Journal of Experimental Psychology:
Human Perception and Performance
2011, Vol. 37, No. 2, 588–596

0096-1523/10/$12.00 DOI: 10.1037/a0018740

OBSERVATION

Competing for Consciousness: Prolonged Mask Exposure Reduces Object Substitution Masking

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In object substitution masking (OSM) a sparse, temporally trailing 4-dot mask impairs target identification, even though it has different contours from, and does not spatially overlap with the target. Here, we demonstrate a previously unknown characteristic of OSM: Observers show reduced masking at prolonged (e.g., 640 ms) relative to intermediate mask durations (e.g., 240 ms). We propose that with prolonged exposure, the mask's visual representation is consolidated, which allows processing of the lingering target icon to be reinitiated, thereby improving performance. Our findings suggest that when the visual system is confronted with 2 temporally contiguous stimuli, although one may initially gain access to consciousness above the other, the "losing" stimulus is not irreversibly lost to awareness.

Keywords: object substitution masking, attention, consciousness, re-entrant processing, visual masking

Our visual world constantly changes over time and across space. The resulting volume of sensory input precludes all of it from reaching awareness. Instead, stimuli that appear in close spatiotemporal proximity must compete with one another for access to consciousness (Desimone & Duncan, 1995; Kastner & Ungerleider, 2000). In the laboratory, this competition can be seen in the phenomenon of object substitution masking (OSM; Enns & Di Lollo, 1997). In OSM, a target (e.g., a ring with a gap on the right or left) and a sparse surrounding mask (e.g., four dots adjacent to the corners of the target) appear among an array of distractors (Figure 1A). All items offset after a brief interval (e.g., 30 ms), except the mask, which remains on the display for a variable duration. Under these conditions, masking increases with the number of distractors (due to increased dispersal of spatial attention) and the duration of the mask (Di Lollo, Enns, & Rensink, 2000).

A number of characteristics distinguish OSM from other types of masking (e.g., Di Lollo et al., 2000; but see Breitmeyer & Ogmen, 2000). For example, the common onset of the target and mask and their nonoverlapping contours differentiate OSM from backward pattern masking, in which the target and mask share the same spatial location and the mask is presented after the target (Breitmeyer, 1984). OSM can also be differentiated from metacontrast masking. First, unlike OSM, in metacontrast masking, the target and mask have little or no spatial separation (e.g., a small disc target with a surrounding annulus mask). Second, unlike OSM, metacontrast masking is absent when the target and mask are presented simultaneously, and reaches a maximum at nonzero stimulus-onset asynchronies (SOA), producing a U-shaped masking function (e.g., Alpern, 1953; Bernstein, Proctor, Belcher, & Schurman, 1973, 1974; Breitmeyer, 1984; Cox & Dember, 1972; Kahneman, 1968; Werner, 1935). Finally, although strong metacontrast masking can be obtained with a single, centrally presented target and mask combination, little OSM occurs when spatial attention is not dispersed (Enns & Di Lollo, 1997). This is not to say that metacontrast masking is immune to spatial attention manipulations (Boyer & Ro, 2007; Neumann & Scharlau, 2007; Ramachandran & Cobb, 1995; Shelley-Tremblay & Mack, 1999; Tata, 2002); however, unlike OSM, distribution of spatial attention is not necessary for it to be elicited.

To explain the unique properties of OSM, Di Lollo et al. (2000) proposed a re-entrant processing account, which suggested that visual input proceeds from lower visual areas (e.g., V1) to higher extrastriate regions via feed-forward connections (Hubel & Wiesel, 1977). From this information, higher areas generate a "perceptual hypothesis" regarding the identity of the stimulus input. Extrastriate regions alone cannot verify this hypothesis because stimulus representations here are coarsely coded due to large receptive field sizes. Instead, feedback processing is initiated, comparing the perceptual hypothesis with continuing stimulus input in lower visual areas. These reiterative processing loops continue until stimulus identity is resolved, allowing it to enter awareness.

The re-entrant framework explains the dependence of OSM on dispersal of spatial attention by suggesting that increasing the number of distractors delays allocation of spatial attention to the target and thus hypothesis formation. As a result, by the time

This article was published Online First August 9, 2010.

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This article was supported by an Australian Postgraduate Award (Stephanie C. Goodhew), University of Queensland Early Career Research Grant 2008003700 (Troy A. W. Visser), an Australian Research Council Australian Professorial Research Fellowship (Grant number: DP0770844) (Ottmar V. Lipp), and an Australian Research Council APD Fellowship (Grant number: DP0986387) (Paul E. Dux).

