded parity judgment task. To be precise, the presence of this parity judgment task produced a pronounced retroactive interference effect that decreased across SOAs of 250–1,000 ms and then appeared to remain stable across SOAs of 1,000–1,494 ms, suggesting that the processing elicited by this second task interfered with the gradual consolidation of the earlier shown stimuli. Importantly, the magnitude of and time course of this effect were not affected by whether the to-be-remembered stimuli were masked, even though the presence of a mask did have a pronounced detrimental effect on the memory task.[5] Suffice it to say, the results of Experiments 1 and 2 show that memory for a string of letters or an unfamiliar complex shape derives from a time-consuming consolidation process that continues for several hundred milliseconds after a mask and that can be disrupted by a trailing speeded visual parity judgment task.

Experiments 3–5: Boundary Conditions of the Retroactive Interference Effect

In demonstrating a strong and highly significant retroactive interference effect for two different types of memory tasks, the results of Experiments 1 and 2 differ markedly from those obtained in related previous studies. To wit, the results of these previous studies typically show that performance for the first of two successive targets is accurate, whereas performance for the second target suffers a pronounced attentional blink or psychological refractory period effect, meaning that the second target tends to be missed (i.e., an attentional blink effect), or responded to slowly (i.e., a psychological refractory period effect), when it appears shortly after the first target (e.g., Arnell & Duncan, 2002; Arnell et al., 2004; Jolicœur & Dell'Acqua, 1998, 1999; Koch & Rumiati, 2006; Ruthruff & Pashler, 2001; Stevanovski & Jolicœur, 2007, 2011; Tombu et al., 2011). In contrast, the results of Experiments 1 and 2 showed only a minor psychological refractory period effect, but they did show a pronounced retroactive interference effect. To address the reasons for this discrepancy, Experiments 3–5 aimed to examine the boundary conditions for the retroactive interference effect found in Experiments 1 and 2.

As a first step toward examining these boundary conditions, Experiment 3 used the same memory task as Experiment 1 and examined if the retroactive interference effect would also occur with a different type of 2-AFC task (i.e., a color discrimination task). In addition, this experiment examined whether the interference would be attenuated if this task were to be changed to a speeded color detection task, the idea being that such a detection task would not pose as strong a demand on decision making and response selection processes and thus produce less interference. In Experiment 4, we again replicated Experiment 1 and this time examined if the retroactive interference effect would be attenuated if the encoding load for the first task is reduced from four to two letters, the idea being that the interference effect should be more pronounced when the processing demands for WMC are higher. Last, Experiment 5 replicated Experiment 2 and examined if the retroactive interference effect would also occur when the target for the second task—a speeded parity judgment task—would be presented in the auditory modality, the idea being that if the interference derives from the engagement of amodal, central processing mechanisms involved in decision making and response selection processes, then it should occur regardless of the input modality of the second target (e.g., Pashler, 1998).

Experiment 3

In Experiment 3, we examined if the retroactive interference effect we found in Experiment 1 would be replicated in case the second task involved a color discrimination task that required participants to make a speeded 2-AFC for a red or green colored square. The second goal of Experiment 3 was to determine if any retroactive interference produced by this color discrimination task would be reduced if this task would be changed into a less demanding color detection task wherein participants had to respond as quickly as possible to any colored square, using the same response key. Assuming that the retroactive interference effect stems from the decision making and response selection requirements for a 2-AFC task, we predicted that the effect observed in

[5] Indeed, if anything, it appears as though the presence of the mask may have rendered the consolidation of the earlier shown stimuli more susceptible to the interference from the trailing 2-AFC task. Specifically, the analyses reported above examined overall recall or recognition accuracy and showed that the detrimental effect of the mask was constant across SOA and the presence of the second task. By implication, if one were to normalize the data according to the level of performance achieved in the single-task condition, the magnitude of interference produced by the parity judgment task would be greater for the condition in which the memory display was followed by a mask.

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Experiment 1 would be replicated with a color discrimination task and that it would be attenuated in case of a color detection task.

Method.

Participants. A sample of 34 undergraduate students from the University of Groningen participated in Experiment 3 in return for course credit. The participants were randomly assigned to the color-detection or color-discrimination task, which each included 17 participants. None of the participants reported any difficulty in distinguishing red and green.

Materials, design, procedure, and data-analysis. The materials, design, procedure and data-preprocessing steps taken in Experiment 3 were identical to those of Experiment 1, with three changes. The first and primary change was that the digit that was used as a second target in Experiment 1 was replaced by a red or a green square of 32 $\times$ 32 pixels. The second change was that Experiment 3 only included two SOAs, namely, 300 and 1,000 ms. The third change was that the letters were always followed by a mask. Thus, the design of Experiment 3 comprised a 2 $\times$ 2 $\times$ 2 design, with two within-subject factors (SOA and presence vs. absence of a second task), and one between-subjects factor (color discrimination vs. color detection task). Participants were told that they would see a brief and masked display of four letters that had to be identified and that could be followed by a red or a green square. Participants in the color-detection condition were told to respond as quickly as possible to any colored square by pressing the "0" key of the number pad of the keyboard. For participants in the color-discrimination condition, the instructions for the colored square were to press the "1" key as quickly as possible in case it was red, or the "2" key in case it was green. The experiments with a color discrimination and detection task each comprised a total of 144 trials, which were preceded by 16 practice trials.

Results.

The memory task. Performance for the memory task is shown in Figures 2a and 2b. The total number of letters recalled was examined using a repeated measures analysis of variance that included SOA (300 vs. 1,000 ms) and the presence of a second task (single vs. dual task) as within-subject factors, and the nature of the second task (color detection vs. discrimination) as a between-subjects factor. The results of this analysis showed that the main effects of SOA and the presence of a second task were both significant, $F(1, 32) = 23.50$, $p < .001$, $h_p^2 = .42$, and, $F(1, 32) = 33.11$, $p < .001$, $h_p^2 = .51$, respectively. There was no significant main effect of the nature of the second task, $F(1, 32) = 0.47$, $p = .5$, indicating that overall, there was no difference in recall accuracy between participants who performed the color detection and discrimination tasks. The results also showed a highly significant interaction of SOA and the presence of a second task, $F(1, 32) = 20.97$, $p < .001$, $h_p^2 = .40$, indicating that the detrimental effect of both types of second tasks was stronger at the short than at the long SOA, and all other two-way interactions were close to significance (all Fs > 3.95, all ps $< .056$, and all h_p^2s $> .11$). Most important, the three-way interaction closely approximated statistical significance, $F(1, 32) = 4.00$, $p = .054$, $h_p^2 = .11$, reflecting that the retroactive interference effect was stronger in the color discrimination than in the color detection condition (see Figures 2A and 2B). Indeed, a planned between-experiment comparison of perfor-

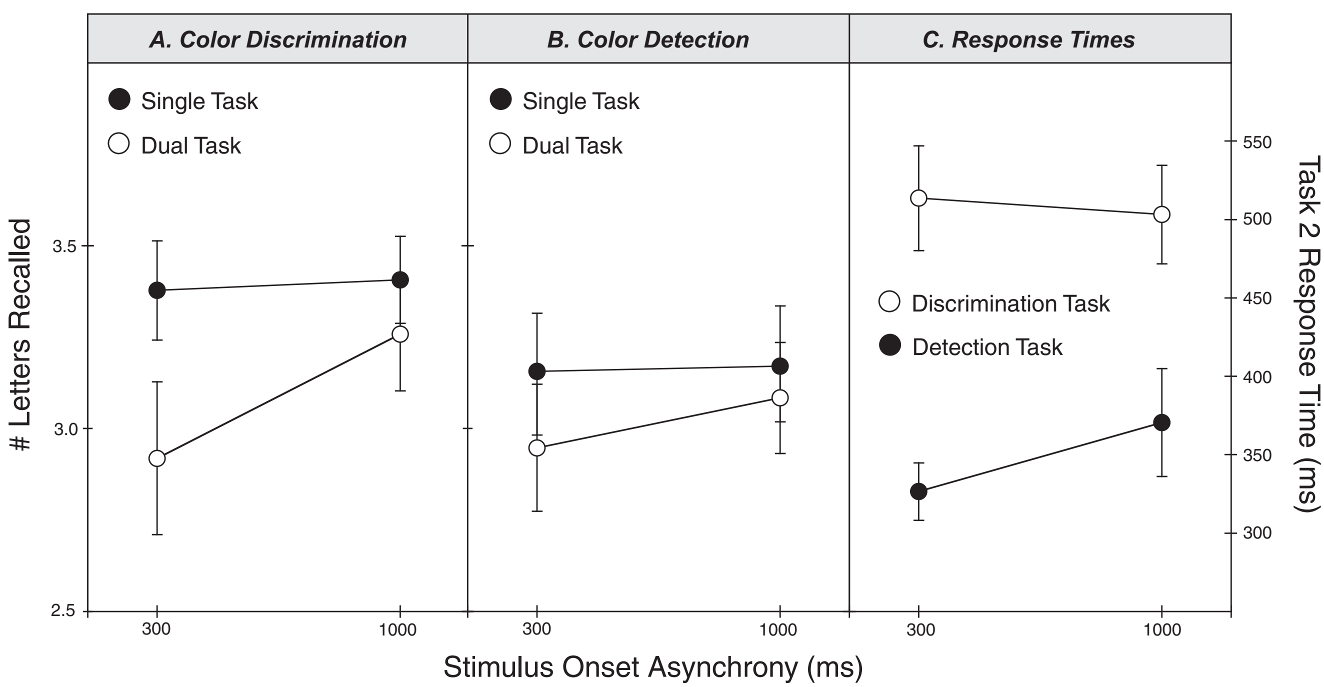

Figure 2. Results of Experiment 3. A. Performance in the memory task for participants in the color discrimination condition. The color discrimination task was present in the dual-task condition and absent in the single task condition. B. Performance in the memory task for participants in the color detection condition. The color detection task was present in the dual-task condition and absent in the single task condition. C. Response times for the color discrimination and detection tasks. Error bars show the *SE* of the mean.

