

## Research Article

## DISSOCIATIONS AMONG ATTENTION, PERCEPTION, AND AWARENESS DURING OBJECT-SUBSTITUTION MASKING

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**Abstract**—When a visual target object is surrounded by four dots that onset at the same time as the target but remain visible after the target terminates, the four dots dramatically impair target discrimination performance. This phenomenon is called *object-substitution masking*, reflecting the hypothesis that both the target and the four dots are identified, but the representation of the four dots replaces the representation of the target object before the target can be reported. The present study used the event-related potential technique to demonstrate that a target masked in this manner is identified by the visual system and triggers a shift of attention. However, by the time attention is shifted to the target, only the mask remains visible, leading to impaired behavioral detection performance. These findings support the object-substitution hypothesis and provide new evidence that perception, attention, and awareness can be dissociated.

An enormous number of studies have used *visual masking* as a tool to study the processing of visual information (Breitmeyer, 1984; Kahneman, 1968). Visual masking refers to a procedure in which the processing of a target stimulus is disrupted by an irrelevant stimulus presented close to the target in location and time. Di Lollo, Enns, and their colleagues have recently introduced a masking procedure known as *object-substitution masking* (e.g., Di Lollo, Enns, & Rensink, 2000; Enns & Di Lollo, 1997, 2000). In object-substitution masking (see Fig. 1a), detection of the target is impaired when it is surrounded by four dots that persist after the target is extinguished. Di Lollo and Enns proposed that the visual system initially forms a representation that includes both the target object and the four dots; the dots are sufficiently small relative to the target and sufficiently far from the target's edges that they do not initially impair target identification. If, however, the dots persist after the target is extinguished, this initial target-plus-dots representation is replaced by a representation containing only the four dots. In the present study, we tested this object-substitution hypothesis by means of event-related potential (ERP) recordings.

Object-substitution masking can be distinguished in several ways from other commonly studied varieties of masking. For example, *integration masking* occurs when the contours of the mask overlap with and directly obscure the contours of the target (Breitmeyer, 1984; Turvey, 1973), whereas the four dots in object-substitution masking do not obscure the contours of the target. Specifically, object-substitution masking can be observed when the four-dot masks are presented at locations relatively far from the target object (Jiang & Chun, 2001; Lleras & Moore, 2003). Moreover, integration masking is highly effective when the target and mask terminate simultaneously, whereas object-substitution masking is ineffective unless the mask persists after target offset. *Metaccontrast masking* does not require that the contours of the mask directly overlap with the target, but the contours of the mask

must be very close to the contours of the target (Breitmeyer, 1984; Turvey, 1973), much closer than the four dots used in object-substitution masking. In addition, metaccontrast masking requires that the mask onsets after the offset of the target, whereas the target and mask can begin at the same time in object-substitution masking.