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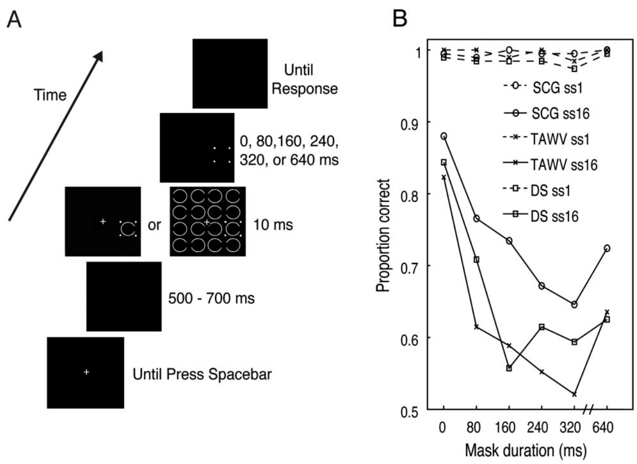

Figure 1. A: Schematic illustration of a trial in Experiment 1A. B: Trained observers' proportion correct as a function of set size and trailing mask duration. SCG = Stephanie C. Goodhew; ss1 = Set Size 1; ss16 = Set Size 16; TAWV = Troy A. W. Visser.

iterative loops have begun, only the mask remains on the display, leading to a conflict between the perceptual hypothesis and sensory input. In the face of this conflict, the perceptual hypothesis is revised, and the mask wins the competition for conscious representation (Di Lollo et al., 2000). Similarly, increasing mask duration enhances OSM because it makes it more likely that the perceptual hypothesis will conflict with the bottom-up representation of the mask still on the display.

It is clear that presentation of four nonoverlapping, trailing dots impairs report of a target. However what is the fate of a masked target? Or, put differently, to what extent is it processed? To examine this issue, Chen and Treisman (2009) had observers make a speeded response to the mask before indicating whether the target was present or absent in an OSM paradigm. When the target was missed, responses were faster when the target and mask were compatible at a featural level (arrows pointing in the same direction), as opposed to incompatible (arrows pointing in a different direction). However, no compatibility effect was observed when the target and mask were related at a categorical level (vowels versus consonants). This suggests that OSM impairs processing of the target prior to categorical or semantic processing, but subsequent to basic featural analysis.

In a similar vein, Reiss and Hoffman (2006) showed that the N400 to a target, an event-related potential (ERP) component that is elicited by semantic mismatches, was obliterated when the mask offset was delayed by 400 ms. This suggests that masked targets do not reach a semantic level of analysis. In a follow-up study, Reiss and Hoffman (2007) investigated the effects of OSM on the N170, a postperceptual ERP component that is elicited by faces and face-like stimuli. They found a reliable N170 to face targets when the mask offset simultaneously with the target, but not when offset was delayed by 400 ms (Reiss & Hoffman, 2007). This reveals the powerful nature of the masking: even faces, which are highly familiar, biologically relevant stimuli (e.g., Bruce & Young, 1986), are not resistant to OSM. In contrast, the N2pc, which is sensitive to the perceptual features of the target (Kiss, Van Velzen, & Eimer, 2008), is robust to OSM (Woodman & Luck, 2003).

Taken together, the findings from Chen and Treisman (2009), Reiss and Hoffman (2006, 2007), and Woodman and Luck (2003) show that a stimulus that initially loses the competition for consciousness in OSM is lost to visual awareness after only cursory processing. In the present study, however, we demonstrate that while strong masking is observed at intermediate mask durations (e.g., up to 240 ms), there is a recovery from OSM with prolonged exposure (e.g., 640 ms). This suggests that despite being substituted by the mask without undergoing analysis at a categorical stage, the target representation remains a viable candidate for conscious representation even after prolonged mask exposure.

Experiment 1A

Method

Stimuli were presented on a Pentium computer, connected to a 19-in. CRT monitor (Acer AC716) running at a refresh rate of 100 Hz, using the Presentation software package (Neurobehavioral systems, 2009, Albany, CA). Targets were white rings with a gap to the left or right (Landolt-Cs; ~1.99°, luminance 5.07 cd/m^2, gap size ~0.53°), and the mask was four white dots appearing on the corners of a notional square (~2.13 × 2.13°) surrounding the target. The edge of the dots was separated from the edge of the target by ~0.23°.

Each trial began with a white, centrally presented, fixation cross. Observers initiated the search display by pressing the spacebar. After a random delay of 500 to 700 ms the target appeared either alone (Set Size 1), or with 15 accompanying distractor Landolt-Cs (Set Size 16; Figure 1A), in a 4 × 4 matrix of possible locations (0.69° separation horizontally and 0.39° vertically). The location of the target was randomly determined for each trial with its position signaled by the mask. This search array, consisting of the target, mask, and distractors (if any) was presented for 10 ms and was followed by the mask alone for 0, 80, 160, 240, 320, or 640 ms (Figure 1A). Observers indicated the identity of the target (whether the Landolt-C surrounded by the mask had its gap missing on the left or the right) by pressing the left or right arrow key on the keyboard respectively (unspeeded response). There were 192 trials per condition (set size × mask duration, randomly intermixed), yielding 2,304 total trials. We tested three trained psychophysical observers: two were authors (Stephanie C. Goodhew [SCG] and Troy A. W. Visser [TAWV]), and one (DS) was naïve to the study's predictions. The University of Queensland Ethical Review Board approved the experimental protocol.