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mance in the dual-task condition showed a significant interaction of SOA and the nature of the second task, $F(1, 32) = 5.21$, $p < .029$, $h^2_p = .14$, indicating that the effect of SOA was more pronounced in the condition with a color discrimination task than in the condition with a color detection task. Furthermore, a comparison of the dual-task interference effect at the 300-ms SOA showed that this interference effect was significantly stronger when the second task was a color discrimination task, $t(32) = 2.25$, $p = .032$.

The color detection and discrimination tasks. Responses for the color detection task were accurate on 100% of the trials, indicating that the colored square was impossible to miss due to the fact that the program would wait until a response to the square was registered. For the color discrimination task, responses were accurate on 89.8% of the trials, and response accuracy did not depend on SOA ($F < 1$). Response times on the detection and discrimination tasks were examined for effects of SOA and task. The results showed a significant main effect of task, $F(1, 32) = 15.34$, $p < .001$, $h^2_p = .32$, with the mean response times being 348.5 and 508.4 ms, respectively, for the color detection and discrimination tasks. In addition, there was a significant interaction of SOA and the nature of the task, $F(1, 32) = 5.09$, $p < .031$, $h^2_p = .14$ (see Figure 2C). This interaction was further explored by examining the effect of SOA for each task condition separately. These analyses showed that while there was a significant increase in response times across SOA in the color detection task, $F(1, 16) = 4.95$, $p < .041$, $h^2_p = .24$, there was no effect of SOA on response times in the color discrimination task ($F < 1$). Last, we examined if response times for the color discrimination task in the condition with a 300-ms SOA depended on the number of letters that could be recalled for the memory task. The results of this analysis corroborated those of the same analyses done for Experiments 1 and 2, as response times were again found to be independent of whether 0–2 or 3–4 letters could be recalled ($M = 532$ vs. $M = 555$ ms, respectively; $F < 1$).

Discussion. The results of Experiment 3 present two main findings of interest. To start, they show that the retroactive interference effect observed in Experiment 1 could be replicated with a different type of 2-AFC task than a speeded visual parity judgment task, namely, a speeded color discrimination task. Second, they show that the retroactive interference effect was significantly attenuated when the color discrimination task was changed to an easier color detection task that did not require response selection, whereas it did require the speeded execution of a response. Taken together, these findings attest to the generality of the retroactive interference effect observed in Experiments 1 and 2, and they make clear that the magnitude of this effect depends on the processing load and difficulty of the second task.

Experiment 4

While the results of Experiment 3 show that the processing load associated with the second task is an important determinant of the retroactive interference effect, Experiment 4 aimed to determine if the magnitude of this effect also depends on the amount of information that needs to be consolidated in working memory for the first task. To this end, we replicated the masked condition of Experiment 1 and varied the number of letters that had to be consolidated in memory for the memory task. Specifically, in half the trials, the memory display included two letters that were shown simultaneously for 50 ms, and followed by a 100-ms mask. In the other trials, the memory display included four letters that were shown for 100 ms and followed by a 100-ms mask. The reason for using a shorter exposure duration for the two-letter displays was that we anticipated that performance would be close to ceiling in case the two letters would be shown for 100 ms. As in Experiments 1 and 2, the second task was a speeded visual parity judgment task, and this task was present in half the trials.

Method.

Participants. A sample of 18 undergraduate students from the University of Groningen participated in Experiment 4 in return for course credit.

Materials, design, procedure, and data-analysis. The materials, design, procedure and data-preprocessing steps in Experiment 4 were similar to those of Experiment 1. The differences were that in Experiment 4, the memory display could comprise two or four letters that were followed by a mask comprising two or four hashtags and that the presentation duration of the memory display was set to 50 ms for the two-letters condition. Trials with two and four letters were randomly intermixed. Thus, the design of Experiment 4 comprised a 3 (SOA: 250, 500, or 1,000 ms) $\times$ 2 (consolidation load: two or four letters) $\times$ 2 (second task—a speeded visual parity judgment task—present vs. absent). The experiment consisted of a total of 240 trials, and it was preceded by 16 practice trials.

Results.

The memory task. The number of correctly recalled letters for the memory tasks with two and four letters are shown in Figure 3a. To examine these results, we first performed two separate repeated measures analyses of variance for the conditions with two and four letters. These two analyses yielded the same pattern of results, such that all main effects and the interaction of SOA and the presence of a second task were significant regardless of whether the memory set comprised two and four letters (all Fs > 3.49, all ps $< .042$, and all h^2_ps $> .17$). To compare the retroactive interference effects for the conditions with two and four letters, we computed the difference between the single and the dual-task conditions (data shown in Figure 3b) and then subjected the resulting difference scores to a 3×2 repeated-measures ANOVA that included SOA (250; 500; or 1,000 ms) and consolidation load (two vs. four letters) as factors. The results of this analysis showed that the main effects of SOA and consolidation load were significant, with Fs > 13.98, ps $< .001$, and h^2_ps $> .45$. In addition, the interaction of SOA and consolidation load was significant, $F(2, 34) = 3.67$, $p = .036$, $h^2_p = .18$. The results of pair-wise comparisons between the conditions with two and four letters showed that the dual-task interference effect was significantly stronger with a memory set of four letters than with a memory set of two letters, and this was true at the SOAs of 250 and 500 ms (both ts > 4.57, both ps $< .001$) but not at the 1,000-ms SOA, $t(17) = 1.64$, $p = .12$.

The parity judgment task. Responses for the parity judgment task were accurate on 92.3%, of the trials, and response accuracy did not show significant effects of SOA or consolidation load (all Fs < 1.45). The analysis of response times also showed no significant effects of these factors (all Fs < 2.0, all ps $> .14$; see Figure 3C). As in the previous experiments, we also examined if response times depended on performance for the memory task,

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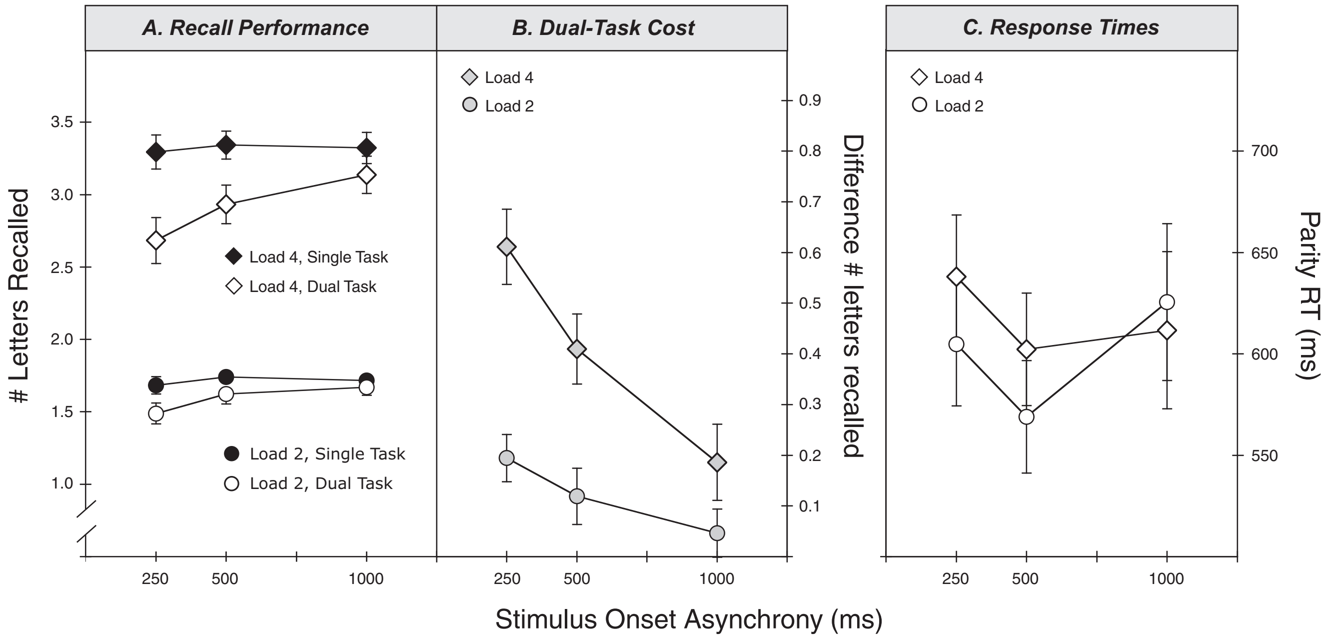

Figure 3. Results of Experiment 4. A. Performance in the memory task. B. Dual-task interference effect, defined in terms of the number of letters lost due to the presence of the parity judgment task. C. Response times (RTs) for the parity judgment task. Error bars show the *SE* of the mean.

focusing on trials with a consolidation load of four letters, and an SOA of 250 ms. The results of this analysis showed that response times for this condition did not differ significantly between trials in which 0–2 or 3–4 letters were correctly recalled (M = 671 vs. M = 651 ms, respectively; $F < 1$).

Discussion. The results of Experiment 4 show that the retroactive interference effect was attenuated when the consolidation load for the memory task was reduced from four to two letters. This finding is of importance because it suggests that the extent to which consolidation is vulnerable to interference from a trailing 2-AFC task depends on the amount of information that needs to be consolidated into working memory. Taken together with the results of Experiment 3, this finding shows that the occurrence and magnitude of the retroactive interference effect depend on both the difficulty of the second task and the consolidation load associated with the first task.

Experiment 5

In the previous experiments, the consolidation of verbal or nonverbal stimuli was found to be disrupted by trailing 2-AFC task requiring the speeded discrimination of a visual target (i.e., a digit or a colored square). If the cause of this interference effect lies in the amodal, central processing requirements for the 2-AFC task, it follows that a similar effect should be found if the target for this task would be presented in the auditory modality. The goal of Experiment 5 was to test this prediction. To this end, we conducted a second version of Experiment 2 to examine if the consolidation of a masked Kanji character would also be disrupted by a trailing speeded auditory parity judgment task.

Method.

Participants. A sample of 19 undergraduate students from the University of Groningen participated in Experiment 5 in return for course credit. All participants were native Dutch speakers.

Materials, design, procedure, and data-analysis. Experiment 5 was a replication of Experiment 2, with the following differences. To start, Experiment 5 was conducted at the University of Groningen, using a monitor set to 1,024 × 768 pixels and a refresh rate of 100 Hz. The primary difference with Experiment 2 was that in Experiment 5 the target for the second task was an auditory digit drawn from the set {1–6}. This digit was recorded in Dutch and compressed to a 93-ms presentation duration (see also Van der Burg, Brederoo, Nieuwenstein, Theeuwes, & Olivers, 2010), and it was presented over headphones, at a volume comfortable to the participant.

The design of Experiment 5 comprised a 2 × 2 within-subject design, including as factors the presence versus absence of the auditory parity judgment task, and the SOA separating the Kanji character and the presentation of the auditory target (300 or 1,000 ms). The Kanji character was shown for 100 ms, and followed by a 100-ms mask that comprised three overlapping Kanji characters. The other characteristics of the procedure were identical to the procedure used in Experiment 2. The experiment comprised a total of 96 trials, yielding 24 replications per SOA for the single and the dual-task conditions, and it started with 16 practice trials.

Results.

The memory task. Figure 4a shows recognition accuracy for the Kanji character for the single and dual-task conditions, with accuracy plotted as a function of SOA. A repeated measures analysis of variance showed that the main effect of SOA failed to reach significance, $F(1, 18) = 2.42$, $p = .14$, whereas the main effect of the presence vs. absence of the second task did reach significance, $F(1, 18) = 5.04$, $p = .038$, $h_p^2 = .22$. Most important, the results showed a significant interaction of SOA and the presence of the second task, $F(1, 18) = 4.62$, $p = .046$,

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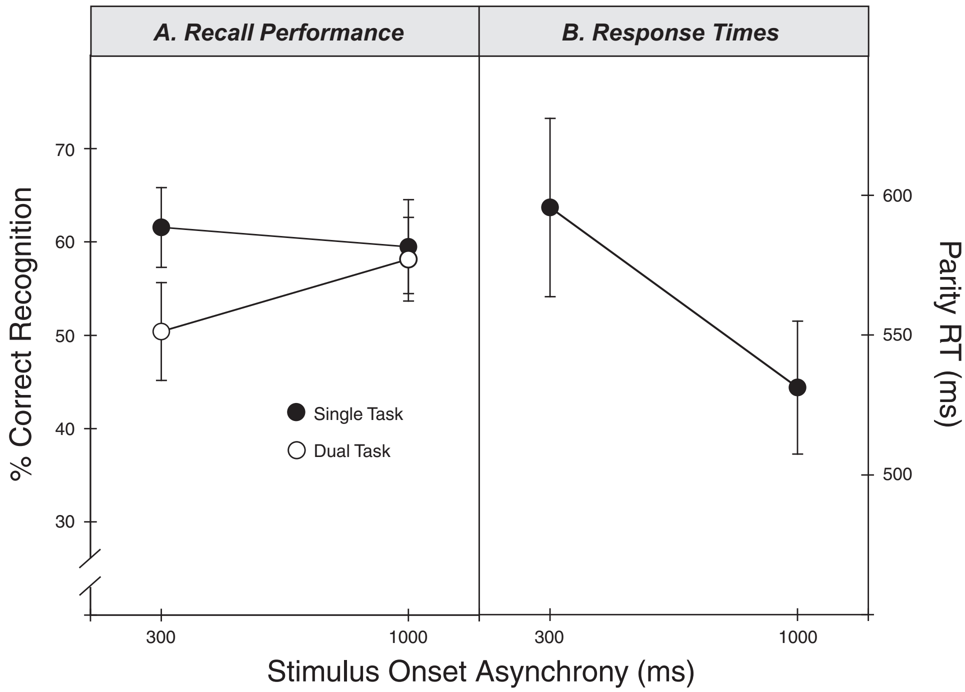

Figure 4. Results of Experiment 5. A. Recognition accuracy for the memory task. B. Response times (RTs) for the auditory parity judgment task. Error bars show the *SE* of the mean.

h_p^2 = .20. Recognition accuracy was significantly worse in the dual than in the single task condition at the 300-ms SOA, $t(18) = 2.68$, $p = .015$, but not at the 1,000-ms SOA, $t(18) = 0.46$.

The parity judgment task. Responses for the parity judgment task were accurate on 91.3%, of the trials, and response accuracy did not show a significant effect of SOA ($F < 1$). The analysis of response times did show a significant effect of SOA, $F(1, 18) = 7.95$, $p = .011$, $h_p^2 = .31$ (see Figure 4b), with responses being slower at the 300 than at the 1,000-ms SOA ($M = 591.15$ vs. $M = 526.77$ ms, respectively). However, response times for the 300-ms SOA condition did not depend on whether the Kanji character could be correctly recalled, with the average response times being 580 and 590 ms, respectively, for trials in which the response for the recognition test was correct or incorrect ($F < 1$).

Discussion. The results of Experiment 5 extend those of the previous experiments in showing that the processing of a first to-be-remembered stimulus (a masked Kanji character) can also be disrupted by means of a trailing auditory 2-AFC task. This finding shows that the retroactive interference effect seen in the previous studies did not stem from modality-specific interference between the processing of the visual to-be-remembered stimuli and the visual target for the trailing 2-AFC task. Rather, the results of Experiment 5 can be said to corroborate those of Experiment 3 in demonstrating that the retroactive interference effect appears to occur due to the engagement of amodal, central processing mechanisms for decision making and response selection in an 2-AFC task.

General Discussion

While studies on visual memory commonly assume that the consolidation of a stimulus into working memory stops when that stimulus is replaced by a backward mask, studies on dual-task interference suggest that consolidation can continue for hundreds of milliseconds after a mask. As a result of these opposing views, estimates of the time course of working memory consolidation (WMC) differ by more than an order of magnitude, hindering our understanding of phenomena wherein the dynamics and limits of WMC play a central role. To resolve this state of affairs, the current study aimed to adjudicate between the opposing views by examining if and for how long the processing of a to-be-remembered visual stimulus can still be disrupted after it has been masked, by a trailing 2-AFC task. The rationale guiding this approach was that if the consolidation of the stimulus is completed only sometime after the mask, then the requirement to decide and respond rapidly for the trailing 2-AFC task might cause interference with this still ongoing consolidation process. Consistent with this hypothesis, the results of five experiments showed that the ability to recognize or recall a visual stimulus (an unfamiliar, complex visual shape or a string of letters) is significantly impaired when this stimulus is followed within less than 1 s by the target for a speeded 2-AFC task (a visual or auditory parity judgment task, or a color discrimination task). To be precise, the current experiments showed that performance on the memory task improved as the SOA separating the to-be-remembered stimuli and the trailing 2-AFC task increased from 250–1,000 ms, suggesting that it took about 1 s of processing time before the stimuli had been consolidated into a durable working memory representation that

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could outlive the execution of the 2-AFC task.[6] Furthermore, this effect was found regardless of whether the stimulus had first been followed by a mask, though the presence of the mask did lead to lower performance on the memory task. Taken together, these findings suggest that although the appearance of the mask did restrict the amount of information that could be selected for consolidation in working memory, it did not interrupt the consolidation process itself, as this process could still be disrupted for up to several hundred milliseconds after a mask, by a trailing 2-AFC task.

Aside from demonstrating that a speeded 2-AFC task can disturb the formation of a durable (visual) working memory representation for up to several hundred milliseconds after a stimulus has been masked, the current experiments also identified two boundary conditions for this retroactive dual-task interference effect. Specifically, Experiment 4 showed that the magnitude of the retroactive interference effect was markedly attenuated when the consolidation load for the memory task was decreased from four to two letters, suggesting that the extent to which WMC is vulnerable to interference depends on the amount of information that is being consolidated. Second, the results of Experiment 3 showed that the retroactive interference effect was markedly attenuated when the second task was changed from a color discrimination task to a color detection task, thus suggesting that the cause of the retroactive interference stems from the requirement to make a rapid choice. Indeed, the results of Experiment 5 showed that the consolidation of a masked visual stimulus was also significantly disrupted by a trailing auditory 2-AFC task, thus providing additional evidence that the interference indeed derived from the engagement of amodal processing mechanisms required for decision making and response selection in the 2-AFC task.

While the current experiments consistently showed that a speeded 2-AFC task can interfere with memory for an earlier presented stimulus, they also showed remarkably little evidence for a concomitant proactive interference effect for the 2-AFC task. To be precise, the response times for the 2-AFC task were only slightly elevated at the shortest SOAs in Experiments 1, 2, and 5, and there was no significant effect of SOA on response times in Experiments 3 and 4. Furthermore, the results of Experiment 4 showed that response times were not significantly affected by whether the memory task required recall of two or four letters, indicating that the response time for the 2-AFC task was relatively independent of the processing load associated with the memory task. Indeed, the results of all five experiments showed that response times at the shortest SOAs were independent of performance on the memory task. Accordingly, it may be concluded that the processing required for the 2-AFC task was little affected by the consolidation of information for the memory task, as the 2-AFC task appeared to be executed without much delay even though the consolidation of the earlier shown stimuli was clearly not yet completed.