Results and Discussion

Figure 1B plots each observer's proportion correct on the target identification task as a function of set size and mask duration. At Set Size 1, masking was small or absent, as is typically found in OSM (Di Lollo et al., 2000; Enns & Di Lollo, 1997). In contrast, at Set Size 16, for all three observers, accuracy initially decreased with increasing mask duration, and then improved at longer durations. Although this improvement emerged earlier for DS than either TAWV or SCG, recovery was reliably present for all observers at the 640-ms mask duration.

Under the present conditions we observed reduced interference with prolonged exposure to the masking stimulus. However, the

640-ms mask duration, where recovery was most reliable, was an “odd-ball” relative to the other conditions because it was much longer than all the other mask durations presented. Thus, it is possible, that the novelty or infrequency of the extended mask duration trials in the present experiment contributed to the recovery effect. To examine this issue, we conducted Experiment 1B in which we sampled mask durations from 0 to 600 ms in even 100-ms increments, as well as including an extended 1,000-ms mask duration to test the consistency of the observed OSM recovery.

Experiment 1B

Method

The stimuli and procedures were identical to those employed in Experiment 1A, except for the following changes: After the search array offset, the four dot mask trailed for one of the following mask durations: 0, 100, 200, 300, 400, 500, 600, or 1,000 ms (see Figure 2A). There were 200 trials per condition (set size × mask duration, randomly intermixed), yielding 3,200 total trials. We tested two observers from Experiment 1A (SCG & TAWV).

Results and Discussion

Figure 2B plots both observers’ proportion correct on the target identification task as a function of set size and mask duration. Observer SCG shows a decrease in accuracy across the 0- to 300-ms mask durations, followed by a steady increase in performance (recovery) until 600 ms, which is then maintained at 1,000 ms. Observer TAWV also shows a decrease in accuracy across the 0- to 300-ms mask durations, but reaches maximal masking at 500 ms, and then recovers at 600 ms, and maintains this recovery at 1,000 ms.

Critically, as in Experiment 1A, both observers demonstrated recovery at the 600 ms mask duration, even though this point was no longer an odd-ball trial relative to the other mask durations employed. This demonstrates that the recovery effect does not depend on the prolonged mask exposure being an infrequent or unusual event. In addition, the fact that performance at the 1,000-ms mask duration was similar to that found for the 600-ms mask duration suggests that the recovery from OSM is not limited to mask durations of approximately 600 ms.

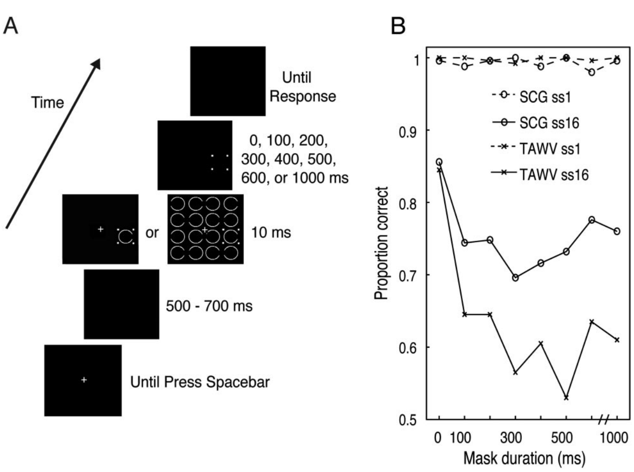

Figure 2. A: Schematic illusion of a trial in Experiment 1B. B: Trained observers’ proportion correct as a function of set size and trailing mask duration. SCG = Stephanie C. Goodhew; ss1 = Set Size 1; ss16 = Set Size 16; TAWV = Troy A. W. Visser; DS = anonymous observer.

The recovery from OSM seen with prolonged mask exposure suggests that a representation of the target remains available to consciousness at least several hundred milliseconds after its offset and substitution. However, in Experiment 1A and 1B, recovery was only demonstrated using trained observers. Thus, it was possible that these findings would not generalize to untrained observers under similar conditions. We tested this possibility in Experiment 2.

Experiment 2A

In Experiment 1, we demonstrated an unexpected recovery from OSM at prolonged mask durations. The purpose of the current experiment was to determine whether this result would generalize beyond trained observers by conducting a similar experiment with untrained observers who were naïve to the purpose of the study.