Relationship With Previous Findings

In demonstrating that the formation of a durable memory trace can be disturbed for up to 1 s after the appearance of a to-be-remembered stimulus, with little evidence for a concomitant proactive interference effect on the 2-AFC task that caused this disturbance, the current findings present a remarkably different pattern of results than that commonly seen in closely related previous work. To be precise, there have been several previous studies that combined a memory task with an ensuing speeded 2-AFC task, and the results of these studies typically show a pronounced psychological refractory period effect for the 2-AFC task and little to no retroactive interference for the memory task (Arnell & Duncan, 2002; Arnell et al., 2004; Jolicœur & Dell'Acqua, 1998, 1999; Koch & Rumiati, 2006; Ruthruff & Pashler, 2001; Stevanovski & Jolicœur, 2007, 2011; Tombu et al., 2011). Likewise, research on the attentional blink has yielded hundreds of studies that show a severe attentional blink deficit for recall of the second target, whereas recall of the first target is typically highly accurate (Dux & Marois, 2009; Martens & Wyble, 2010), although in some conditions, recall of the first target does show a slight impairment when the second target follows within 100 ms or less (e.g., Bowman & Wyble, 2007; Chun & Potter, 1995; see also Bachmann & Hommuk, 2005; Potter, Staub, & O'Connor, 2002). Last, the current findings can also be contrasted to those obtained in studies that examined whether the retention of information in working memory can be interfered with by means of a distractor stimulus or a second task, as the pattern of results obtained in these studies also differs in interesting regards from that observed in the current experiments. In the following sections, we elaborate on these matters as we review and compare the methods and findings of these three sets of previous studies to those of the current experiments.

Studies combining a memory task with a trailing 2-AFC task. As alluded to above, a remarkable aspect of the current findings is that the pattern of interference effects seen for the first and second task was opposite to the pattern commonly found in studies that combined a memory task with a trailing speeded 2-AFC task. To wit, the archetypal pattern of results in these previous studies is that response times for the 2-AFC task show a pronounced and protracted psychological refractory period effect (hereafter abbreviated as "PRP effect"), whereas performance on the memory task shows little to no evidence for retroactive interference (see Figure 5A; Arnell & Duncan, 2002; Arnell et al., 2004; Jolicœur & Dell'Acqua, 1998, 1999; Koch & Rumiati, 2006; Ruthruff & Pashler, 2001; Stevanovski & Jolicœur, 2007, 2011; Tombu et al., 2011). In contrast, the current experiments showed a pronounced and protracted retroactive interference effect, and they showed only a minor PRP effect for the 2-AFC task.

In accounting for this discrepancy, an important first consideration is that the above-described previous studies were focused primarily on characterizing the PRP effect for the second target. This is reflected in several aspects of the methods and analyses reported in these studies. For instance, some of these studies did not report an analysis of the effect of SOA on the memory task, and the studies that did examine this effect did not restrict the data to trials in which the response for the second task was correct,

[6] In an unpublished experiment similar to Experiment 1, we also included an SOA of 750 ms. The results replicated those of Experiment 1, and they showed that the interference effect produced by the 2-AFC task was significant at an SOA of 750 ms. Furthermore, this experiment also showed that performance in the dual-task condition improved significantly from an SOA of 750 ms to an SOA of 1,000 ms, indicating that it indeed seems to take up to 1 s to complete the consolidation of a string of four letters.

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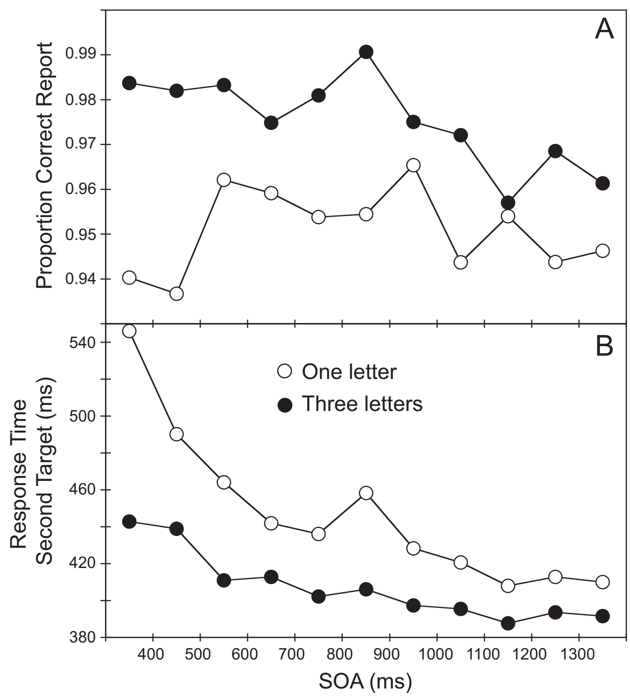

Figure 5. Results of Experiment 1 of Jolicœur and Dell'Acqua (1998). Participants had to memorize one or three letters that were shown for 250 ms and followed by a 100-ms pattern mask. The letters were followed by a speeded two-alternative pitch discrimination task. A. Proportion of trials in which all letters were correctly recalled. B. Response times for second task. SOA = stimulus onset asynchrony. Reprinted from "The Demonstration of Short-Term Consolidation," by P. Jolicœur & R. Dell'Acqua, 1998, *Cognitive Psychology, 36,* p. 146. Copyright 1998 by Elsevier.

which is desirable if one wants to assess if the processing of the second target—as evidenced by a correct response—interfered with the processing for the memory task. Likewise, the majority of these studies did not include a single-task control condition in which the memory task was performed without a trailing task, and the studies that did incorporate such a control condition used a blocked design, and this entails that any difference in performance could also reflect a strategic difference in resource allocation between the single and the dual-task conditions. Most important, however, many of the experiments in question used a memory task for which performance was very close to ceiling (i.e., above 93% correct; see, e.g., Figure 5A), and this could, in principle, obscure a retroactive interference effect. Indeed, the few experiments that did show a hint of retroactive interference all employed a memory task for which performance remained well below ceiling (Experiment 2 in Arnell & Duncan, 2002; Experiments 3 and 5 in Jolicœur and Dell'Acqua, 1998; Experiment 3 in Stevanovski & Jolicœur, 2007), highlighting the plausibility of the ceiling effect account. Indeed, it is also important to bear in mind that although the current experiments showed that the retroactive interference effect can be found across different combinations of memory and 2-AFC tasks, the magnitude of this effect was also found to depend on the consolidation load for the first task, and the decision-making requirements for the second task. Accordingly, it may be concluded that while the retroactive interference effect is a robust and replicable effect,[7] the manifestation of this effect does require a sufficiently demanding first and second task.

While the use of an easy memory task may thus account for the lack of retroactive interference in previous studies, it is not immediately clear why the use of an easy memory task would also give rise to a stronger PRP effect than a more difficult memory task, such as that used in the current study. Indeed, the magnitude of the PRP effect is typically found to be stronger—not weaker—when the consolidation load for a memory task is increased by increasing the number of to-be-remembered letters (e.g., Jolicœur & Dell'Acqua, 1998, 1999; Tombu et al., 2011), a finding that was not replicated in Experiment 4 of the current study. Interestingly, however, the effect of consolidation load on the PRP effect appears to depend on whether participants can use verbal coding in memorizing the to-be-remembered items (Stevanovski & Jolicœur, 2007). Specifically, Stevanovski and Jolicœur (2007) showed that the effect of consolidation load that was found by Tombu et al. (2011) and Jolicœur and Dell'Acqua (1998, 1999) could not be replicated when participants concurrently performed an articulatory suppression task, thus suggesting that an increase in the number of to-be-remembered items only leads to a stronger PRP effect if those items can be articulated during encoding. Furthermore, although Stevanovski and Jolicœur did not include a condition without articulatory suppression, a comparison with a highly similar experiment by Jolicœur and Dell'Acqua (1998) suggested that the magnitude of the PRP effect seems to be attenuated overall when articulatory suppression is performed.

The idea that verbal coding might lead to a stronger PRP effect offers an interesting explanation for why the current experiments did not show a strong PRP effect. To wit, it can be argued that verbal coding was much less likely to occur in the current experiments than in the experiments that did show a pronounced PRP effect because the to-be-remembered stimuli were presented for only 100 ms in the current experiments, whereas they were presented for 250 ms in the previous experiments (Jolicœur & Dell'Acqua, 1998, 1999; Tombu et al., 2011). As suggested by Stevanovski and Jolicœur (2007), verbal coding is more likely to occur with longer display durations—if only because phonological codes are not activated instantaneously upon the appearance of a stimulus (see also Ferrand & Grainger, 1993)—thus offering a possible explanation for why the current experiments did not show a strong PRP effect. Indeed, it is also of interest to note that Experiments 1 and 2 showed that a memory task with verbal (i.e., letters) and nonverbal stimuli (a complex visual shape—the Kanji character) led to a comparable PRP effect, suggesting that the use of a short exposure indeed prevented verbal coding as one would otherwise expect a stronger PRP effect for the experiment with letter targets. Taken together, these considerations lead us to hypothesize that the reason why the current experiments did not show a strong PRP effect is because the use of a short and masked exposure precluded the use of verbal coding in memorizing the target stimuli.

[7] In an as yet unpublished series of studies, we found that the retroactive interference effect also occurs when a to-be-reported sequence of letters—shown in rapid serial visual presentation—is followed by a 2-AFC task (Nieuwenstein & Wyble, 2013), which is worth mentioning as it underscores the generality of the effect.

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Studies on the attentional blink. A second set of studies that present a markedly different pattern of results than that seen in the current study can be found in studies in which participants were asked to report two target stimuli (e.g., letters) that were embedded in a rapid sequence of distractors (e.g., digits). To wit, the typical pattern of results obtained in these experiments is that performance on the second target suffers a pronounced attentional blink effect, whereas performance on the first target is relatively accurate, unless it is followed within less than about 100 ms by the second target (see Figure 6; Dux & Marois, 2009; Martens & Wyble, 2010). In accounting for this pattern of results, it is often assumed that the attentional blink effect for the second target reflects an interference effect that is caused by the consolidation of the first target, with one proposal being that the consolidation of the first target results in an attentional blink because it involves a slow and immutable processing bottleneck (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Shih, 2008), whereas another proposes that the consolidation of the first target results in an attentional blink because it leads to a momentary lack of attention for newly encountered stimuli (e.g., Bowman & Wyble, 2007; Wyble et al., 2009, 2011; see also Taatgen et al., 2009). According to both accounts, the initial "sparing" effect seen for second-target recall at an SOA of 100 ms occurs because the selection of information for consolidation in working memory occurs during an attentional episode that is initiated upon detection of the first target and that lasts approximately 100–200 ms, thus allowing a second target to be selected for consolidation in the slipstream of the first target.