Method

The stimuli and procedures were identical to those used in Experiments 1A and 1B, except for the following changes. To reduce task difficulty for the untrained subjects, we increased the search array exposure duration from 10 ms to 100 ms. In addition, to increase the number of trials per condition, we removed the 80-ms mask duration, leaving only 0-, 160-, 240-, 320-, and 640-ms mask durations (Figure 3A). There were 100 trials per combination of set size and mask duration, yielding a total of 1,000 trials. Trial types were randomly intermixed for each observer. We recruited 29 new observers from the undergraduate psychology research participation pool at the University of Queensland. In this and subsequent experiments, participants whose proportion correct in the Set Size 1, simultaneous mask offset condition, fell below .90 were excluded from analyses. This resulted in the exclusion of eight observers (inclusion of this data did not change the pattern of the results).

Results and Discussion

Figure 3B plots mean proportion correct on the target identification task in Experiment 2A as a function of mask duration and set size. A repeated-measures analysis of variance (ANOVA) revealed a significant main effect of set size, $F(1, 20) = 1{,}096.83$, $p < .001$, $\eta_p^2 = .982$, such that target identification accuracy was higher at Set Size 1 than Set Size 16, and a significant main effect of mask duration, $F(4, 80) = 12.51$, $p < .001$ $\eta_p^2 = .385$, which indicated that overall target accuracy was influenced by the duration of the trailing mask. In addition, there was a significant interaction between set size and mask duration, $F(4, 80) = 4.40$, $p = .003$, $\eta_p^2 = .180$, with the effect of mask duration more pronounced at Size 16 than Set Size 1. This interaction is the hallmark of OSM (Di Lollo et al., 2000). Planned comparisons revealed that at Set Size 16, proportion correct decreased between the 0- and 160-ms mask durations, $t(20) = 3.49$, $p = .001$, $\eta_p^2 = .411$, but did not significantly differ between the 160- and 240-ms

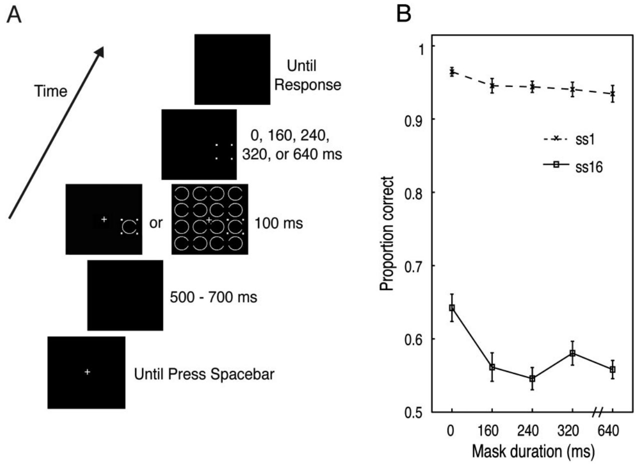

Figure 3. A: Schematic illustration of a trial in Experiment 2A. B: Untrained observers' proportion correct as a function of set size and trailing mask duration. Error bars represent standard errors of the mean. ss1 = Set Size 1; ss16 = Set Size 16.

mask durations, $t(20) = 0.81$, $p = .431$, $\eta_p^2 = .031$. Target identification accuracy then increased significantly from the 240-ms to the 320-ms mask duration, $t(20) = 2.18$, $p = .042$, $\eta_p^2 = .191$, whereas the 320- and 640-ms mask durations did not significantly differ from one another, $t(20) = 1.37$, $p = .186$, $\eta_p^2 = .086$. This indicates that there was a significant recovery in target accuracy between the intermediate (240 ms) and longest (320 and 640 ms) mask durations. Consistent with this, within-subjects contrasts indicated a significant quadratic component underlying the main effect of mask duration, $F(1, 20) = 11.80$, $p = .003$, $\eta_p^2 = .371$, along with a quadratic component in the interaction between set size and mask duration, $F(1, 20) = 4.97$, $p = .037$, $\eta_p^2 = .199$.

In examining Figure 3B, it is clear that overall performance at Set Size 16 was quite low. Even with simultaneous target and mask offset (mask duration = 0), mean proportion correct reached only .64 (relative to chance at .50), whereas in Experiment 1A, proportion correct was .85. Such relatively low accuracy levels constrain variability at longer mask durations, and thus may distort the shape of the function and the nature of the recovery from masking. To determine whether this was the case, in Experiment 2B we further reduced the difficulty of the OSM task to allow to a greater performance range.

Experiment 2B

Method

Experiment 2B was identical to 2A except as follows. The larger set size was reduced from 16 to nine items. As a result, the Landolt-Cs were separated horizontally by ~1.53° and vertically by ~1.68°. In addition, the search array was displayed for 80 ms (Figure 4A). We recruited 10 new observers, two of whom were excluded for falling below the performance criterion outlined in Experiment 2A (inclusion of this data did not change the pattern of the results).