In relating the current findings to those obtained in the attentional blink paradigm, an interesting question is whether the retroactive interference effect seen in the present experiments could be due to a similar mechanism as the first-target impairment seen at an SOA of 100 ms in the attentional blink paradigm. The answer is that this is highly unlikely because the latter first-target impairment is only found in combination with a sparing effect for the second target, and this combination of results is in turn only found when the temporal, and featural similarity of the two targets is high. To be precise, the results of studies on the attentional blink rarely show a first-target impairment if the two targets are presented at an SOA of more than 100 ms (e.g., Arnell & Jolicœur, 1999; Nieuwenstein, Potter, & Theeuwes, 2009; Nieuwenstein, Van der Burg, Theeuwes, Wyble, & Potter, 2009; but see Hommel & Akyurek, 2005, for an interesting exception), when they are drawn from different stimulus categories (e.g., Juola, Botella, & Palacios, 2004), or when they are presented in different modalities (e.g., Potter, Chun, Banks, & Muckenhoupt, 1998; see also Visser, Bischof, & Di Lollo, 1999). In contrast, the retroactive interference effect seen in the current experiments occurred across SOAs of up to 500 ms, it occurred after a mask, and it occurred across different combinations of modalities, target categories, and tasks. Accordingly, it may be concluded that while the first-target impairment seen in the attentional blink paradigm reflects a cost that is specific to tightly circumscribed conditions in which the two targets can be selected and consolidated in parallel, the retroactive interference effect found in the current experiments may be better explained in terms of a disruption of an already initiated consolidation process for the first target.

A second question that may be asked with regard to studies on the attentional blink is why these studies do not show a more pronounced and protracted retroactive interference effect such as that observed in the current experiments. There are two reasons why this effect may rarely be found in the attentional blink paradigm. The first derives from the current finding that the magnitude of retroactive interference was markedly attenuated when the consolidation load for the memory task was reduced from four to two letters. Since the targets used in the attentional blink paradigm typically each comprise only a single familiar stimulus such as a letter or a digit, it stands to reason that the consolidation load imposed by such a first target may simply be too low to render its consolidation vulnerable to interference from a trailing target. Furthermore, it also stands to reason that the second target in the attentional blink paradigm—which typically comprises a single letter or a digit that is embedded among distractor stimuli—is much less likely to "breakthrough" the attentional blink and perturb the ongoing consolidation of an earlier target than an unmasked target that appears abruptly on a blank screen and that requires a rapid decision and response. Indeed, it is of interest note that the only study on the attentional blink that found a strong and protracted retroactive interference effect involved a study in which the consolidation load was high (i.e., participants had to recall a string of five digits or letters in the correct order) and in which the second target was highly salient (i.e., the second target also comprised a string of five characters, but it depicted the same letter or digit five times in a row, for example: "EEEEE"; Ouimet & Jolicœur, 2007). Accordingly, it may be concluded that the reason why studies on the attentional blink typically show little evidence for retroactive interference beyond an SOA of 100 ms lies in the combination of a relatively low consolidation load for the first target and the use of a weak and relatively unobtrusive second target.

Studies showing interference during memory retention. A last set of findings that is of interest to the interpretation of the current findings stems from studies that examined the extent to which information retained in working memory may be vulnerable to interference from a trailing stimulus or task. To wit, there are

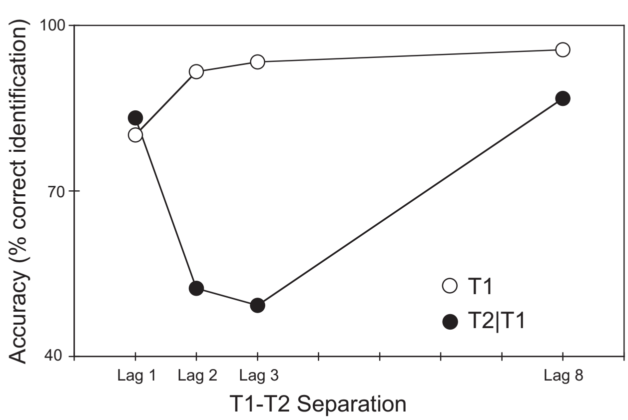

Figure 6. Archetypal pattern of results for recall of the first (T1) and second target (T2) in the attentional blink paradigm, with performance for T2 shown only for trials on which recall of T1 was correct (T2|T1). The lag variable on the *x*-axis denotes the temporal position of T2 in steps of 100 ms. Reprinted from "The Attentional Blink: Past, Present, and Future of a Blind Spot in Perceptual Awareness," by S. Martens and B. Wyble, 2010, *Neuroscience and Biobehavioral Reviews, 34,* p. 948. Copyright 2010 by Elsevier.

several studies that show that the execution of a second task can interfere with memory for one or more stimuli that were presented several seconds earlier (Barrouillet et al., 2004, 2007; Ricker & Cowan, 2010; see also Ueno, Allen, Baddeley, Hitch, & Saito, 2011), and there have also been several studies that found that a distractor can interfere with retention of a similar stimulus shown 1–5 s earlier (e.g., Magnussen & Greenlee, 1999; Magnussen, Greenlee, Asplund, Dyrnes, 1991; Vuontela, Rämä, Raninen, Aronen, & Carlson, 1999).

An interesting and important difference between these findings and those of current experiments, however, is that the interference effects follow a markedly different time course. This is perhaps most clearly illustrated by comparing the results of Experiments 1, 3, and 4 of the current study to those reported by Ricker and Cowan (2010; see Figure 7). In the study by Ricker and Cowan participants performed a speeded auditory parity judgment task for a target that was presented 1.5–6.0 s after the appearance of a to-be-remembered array of letters. As can be seen in Figure 7, the presence of the parity judgment task interfered with memory, but this interference effect increased as SOA increased from 1.5 to 6 s. In contrast, the retroactive interference effect observed in the current experiments decreased as SOA increased from 250–1,000 ms. Thus, whereas the results of Ricker and Cowan suggest that information retained in working memory becomes increasingly *more* vulnerable to interference across a seconds-long retention interval, the current findings show that a memory trace initially becomes increasingly *less* vulnerable to interference as the period of time available for WMC increases from 250–1,000 ms. By implication, the retroactive interference effects seen in the current study cannot be explained by assuming that the consolidation of the stimuli was already completed before the 2-AFC task and that the interference arose during the retention—as opposed to the consolidation—of information in working memory.

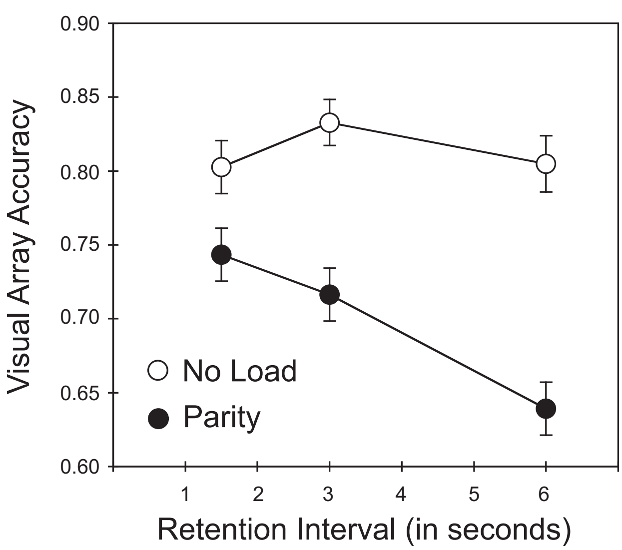

Figure 7. Retroactive interference during the retention phase of a working memory task. Recognition performance for an array of letters is shown as a function of the duration of the retention interval for the memory task. In the "Parity" condition, the retention interval was followed by the target for an auditory parity judgment task. In the No Load condition, there was no second task. Error bars show *SE*. Adapted from "Loss of Visual Working Memory Within Seconds: The Combined Use of Refreshable and Non-Refreshable Features," by T. J. Ricker and N. Cowan, 2010, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36,* p. 1362. Copyright 2011 by the American Psychological Association.

Synthesis and conclusions. In summary, it can be concluded that the current experiments are the first to demonstrate that the process of consolidating visual information into working memory can be disrupted by a trailing task. As is indicated by the results from studies on the attentional blink, a stimulus that has been selected for consolidation is no longer as easily disturbed as it is during the first 100 ms of processing, but the current findings make clear that such a disturbance does occur when consolidation load is high, and when the second task involves an unmasked target for a speeded discrimination task. Thus, the current findings not only present a compelling argument against the idea that the consolidation of a visual stimulus is interrupted by a mask, but they also present an important novel challenge to theories of dual-task interference that have taken the results from previous studies to suggest that WMC involves an immutable information processing bottleneck (e.g., Jolicœur & Dell'Acqua, 1998, 1999; Marois & Ivanoff, 2005; Tombu et al., 2011; Zylberberg et al., 2010, 2011).