Results and Discussion

Figure 4B plots mean proportion correct on the target identification task as a function of set size and mask duration. Inspection of this figure shows that the procedural changes in this experiment were successful in increasing the range of performance at set size nine. As was the case in Experiment 2A, a repeated-measures ANOVA revealed a significant main effect of set size, $F(1, 7) = 332.70$, $p < .001$, $\eta_p^2 = .979$, such that target identification accuracy was greater at Set Size 1 than Set Size 9, and a significant main effect of mask duration, $F(4, 28) = 16.03$, $p < .001$, $\eta_p^2 = .696$, indicating that target accuracy varied with mask duration. Crucially, a significant interaction between set size and mask duration was also obtained, $F(4, 28) = 6.82$, $p = .001$, $\eta_p^2 = .494$, demonstrating that mask duration had a greater influence at Set Size 9 than Set Size 1. Planned comparisons revealed that at Set Size 9, proportion correct decreased significantly from the 0- to the 160-ms mask duration, $t(7) = 3.79$, $p = .007$, $\eta_p^2 = .672$, but did not differ significantly from the 160- to the 240-ms mask durations, $t(7) = 0.91$, $p = .394$, $\eta_p^2 = .105$. Furthermore, the decrease from the 240- to the 320-ms mask duration, $t(7)$, $= 4.37$, $p = .003$, $\eta_p^2 = .732$, and the increase in target identification accuracy from the 320-ms to the 640-ms mask duration were significant $t(7) = 6.61$, $p < .001$, $\eta_p^2 = .862$. In addition, within-subjects contrasts revealed a significant quadratic component underlying the main effect of mask duration, $F(1, 7) = 12.85$, $p = .009$, $\eta_p^2 = .647$, along with a quadratic component in the interaction between set size and mask duration, $F(1, 7) = 22.47$, $p = .002$, $\eta_p^2 = .762$. That is, at Set Size 9, there was a significant recovery in accuracy between the longest two mask durations.

The consistent pattern of recovery from OSM at longer mask durations obtained across Experiments 1A, 1B, 2A, and 2B suggests that the target representation remains a viable candidate for conscious representation several hundred milliseconds after its offset, despite the fact that the mask is the only remaining sensory input. We hypothesize that this recovery from OSM reflects the fact that after prolonged mask exposure, the representation of

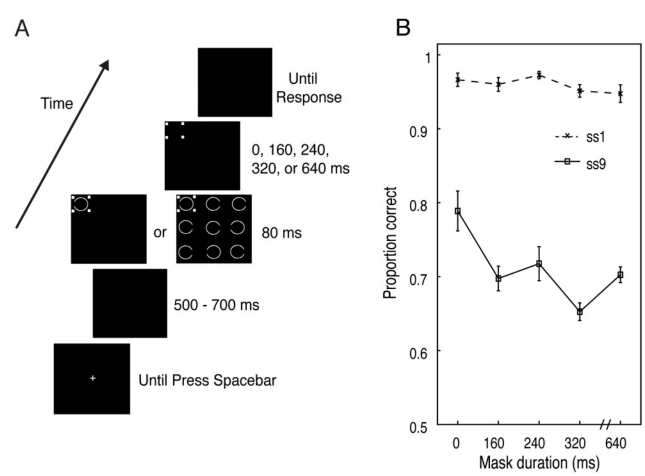

Figure 4. A: Schematic illustration of a trial in Experiment 2B. B: Untrained observers' proportion correct as a function of set size and trailing mask duration. Error bars represent standard errors of the mean. ss1 = Set Size 1; ss9 = Set Size 9.

the mask is consolidated and attains "objecthood" independent of the target. Once this has occurred, re-entrant perceptual hypothesis testing begins anew on the lingering low-level representation of the target. On some trials, this results in the target also attaining objecthood, thereby improving identification performance. We return to this hypothesis and a discussion of alternative accounts in the General Discussion.

The validity of this objecthood explanation rests on the assumption that OSM is the result of object-level rather than image-level interference. Here, object-level interference refers to higher level interactions produced by stimulus representations competing for limited resources, subsequent to early sensory-level registration, whereas image-level interference refers to interactions at the earliest levels of visual representation (low-level interference), such as when a stimulus is degraded by an overlapping pattern mask. Although this assumption is certainly in keeping with previous studies (Di Lollo et al., 2000; Enns, 2004; Enns & Di Lollo, 1997; Kahan & Lichtman, 2006; Lleras & Moore, 2003; Moore & Lleras, 2005), a more explicit test would be to examine whether recovery would still be obtained with image-level degradation of the target icon. According to our hypothesis, such degradation would be expected to destroy the image-level representation of the target, thus preventing recovery. To test this, in Experiment 3 we repeated our previous experiment with a new set of observers but employed a noise mask overlapping the target location.

Experiment 3

Method

As in Experiment 2B, we employed Set Size 1 and Set Size 9 search arrays in which the four dot mask signaled target location. Here, however, rather than using a prolonged masking display of four dots, the dots were replaced by a black and white random visual noise mask centered at the target location, following target offset. This mask remained on the display for 0, 160, 240, 320, or 640 ms (Figure 5A). We tested 14 new observers, seven of whom were excluded for falling below the performance criterion outlined in Experiment 2A (inclusion of this data did not change the pattern of the results).

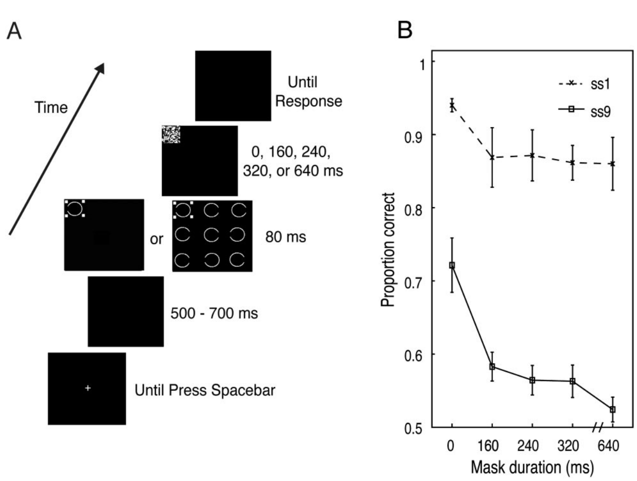

Figure 5. A: Schematic illustration of a trial in Experiment 3. B: Untrained observers' proportion correct as a function of set size and trailing mask duration. Error bars represent standard errors of the mean. ss1 = Set Size 1; ss9 = Set Size 9.

Results and Discussion

Figure 5B plots mean proportion correct on the target identification task as a function of set size and mask duration. As in earlier experiments, a repeated-measures ANOVA revealed significant main effects of set size, $F(1, 6) = 555.70$, $p < .001$, $\eta_p^2 = .989$, such that performance was higher at Set Size 1 than Set Size 9, and mask duration, $F(4, 24) = 32.31$, $p < .001$, $\eta_p^2 = .843$, which indicates that performance varied as a function of mask duration. The interaction between set size and mask duration was not significant, $F(4, 24) = 2.00$, $p = .126$, $\eta_p^2 = .250$. However, contrast analyses revealed the quadratic component of the main effect of mask duration was significant, $F(1, 6) = 28.45$, $p = .002$, $\eta_p^2 = .826$, whereas this component for the interaction between set size and mask duration was not, $F(1, 6) = .88$, $p = .383$, $\eta_p^2 = .128$. More important, planned comparisons revealed that at Set Size 9, target identification performance decreased from the 0- to the 160-ms mask durations, $t(6) = 4.59$, $p = .004$, $\eta_p^2 = .778$, but there was no significant difference between the 160- and 240-ms, $t(6) = 0.86$, $p = .422$, $\eta_p^2 = .110$, the 240- and 320-ms, $t(6) = .06$, $p = .958$, $\eta_p^2 = .001$, or the 320- and the 640-ms mask durations, $t(6) = 1.46$, $p = .196$, $\eta_p^2 = .261$. That is, there was no recovery with increased mask duration. The fact that no recovery was obtained when the mask interfered with the target at an image level supports the assumption that OSM occurs at an object level and, more important, is consistent with the notion that an intact representation of the target supports the recovery from OSM observed in our experiments.

General Discussion

Across four experiments, we found a recovery from OSM with prolonged mask exposure. Furthermore, this recovery was eliminated when a backward mask was used that degraded the target representation at an image level. Collectively, the results demonstrate that in OSM, the target representation remains available for consciousness at least several hundred milliseconds after its offset. Below we offer a preliminary theoretical account for this OSM recovery effect, and discuss alternative models. In addition, we examine the implications of the present findings for understanding the relationship between OSM and other forms of masking.

Preliminary Account of the OSM Recovery Effect

Di Lollo et al. (2000) explained OSM using a re-entrant processing framework. According to this model, the briefly present target is processed via a feedforward sweep, and then, because the target representation has low resolution (due to the receptive field sizes of higher level neural areas), feedback is initiated from extrastriate regions for a more detailed representation of this stimulus to be established. Because the target appears briefly, however, it is only the mask stimulus that is still present at the target location once feedback processing begins. This means that the mask, instead of the target, becomes the subject of extended processing and thus available to consciousness. This model, therefore, predicts that the strength of masking will increase with mask duration until a constant baseline level of accuracy is reached.

Contrary to this hypothesis, the present experiments demonstrate that OSM varies nonmonotonically with mask duration, with masking magnitude reduced at prolonged mask durations relative to intermediate durations. Thus, at present, Di Lollo et al.'s (2000) model cannot account for the recovery effect without some modification. In this regard, we suggest that the target representation lingering in the visual system can induce a second cascade of reiterative processing in the face of the mask, once the mask has been consolidated and achieves objecthood. It is via this second feedforward wave of target information that a new series of reiterative loops are triggered, resulting in the target entering consciousness after prolonged mask exposure.