A Possible Account of the Current Findings

Last, we consider a possible account of how WMC operates, how it might continue after a mask and how it might be disturbed by a trailing 2-AFC task, especially when the amount of to-be-consolidated information is relatively high. In addressing these matters, we use the episodic simultaneous type—serial token (eSTST) model proposed by Wyble and colleagues as our starting point (Wyble et al., 2009; see also Bowman & Wyble, 2007). This model is a neural network implementation of a theory of attention and WMC, which has been shown to be capable of simulating both behavioral and electrophysiological indices of attentional selection and memory consolidation in the attentional blink, and a number of related phenomena (e.g., Craston, Wyble, Chennu, & Bowman, 2009; Dell'Acqua, Wyble, Dux, & Jolicœur, 2012; Lagroix et al., 2012; Spalek, Lagroix, Yanko, & Di Lollo, 2012; Wyble et al., 2011). Furthermore, in comparison to other accounts of the role of WMC in dual-task interference (e.g., Chun & Potter, 1995; Dehaene, Sergent, & Changeux, 2003; Jolicœur & Dell'Acqua, 1998; Shih, 2008; Taatgen et al., 2009; see also Zylberberg et al., 2010), the eSTST account appears especially well suited to explain the current findings because it is the only account that does not assume that WMC involves an immutable serial processing bottleneck, and it also offers a mechanism that can explain how consolidation may be disturbed by a trailing target. In the following sections, we first present the architecture and assumptions of the model, and then turn to the insights the model offers for explaining the current findings.

Architecture and assumptions of the eSTST model. In accordance with most accounts of visual information processing, the eSTST model distinguishes between sensory processing mechanisms that operate rapidly in representing visual stimuli (the first stage, labeled as "input" in Figure 8), a mechanism of WMC that operates more slowly (the second stage, labeled as "encoding" in Figure 8), and an attentional enhancement mechanism that can facilitate the transfer of potentially task-relevant stimuli between

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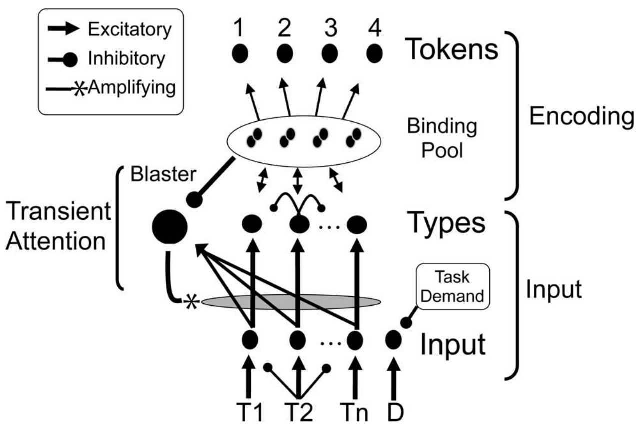

Figure 8. The eSTST model of attention and working memory consolidation. The model includes an input layer that provides the input to a mechanism of attentional enhancement, called the blaster, and a mechanism of working memory consolidation, denoted as encoding. For the input layer, "T" denotes target, that is, a to-be-remembered stimulus, whereas "D" denotes distractor. Adapted from "The Attentional Blink Provides Episodic Distinctiveness: Sparing at a Cost," by B. Wyble, H. Bowman, & M. R. Nieuwenstein, 2009, *Journal of Experimental Psychology: Human Perception and Performance, 35,* p. 791. Copyright 2009 by the American Psychological Association.

these two stages of processing (the so-called blaster, labeled as "transient attention" in Figure 8).

Stage 1: Activation of types and modulation by attention. The workings of the model are such that when a to-be-remembered stimulus is presented, this triggers a cascade of activation from the input layer into the type layer, mirroring the rapid feedforward activation of high-level representations along the ventral visual pathway (e.g., Keysers et al., 2001; Logothetis & Sheinberg, 1996). Transfer of activation along this feedforward pathway can be enhanced by a transient attention mechanism that produces a temporary enhancement of visual processing upon detection of a (potentially) task-relevant stimulus (see also Chun & Potter, 1995; Nakayama & Mackeben, 1989; Olivers & Meeter, 2008), and such enhancement plays an important role in the encoding of a masked visual stimulus. To wit, according to the eSTST model, consolidation is initiated only once the activation of a type node reaches a threshold of activation, and the effect of a mask is to curtail the accumulation of this activation (cf. Kovács et al., 1995; Rolls et al., 1999; see also Breitmeyer & Ogmen, 2000). Hence, the initiation of encoding for a masked stimulus depends on the extent to which its representation can be strengthened by attentional enhancement (see also Dehaene et al., 2006; Shih, 2008).

Stage 2: Encoding by binding types to tokens. Once a type node reaches the threshold of activation, encoding is initiated. The encoding process is implemented as a binding process wherein a link is established between a type and a token. Similar to the item-position units assumed in models of serial recall tasks (e.g., Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Oberauer et al., 2012), and similar to prefrontal cortex neurons that are found to show sustained stimulus-selective responses during working memory maintenance (e.g., Fuster & Alexander, 1971; Miller et al., 1996), the tokens in eSTST can be considered as episodic markers that are capable of sustaining their activation over time and that can store information about a perceived stimulus by means of being linked to the type nodes that represent that stimulus. The establishment of such a link occurs by means of recurrent interactions within an intermediate binding pool, which includes nodes that can be activated by types and that can in turn activate a token. During this binding process, the activation of a type is sustained by means of recurrent activations until a token enters a self-sustaining state that supports the retention and retrieval of the associated type at a later point in time.

Parallel encoding of multiple types. In simulating the encoding of several items, as would be required for the current experiments involving a display of two or four letters, the eSTST model assumes that those letters that produce sufficient activation in the corresponding type nodes are admitted to the consolidation stage, thus resulting in the parallel consolidation of these letters. In this regard, the model differs from most other accounts of WMC, which typically assume that consolidation involves a slow and serial process (e.g., Chun & Potter, 1995; Dehaene et al., 2003; Shih, 2008; Taatgen et al., 2009; see also Zylberberg et al., 2010). Importantly, however, this is *not* to say that eSTST assumes no limit to the consolidation of information in working memory. Rather, the model includes two mechanisms that limit the encoding of visual information in working memory. The first is that the consolidation of a stimulus is assumed to result in a *suppression of attention* for newly perceived stimuli, thus resulting in an attentional blink in case such a stimulus is shown briefly and followed by a mask. A second limitation arises due to *interference* between co-active types. As a result of this interference, the activation that feeds the type-token binding process will be weakened when multiple items are being consolidated into WM in parallel, thus resulting in a less efficient consolidation process (see also Dell'Acqua et al., 2012; Wyble et al., 2011).

Explaining the current findings: Insights from the eSTST model. In proposing that WMC occurs by means of a recurrent process wherein types are linked to tokens, the eSTST model offers a straightforward explanation for how consolidation could continue after a stimulus is masked. To wit, if a stimulus is masked, the appearance of a mask may indeed interrupt the feedforward activation of the type nodes that represent the stimulus, but the activation of these type nodes can be sustained through the recurrent interactions that mediate the binding to a token. In other words, the model assumes that consolidation can continue after a mask, because the binding process that mediates consolidation sustains the activation of the corresponding type until its consolidation is completed (see also Shih, 2008; Taatgen et al., 2009; Zylberberg et al., 2010). Furthermore, the model also suggests a reason why consolidation may become especially prone to retroactive interference when the amount of to-be-consolidated information is high. Specifically, in assuming that consolidation can occur for multiple types in parallel, though at the expense of mutual interference between co-active types, the model effectively proposes that the representation of a to-be-encoded stimulus will be weakened when it is encoded in parallel with other stimuli. As a result, the consolidation of a stimulus would be expected to become increasingly vulnerable to interference as the number of to-be-consolidated stimuli increases. Last, the model also offers insight into why the current studies yielded evidence for retroactive, whereas this effect has thus far not been found in so many previous studies on the attentional blink. To wit, since the model

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assumes that the consolidation of a first stimulus leads to an attentional blink by means of causing a momentary suppression of attention for newly encountered stimuli, a first requirement for any type of retroactive interference with the consolidation of a first target would be that the second target “breaks through” this attentional blink effect. In the current experiments, such a breakthrough effect could occur because, unlike the second target in an attentional blink task, the second target in our experiments was neither embedded among distractors nor followed by a mask. As a result, the second target’s representation could achieve sufficient strength to allow it to be processed despite the suppression of attention, thus resulting in interference with the ongoing consolidation of the earlier shown stimuli.

What remains to be explained then is how a 2-AFC task may perturb the ongoing consolidation of an earlier shown stimulus. While the mechanisms of attention and WMC proposed by eSTST offer important guidance for understanding how consolidation can continue after a mask, and why it may be vulnerable to interference from a trailing task, the model in its current form does not directly offer an account for the retroactive interference effect as found in the current experiments. In considering how such interference might arise, we can nevertheless conceive of two possibilities (cf. Tombu & Jolicœur, 2005). The first adheres to the notion of a central bottleneck and proposes that since WMC and response selection cannot be performed in parallel, it must be the case that the response selection task interrupted the ongoing consolidation of the earlier stimuli. An interesting perspective on why these two tasks cannot be performed in parallel can be found in recent modeling work by Zylberberg et al. (2010), who proposed a neural-network model of the PRP effect that was also found to be capable of simulating performance in a memory-consolidation task. An important assumption of this model is that it proposes that response selection and WMC both rely on the same neural network, which imposes a serial processing bottleneck because its configuration can only support one of these two tasks at a time. Thus, according to this account, the current finding of a retroactive interference effect could be explained in terms of a process-interruption or task-switching effect, the idea being that the appearance of the target for the 2-AFC task would trigger the reconfiguration of the processing network, thus effectively causing the ongoing consolidation process to be aborted. While intuitively appealing, it is important to note that this account has difficulty in explaining why a color discrimination task produces a much stronger retroactive interference effect than a color detection task, as both these tasks would seem to require a reconfiguration of the processing network. Furthermore, it is also unclear how this account could accommodate the findings by Ouimet and Jolicœur (2007), who showed that an unspeeded target identification task can also produce retroactive interference with the consolidation of an earlier stimulus. Evidently, if the retroactive interference were due to the requirement to switch between two different types of tasks, one would not expect this effect to occur when the two tasks each require the same type of processing.