What remains to be explained, however, is the temporal dynamics of this recovery effect—that is, why does it take almost half-a-second for processing of the target to recommence? Previous work by Brockmole and colleagues (Brockmole, Irwin, & Wang, 2003; Brockmole & Wang, 2003; Brockmole, Wang, & Irwin, 2002) suggested that it takes at least several hundred milliseconds for the visual system to generate a visual representation of a briefly presented stimulus that is of sufficient robustness that it can be integrated with a physically present stimulus. Accordingly, we suggest that it takes a similar amount of time to generate a sufficiently strong representation of the mask that it frees up processing resources for the lingering representation of the target. According to this account, at very short mask durations, OSM is weak because the mask is present for relatively few iterative processing loops, and thus only slightly outweighs the target in representational strength. In contrast, masking is maximal at the intermediate mask durations because here the mask has been the subject of prolonged reiterative processing, and so has greater competitive strength relative to the target representation. Finally, at prolonged mask durations (e.g., ~640 ms), the mask has been the subject of extensive reiterative processing and has attained objecthood. This allows processing resources previously engaged with the mask to begin anew with target processing. This second wave of iterative processing allows the lingering target icon to enter awareness, thereby accounting for improved performance at long mask durations.

Implications for OSM

Previous work has suggested that missed targets in OSM are over-written at a precategorical level of information processing (e.g., Chen & Treisman, 2009; Reiss & Hoffman, 2006, 2007; Woodman & Luck, 2003). Our recovery effect, however, demonstrates that despite this limited processing, a masked target in OSM is not irrevocably lost to awareness. This finding provides evidence that the target icon is not obliterated in OSM, as is the case in backward pattern masking, but rather remains intact in a low-level form that is available to high-level processing after substitution. As to the specific timing of the recovery (or put differently, when the mask achieves objecthood), there is no evidence here to suggest that it invariably begins at a particular point in the masking function. However, our results do suggest that recovery is reliably present at mask durations of 600 ms and beyond.

Relationship to Other Types of Masking

It is well established that when two brief spatiotemporally contiguous stimuli are presented (<~100 ms), the second is usually processed at the expense of the first (i.e., visual masking; Breitmeyer, 1984). We have shown, however, that under certain conditions, the first stimulus can be recovered. In contrast, no recovery was apparent when a backward mask was used in place of the trailing, four dot mask. This suggests that an intact image-level representation of the target is necessary to produce the recovery effect.

Metacontrast is another form of masking in which the target is not degraded at an image level. Moreover, metacontrast also produces U-shaped masking functions, similar to those we observed here with OSM. Despite these similarities, however, a direct comparison between OSM and metacontrast masking is difficult to make based on the current literature. This is because metacontrast masking functions are typically mapped as a function of target-mask SOA, with mask duration held constant, whereas in OSM, SOA is always zero, and instead mask duration is varied. To our knowledge, only one study has varied mask duration in a metacontrast paradigm. Di Lollo, von Muhlenen, Enns, and Bridgeman (2004) found that metacontrast masking increased monotonically with mask duration. In this study, however, the maximum mask duration was 160 ms, which corresponds to the point on the OSM function where masking also increases monotonically. It remains to be seen then whether longer mask durations will yield a similar recovery from metacontrast masking as seen here with OSM. We are currently investigating this question in our lab.

Also of interest here is Macknik and Livingstone's (1998) proposal that stimulus termination asynchrony (STA), or the time interval between the offset of the target and that of the mask, plays a pivotal role in metacontrast and related forms of visual masking. According to this account, the offset transient produced by the mask's disappearance interferes with the offset transient produced by the target, resulting in a decline in target visibility. Could the offset of the mask contribute to OSM? Macknik and Livingstone's model predicts that OSM will be obtained when the target and mask have a simultaneous offset. Yet this is where limited OSM is observed. Furthermore, Macknik and Livingstone found maximal metacontrast masking when mask offset occurred about 100 ms after target offset, whereas in OSM, maximal masking does not occur until much later (several hundred milliseconds after target offset). These discrepancies between Macknik and Livingstone and previous OSM findings suggest that mask offset is not a critical factor in determining the magnitude of OSM.

Bottlenecks in the Mind/Brain

Throughout this paper we have referred to a "competition for consciousness" between the target and the trailing mask representations. The existence of such a competition implies the there is a bottleneck in visual processing that limits the number of stimuli reaching awareness. We suggest that the bottleneck in OSM corresponds to capacity-limitations in the number of items that can be the subject of re-entrant processing at given point in time.