An alternative account that does offer an explanation for these results adheres more closely to the eSTST model and proposes that the retroactive interference effect may be a consequence of interference between the type representations that are activated by processing the targets for the two tasks (Wyble et al., 2009, 2011; see also Bowman & Wyble, 2007). Specifically, it could be argued that a 2-AFC task also involves the activation of a type, such that the activation of a type would drive the accumulation of evidence in a drift diffusion process that eventually results in the selection and activation of a response that is associated with that type (e.g., Ratcliff & Rouder, 2000). From such an extension of the eSTST model, it follows that the retroactive interference effect could arise as a consequence of interference among co-active types, the idea being that the strong activation of the type for the highly salient 2-AFC target would lower the activation of the types for the preceding items that are already in the consolidation pipeline, thus resulting in a loss of some of this information. In comparison to the process-interruption account, this account has the benefit that it can more easily explain why a color discrimination task produces a stronger retroactive interference effect than a color detection task, as the duration of type-activation would be longer in a discrimination task, and this would increase the amount of interference within the type layer. Furthermore, this account also naturally explains why an unspeeded identification task could also produce retroactive interference (Ouimet & Jolicouer, 2007), as the second target for this task would also be expected to produce interference within the type layer.

Conclusion

In conclusion, the current study is the first to show that the consolidation of a visual stimulus can be disturbed for several hundred milliseconds after a mask by a trailing 2-AFC task. This finding provides compelling evidence that WMC is not terminated when a visual stimulus is backward masked, and it provides compelling evidence against the long-standing view that consolidation involves an immutable processing bottleneck. Aside from these important conclusions, this finding raises many interesting new questions for research, as it remains to be determined how the retroactive interference effect can best be explained, and how it relates to other phenomena in research on working memory and dual-task performance.

References

Arnell, K. M., & Duncan, J. (2002). Separate and shared sources of dual-task cost in stimulus identification and response selection. *Cognitive Psychology, 44,* 105–147. doi:10.1006/cogp.2001.0762

Arnell, K. M., Helion, A. M., Hurdelbrink, J. A., & Pasieka, B. (2004). Dissociating sources of dual-task interference using human electrophysiology. *Psychonomic Bulletin & Review, 11,* 77–83. doi:10.3758/BF03206464

Arnell, K. M., & Jolicœur, P. (1999). The attentional blink across stimulus modalities: Evidence for central processing limitations. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 630–648. doi:10.1037/0096-1523.25.3.630

Averbach, E., & Coriell, A. S. (1961). Short-term memory in vision. *Bell System Technical Journal, 40,* 309–328. doi:10.1002/j.1538-7305.1961.tb03987.x

Bachmann, T., & Hommuk, K. (2005). How backward masking becomes attentional blink: Perception of successive in-stream targets. *Psychological Science, 16,* 740–742. doi:10.1111/j.1467-9280.2005.01604.x

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology, 63,* 1–29. doi:10.1146/annurev-psych-120710-100422

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adult’s working memory spans. *Journal of Experi-*

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mental Psychology: General, 133, 83–100. doi:10.1037/0096-3445.133.1.83

Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 570–585. doi:10.1037/0278-7393.33.3.570

Bays, P. M., Gorgoraptis, N., Wee, N., Marshall, L., & Husain, M. (2011). Temporal dynamics of encoding, storage, and reallocation of visual working memory. *Journal of Vision, 11,* Article no. 6. doi:10.1167/11.10.6

Bowman, H., & Wyble, B. (2007). The simultaneous type, serial token model of temporal attention and working memory. *Psychological Review, 114,* 38–70. doi:10.1037/0033-295X.114.1.38

Breitmeyer, B. G., & Ogmen, H. (2000). Recent models and findings in visual backward masking: A comparison, review, and update. *Perception & Psychophysics, 62,* 1572–1595. doi:10.3758/BF03212157

Bundesen, C. (1990). A theory of visual-attention. *Psychological Review, 97,* 523–547. doi:10.1037/0033-295X.97.4.523

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. doi:10.1037/0096-1523.21.1.109

Craston, P., Wyble, B., Chennu, S., & Bowman, H. (2009). The attentional blink reveals serial working memory encoding: Evidence from virtual and human event-related potentials. *Journal of Cognitive Neuroscience, 21,* 550–566. doi:10.1162/jocn.2009.21036

Davelaar, E. J., Goshen-Gottstein, Y., Ashkenazi, A., Haarmann, H. J., & Usher, M. (2005). The demise of short-term memory revisited: Empirical and computational investigations of recency effects. *Psychological Review, 112,* 3–42. doi:10.1037/0033-295X.112.1.3

Dehaene, S., Changeux, J. P., Naccache, L., & Sackur, J. (2006). Conscious, preconscious, and subliminal processing: A testable taxonomy. *Trends in Cognitive Sciences, 10,* 204–211. doi:10.1016/j.tics.2006.03.007

Dehaene, S., Sergent, C., & Changeux, J. P. (2003). A neuronal network model linking subjective reports and objective neurophysiological data during conscious perception. *Proceedings of the National Academy of Science of the United States, 100,* 8520–8525. doi:10.1073/pnas.1332574100

De Jong, R., & Sweet, J. B. (1994). Preparatory strategies in overlapping-task performance. *Perception & Psychophysics, 55,* 142–151. doi:10.3758/BF03211662

Dell'Acqua, R., Dux, P. E., Wyble, B., & Jolicœur, P. (2012). Sparing from the attentional blink is not spared from structural limitations. *Psychonomic Bulletin & Review, 19,* 232–238. doi:10.3758/s13423-011-0209-3

Dux, P. E., & Marois, R. (2009). The attentional blink: A review of data and theory. *Attention, Perception, & Psychophysics, 71,* 1683–1700. doi:10.3758/APP.71.8.1683

Enns, J. T., & Di Lollo, V. (2000). What's new in visual masking? *Trends in Cognitive Sciences, 4,* 345–352. doi:10.1016/S1364-6613(00)01520-5

Ferrand, L., & Grainger, J. (1993). The time course of orthographic and phonological code activation in the early stages of visual word recognition. *Bulletin of the Psychonomic Society, 31,* 119–122.

Fuller, R. L., Luck, S. J., McMahon, R. P., & Gold, J. M. (2005). Working memory consolidation is abnormally slow in schizophrenia. *Journal of Abnormal Psychology, 114,* 279–290. doi:10.1037/0021-843X.114.2.279

Fuster, J. M., & Alexander, G. E. (1971). Neuron activity related to short-term memory. *Science, 173,* 652–654. doi:10.1126/science.173.3997.652

Gegenfurtner, K. R., & Sperling, G. (1993). Information transfer in iconic memory experiments. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 845–866. doi:10.1037/0096-1523.19.4.845

Grill-Spector, K., & Kanwisher, N. (2005). Visual recognition: As soon as you know it is there, you know what it is. *Psychological Science, 16,* 152–160.

Hommel, B., & Akyurek, E. G. (2005). Lag-1 sparing in the attentional blink: Benefits and costs of integrating two events into a single episode. *The Quarterly Journal of Experimental Psychology, 58,* 1415–1433.

Jolicœur, P., & Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology, 36,* 138–202. doi:10.1006/cogp.1998.0684

Jolicœur, P., & Dell'Acqua, R. (1999). Attentional and structural constraints on visual encoding. *Psychological Research, 62,* 154–164. doi:10.1007/s004260050048

Jonides, J., Lewis, R. L., Nee, D. E., Lustig, C., Berman, M. G., & Moore, K. S. (2008). The mind and brain of short-term memory. *Annual Review of Psychology, 59,* 193–224. doi:10.1146/annurev.psych.59.103006.093615

Juola, J. F., Botella, J., & Palacios, A. (2004). Task- and location-switching effects on visual attention. *Perception & Psychophysics, 66,* 1303–1317. doi:10.3758/BF03195000

Kahneman, D. (1968). Method, findings, and theory in studies of visual masking. *Psychological Bulletin, 70,* 404–425. doi:10.1037/h0026731

Keysers, C., Xiao, D. K., Foldiak, P., & Perrett, D. I. (2001). The speed of sight. *Journal of Cognitive Neuroscience, 13,* 90–101. doi:10.1162/089892901564199

Koch, I., & Rumiati, R. I. (2006). Task-set inertia and memory-consolidation bottleneck in dual tasks. *Psychological Research, 70,* 448–458. doi:10.1007/s00426-005-0020-8

Kovács, G., Vogels, R., & Orban, G. A. (1995). Cortical correlate of pattern backward masking. *PNAS Proceedings of the National Academy of Sciences of the United States of America, 92,* 5587–5591. doi:10.1073/pnas.92.12.5587

Lagroix, H. E. P., Spalek, T. M., Wyble, B., Jannati, A., & Di Lollo, V. (2012). The root cause of the attentional blink: First-target processing or disruption of input control? *Attention, Perception, & Psychophysics, 74,* 1606–1622. doi:10.3758/s13414-012-0361-5

Logothetis, N. K., & Sheinberg, D. L. (1996). Visual object recognition. *Annual Review of Neuroscience, 19,* 577–621. doi:10.1146/annurev.ne.19.030196.003045

Magnussen, S., & Greenlee, M. W. (1999). The psychophysics of perceptual memory. *Psychological Research, 62,* 81–92. doi:10.1007/s004260050043

Magnussen, S., Greenlee, M. W., Asplund, R., & Dyrnes, S. (1991). Stimulus-specific mechanisms of visual short-term memory. *Vision Research, 31,* 1213–1219. doi:10.1016/0042-6989(91)90046-8

Marois, R., & Ivanoff, J. (2005). Capacity-limitations of information processing in the brain. *Trends in Cognitive Sciences, 9,* 296–305. doi:10.1016/j.tics.2005.04.010

Martens, S., & Wyble, B. (2010). The attentional blink: Past, present, and future of a blind spot in perceptual awareness. *Neuroscience and Biobehavioral Reviews, 34,* 947–957. doi:10.1016/j.neubiorev.2009.12.005

Marti, S., Sigman, M., & Dehaene, S. (2012). A shared cortical bottleneck underlying attentional blink and psychological refractory period. *NeuroImage, 59,* 2883–2898. doi:10.1016/j.neuroimage.2011.09.063

Miller, E. K., Erickson, C. A., & Desimone, R. (1996). Neural mechanisms of visual working memory in prefrontal cortex of the macaque. *The Journal of Neuroscience, 16,* 5154–5167.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29,* 1631–1647. doi:10.1016/0042-6989(89)90144-2

Nieuwenstein, M. R., Potter, M. C., & Theeuwes, J. (2009). Unmasking the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 159–169. doi:10.1037/0096-1523.35.1.159

Nieuwenstein, M., Van der Burg, E., Theeuwes, J., Wyble, B., & Potter, M. (2009). Temporal constraints on conscious vision: On the ubiquitous nature of the attentional blink. *Journal of Vision, 9*, Article no. 18. doi:10.1167/9.9.18

Nieuwenstein, M. R., & Wyble, B. (2013). *Retroactive dual-task interference in a whole-report RSVP task: A window into the formation of a durable short-term memory trace*. Manuscript in preparation.