The notion of a bottleneck in re-entrant processing is consistent with existing cognitive and neuroscientific models of consciousness. A number of seminal cognitive (bottleneck) models include an initial stage of sensory registration, in which stimuli can be processed without capacity limitations, followed by an effortful, capacity-limited stage in which stimulus representations are sufficiently consolidated to enter consciousness (e.g., Chun & Potter, 1995; Duncan, 1980, 1984; Neisser, 1967). These accounts are similar to Baars's (1989, 1997; see also Dehaene, Kerszberg & Changeux, 1998) global workspace model of consciousness, which consists of an initial stage of modular sensory processing in distinct brain regions that proceeds automatically and in the absence of awareness, followed by a capacity-limited stage in which a stimulus becomes the subject of a global workspace. This global workspace does not constitute a specific brain region, but rather of distributed and heavily interconnected neurons with long-range axons that connect multiple-brain regions (e.g., frontal, parietal, and sensory areas). There is growing evidence to support this model as items that enter awareness typically lead to activity in higher level parietal and prefrontal regions of the brain (Dehaene et al., 2001; Marois, Yi, & Chun, 2004; Sergent, Baillet, & Dehaene, 2005). Dehaene's model, furthermore, explicitly states that only one stimulus at a time can enter the global workspace (and, therefore, consciousness). Thus, although the re-entrant processing and bottleneck accounts are clearly distinct, based on this previous literature and our recovery effect from OSM, it seems reasonable to suggest that feedback processing may be capacity limited.

The recovery from OSM found here demonstrates that stimuli that are initially impaired by this bottleneck in re-entrant processing are not lost, but in fact, can be recovered long after the stimulus has physically offset and another stimulus has been processed in the interim. However, what remains unknown is the nature of the target processing that occurs under the constraints of the bottleneck. This question cuts to the core of an ongoing debate about the nature of consciousness. According to one group of theories, stimulus visibility reflects a continuous, graded phenomenon. That is, perception gradually increases with greater cortical activity evoked by a stimulus (e.g., Bar et al., 2001; Grill-Spector, Kushnir, Hendler, & Malach, 2000; Moutoussis & Zeki, 2002). The opposing view is that consciousness occurs in an all-or-none bifurcation, where stimuli that are processed sufficiently to meet a minimum threshold of processing enter awareness fully, whereas stimuli that do not meet this minimum threshold are excluded from awareness (e.g., Dehaene et al., 2001; Sergent & Dehaene, 2004). The work of Lamme and colleagues (Lamme & Roelfsema, 2000; Lamme, Super, Landman, Roelfsema, & Spekreijse, 2000; Super, Spekreijse, & Lamme, 2001) is consistent with the latter view, suggesting that stimuli that enter conscious awareness do not just require a greater magnitude of processing, but rather a qualitatively distinct type of processing—neural feedback. However, the current data do not allow us (and were not intended to) distinguish whether a gradual continuum or strict bifurcation of consciousness underlies the competition in OSM. At this point, it can only be said that that both theories of consciousness are consistent with the suggestion of a bottleneck in re-entrant processing.

Another phenomenon in psychology that invokes the concept of a bottleneck in visual processing, and is highly related to the discussion above, is the attentional blink (AB; Raymond, Shapiro, & Arnell, 1992; see Dux & Marois, 2009, for a review). Here, when two targets are presented in rapid succession, accuracy on the first is uniformly high, whereas identification of the second is impaired at intertarget intervals ranging from approximately 200 to 600 ms. A prominent account of the AB is that it reflects a bottleneck at the stage of working memory consolidation (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; but see Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Nieuwenstein & Potter, 2006; Olivers & Meeter, 2008; Wyble, Bowman, & Nieuwenstein, 2009). These bottleneck theories draw a distinction between two stages of visual processing (e.g., Duncan, 1980; Neisser, 1967): The first stage involves rapid detection of stimuli and is unconstrained by capacity limitations, whereas the second stage consolidates representations in a form that is consciously available, but is capacity limited. The AB is thought to result from the second target (T2) having to wait for second stage processing when it appears in close temporal proximity to the first target (T1), leaving it susceptible to masking or decay.

The time course of the AB deficit is similar to the timescale of our recovery effect with prolonged mask exposure (e.g., 640 ms). This is not to say that OSM and AB necessarily reflect the same underlying perceptual mechanism. In fact, the evidence suggests that they do not. As outlined in the introduction, Reiss and Hoffman's (2006) work revealed that OSM obliterated the N400 component, while in the AB, a misidentified T2 can still elicit an N400 (Luck, Vogel, & Shapiro, 1996; Vogel, Luck, & Shapiro, 1998), implying that the OSM and AB reflect distinct limitations at different levels of processing (see also Giesbrecht, Bischof, & Kingstone, 2003). The commonality from both paradigms, however, is that they reveal the relatively slow pace at which the visual system consolidates stimuli into unique, consciously perceived objects (see also Brockmole et al., 2003; Brockmole & Wang, 2003; Brockmole et al., 2002).

Conclusions

Target identification in OSM improves at prolonged mask durations. This suggests that the competition for consciousness may have more than one winner, provided that an image-level representation of an object remains available.

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Received July 13, 2009
Revision received October 28, 2009
Accepted November 20, 2009 ■