Oberauer, K. (2009). Design for a working memory. *Psychology of Learning and Motivation, 51,* 45–100. doi:10.1016/S0079-7421(09)51002-X

Oberauer, K., Lewandowsky, S., Farrell, S., Jarrold, C., & Greaves, M. (2012). Modeling working memory: An interference model of complex span. *Psychonomic Bulletin & Review, 19,* 779–819. doi:10.3758/s13423-012-0272-4

Olivers, C. N. L., & Meeter, M. (2008). A boost and bounce theory of temporal attention. *Psychological Review, 115,* 836–863. doi:10.1037/a0013395

Olson, I. R., Chun, M. M., & Anderson, A. K. (2001). Effects of phonological length on the attentional blink for words. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 1116–1123. doi:10.1037/0096-1523.27.5.1116

Ouimet, C., & Jolicœur, P. (2007). Beyond Task 1 difficulty: The duration of T1 encoding modulates the attentional blink. *Visual Cognition, 15,* 290–304. doi:10.1080/13506280600693741

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116,* 220–244. doi:10.1037/0033-2909.116.2.220

Pashler, H. (1998). *The psychology of attention*. MIT Press. Cambridge, MA.

Potter, M. C. (1975). Meaning in visual search. *Science, 187,* 965–966. doi:10.1126/science.1145183

Potter, M. C. (1976). Short-term conceptual memory for pictures. *Journal of Experimental Psychology: Human Learning and Memory, 2,* 509–522. doi:10.1037/0278-7393.2.5.509

Potter, M. C., Chun, M. M., Banks, B. S., & Muckenhoupt, M. (1998). Two attentional deficits in serial target search: The visual attentional blink and an amodal task-switch deficit. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24,* 979–992. doi:10.1037/0278-7393.24.4.979

Potter, M. C., Staub, A., & O'Connor, D. H. (2002). The time course of competition for attention: Attention is initially labile. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 1149–1162. doi:10.1037/0096-1523.28.5.1149

Prinzmetal, W., Amiri, H., Allen, K., & Edwards, T. (1998). Phenomenology of attention: 1. Color, location, orientation, and spatial frequency. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 261–282. doi:10.1037/0096-1523.24.1.261

Ratcliff, R., & Rouder, J. N. (2000). A diffusion model account of masking in two-choice letter identification. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 127–140. doi:10.1037/0096-1523.26.1.127

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 849–860. doi:10.1037/0096-1523.18.3.849

Ricker, T. J., & Cowan, N. (2010). Loss of visual working memory within seconds: The combined use of refreshable and non-refreshable features. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36,* 1355–1368. doi:10.1037/a0020356

Rolls, E. T., Tovée, M. J., & Panzeri, S. (1999). The neurophysiology of backward visual masking: Information analysis. *Journal of Cognitive Neuroscience, 11,* 300–311. doi:10.1162/089892999563409

Ruthruff, E., & Pashler, H. (2001). Central and peripheral interference in RSVP displays. In K. Shapiro (Ed.), *The limits of attention: Temporal constraints on human information processing* (pp. 100–123). Oxford, England: Oxford University Press.

Saults, J. S., & Cowan, N. (2007). A central capacity limit to the simultaneous storage of visual and auditory arrays in working memory. *Journal of Experimental Psychology: General, 136,* 663–684. doi:10.1037/0096-3445.136.4.663

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. doi:10.1037/0096-1523.14.4.591

Shih, S. I. (2008). The attention cascade model and attentional blink. *Cognitive Psychology, 56,* 210–236. doi:10.1016/j.cogpsych.2007.06.001

Spalek, T. M., Lagroix, H. E. P., Yanko, M. R., & Di Lollo, V. (2012). Perception of temporal order is impaired during the time course of the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 402–413. doi:10.1037/a0025050

Stevanovski, B., & Jolicœur, P. (2007). Visual short-term memory: Central capacity limitations in short-term consolidation. *Visual Cognition, 15,* 532–563. doi:10.1080/13506280600871917

Stevanovski, B., & Jolicœur, P. (2011). Consolidation of multi-feature items in visual working memory: Central capacity requirements for visual consolidation. *Attention, Perception, & Psychophysics, 73,* 1108–1119. doi:10.3758/s13414-011-0099-5

Sun, H., Zimmer, H. D., & Fu, X. (2011). The influence of expertise and of physical complexity on visual short-term memory consolidation. *The Quarterly Journal of Experimental Psychology, 64,* 707–729. doi:10.1080/17470218.2010.511238

Taatgen, N. A., Juvina, I., Schipper, M., Borst, J., & Martens, S. (2009). Too much control can hurt: A threaded cognition model of the attentional blink. *Cognitive Psychology, 59,* 1–29. doi:10.1016/j.cogpsych.2008.12.002

Thorpe, S., Fize, D., & Marlot, C. (1996). Speed of processing in the human visual system. *Nature, 381,* 520–522. doi:10.1038/381520a0

Todd, J. J., Han, S. W., Harrison, S., & Marois, R. (2011). The neural correlates of visual working memory encoding: A time-resolved fMRI study. *Neuropsychologia, 49,* 1527–1536. doi:10.1016/j.neuropsychologia.2011.01.040

Tombu, M. N., Asplund, C. L., Dux, P. E., Godwin, D., Martin, J. W., & Marois, R. (2011). A unified attentional bottleneck in the human brain. *PNAS Proceedings of the National Academy of Sciences of the United States of America, 108,* 13426–13431. doi:10.1073/pnas.1103583108

Tombu, M., & Jolicœur, P. (2005). Testing the predictions of the central capacity sharing model. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 790–802. doi:10.1037/0096-1523.31.4.790

Ueno, T., Allen, R. J., Baddeley, A. D., Hitch, G. J., & Saito, S. (2011). Disruption of feature binding in working memory. *Memory & Cognition, 39,* 12–23. doi:10.3758/s13421-010-0013-8

Van der Burg, E., Brederoo, S. G., Nieuwenstein, M. R., Theeuwes, J., & Olivers, C. N. L. (2010). Audiovisual semantic interference and attention: Evidence from the attentional blink paradigm. *Acta Psychologica, 134,* 198–205. doi:10.1016/j.actpsy.2010.01.010

Visser, T. A. W., Bischof, W. F., & Di Lollo, V. (1999). Attentional switching in spatial and non-spatial domains: Evidence from the attentional blink. *Psychological Bulletin, 125,* 458–469. doi:10.1037/0033-2909.125.4.458

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2006). The time course of consolidation in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 32,* 1436–1451. doi:10.1037/0096-1523.32.6.1436

Vuontela, V., Rämä, P., Raninen, A., Aronen, H. J., & Carlson, C. (1999). Selective interference reveals dissociation between memory for location and color. *NeuroReport, 10,* 2235–2240. doi:10.1097/00001756-199908020-00002

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Welford, A. (1952). The “psychological refractory period” and the timing of high speed performance: A review and a theory. *British Journal of Psychology, 43,* 2–19.

Wilken, P., & Ma, W. J. (2004). A detection theory account of change detection. *Journal of Vision, 4,* Article no. 11. doi:10.1167/4.12.11

Wong, K. F. E. (2002). The relationship between attentional blink and psychological refractory period. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 54–71. doi:10.1037/0096-1523.28.1.54

Woodman, G. F., & Vogel, E. K. (2005). Fractionating working memory: Consolidation and maintenance are independent processes. *Psychological Science, 16,* 106–113. doi:10.1111/j.0956-7976.2005.00790.x

Wutz, A., & Melcher, D. (2013). Temporal buffering and visual capacity: The time course of object formation underlies capacity limits in visual cognition. *Attention, Perception, & Psychophysics, 75,* 921–933. doi:10.3758/s13414-013-0454-9

Wyble, B., Bowman, H., & Nieuwenstein, M. R. (2009). The attentional blink provides episodic distinctiveness: Sparing at a cost. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 787–807. doi:10.1037/a0013902

Wyble, B., Potter, M. C., Bowman, H., & Nieuwenstein, M. R. (2011). Attentional episodes in visual perception. *Journal of Experimental Psychology: General, 140,* 488–505. doi:10.1037/a0023612

Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature, 453,* 233–235. doi:10.1038/nature06860

Zylberberg, A., Dehaene, S., Roelfsema, P. R., & Sigman, M. (2011). The human Turing machine: A neural framework for mental programs. *Trends in Cognitive Sciences, 15,* 293–300.

Zylberberg, A., Slezak, D. F., Roelfsema, P. R., Dehaene, S., & Sigman, M. (2010). The brain’s router: A cortical network of serial processing in the primate brain. *PLoS Computational Biology, 6,* e1000765. doi:10.1371/journal.pcbi.1000765

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