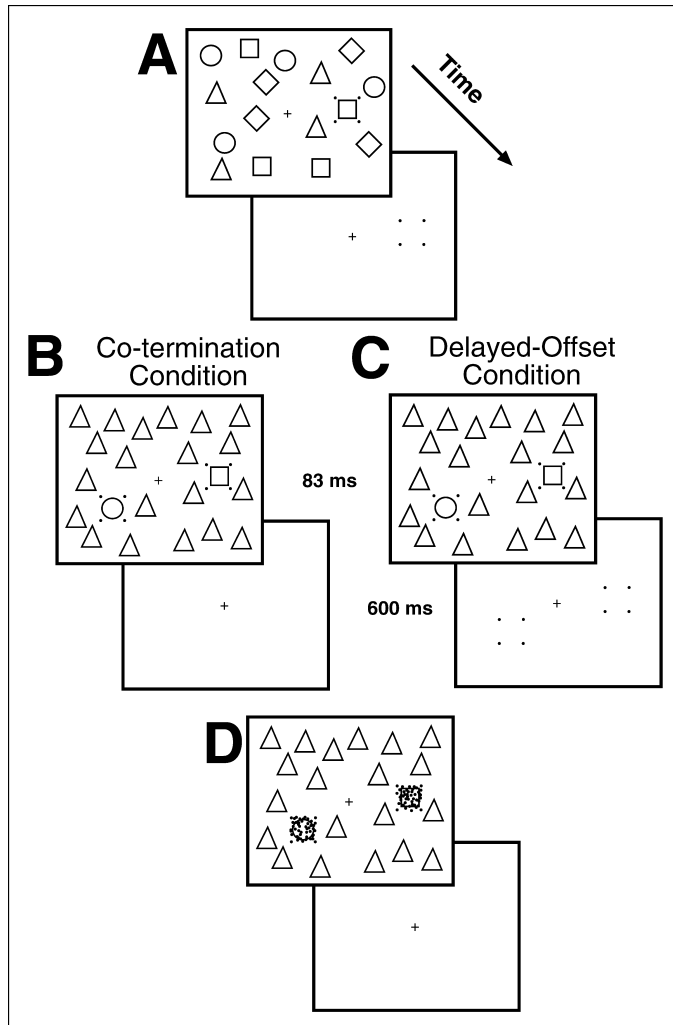
Object-substitution masking is also notable in that it is highly sensitive to the attentional demands of the task (Di Lollo et al., 2000). That is, the effectiveness of the mask increases greatly when the target is surrounded by similar distractor objects; these are exactly the conditions that increase attentional demands in visual search tasks without masks (Treisman & Souther, 1985). Moreover, object-substitution masking is dramatically reduced when attention is directed to the target by a spatial precue (Di Lollo et al., 2000; Neill, Hutchinson, & Graves, 2002). Di Lollo et al. (2000) explained this dependence on attention by positing that four-dot masks are ineffective if attention is directed to the target before the target-plus-mask representation is replaced by the mask-alone representation.

If correct, the object-substitution hypothesis is an important advance in understanding of the temporal dynamics of visual perception. Specifically, it provides a foothold for studying iterative processing in which an initial interpretation of the visual scene is discarded if it is inconsistent with subsequent attention-based analysis (see, e.g., Lamme & Roelfsema, 2000). We therefore sought to test three central predictions of the object-substitution hypothesis.

The first prediction is that targets masked in this manner are accurately identified by the visual system, even though they are not accurately reported. The second prediction is that the identification of the target triggers a shift of attention to the location previously occupied by the target, although attention arrives after the target-plus-mask stimulus has been replaced by the mask-only stimulus. The third prediction is that, even though the target is identified at some level within the visual system, higher-level cognitive systems do not receive accurate information about the target, leading to impaired behavioral detection performance.

To test these predictions, we recorded ERPs in an object-substitution masking paradigm, focusing on the N2pc (N2-posterior-contralateral) component (for general descriptions of the ERP technique, see Hillyard & Picton, 1987; Rugg & Coles, 1995). The N2pc component typically occurs during the time of the N2 family of components (approximately 200–300 ms poststimulus), is largest at posterior scalp sites, and is observed over the hemisphere contralateral to the location of an attended object. That is, when attention is deployed to an item within an array of distractors, the ERP waveform becomes more negative at contralateral scalp sites relative to ipsilateral scalp sites, beginning approximately 200 ms after the onset of the search array (Eimer, 1996; Luck & Ford, 1998; Luck, Girelli, McDermott, & Ford, 1997; Luck & Hillyard, 1994a, 1994b; Wauschkuhn et al., 1998; Woodman & Luck, 1999). Several sources of evidence indicate that the N2pc component reflects the deployment of perceptual-level attention to minimize interference between an attended item and nearby distractors (Luck et al., 1997; Luck & Hillyard, 1994b). This component ap-

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**Fig. 1.** Examples of stimuli used by Di Lollo, Enns, and Rensink (2000) and in the current study. In the study by Di Lollo et al., the task was to report the identity of the shape that appeared within the four dots (a). Performance was accurate when the four dots terminated at the same time as the search array, but error rates systematically increased as the offset time of the four-dot mask increased. In the current study, target detection in three conditions was assessed: co-termination trials (b) in Experiments 1 and 2, delayed-offset trials (c) in Experiment 1, and noise-masking trials (d) in Experiment 2.

pears to be an ERP analogue of attentional modulations of single-unit activity that have been observed in extrastriate and inferotemporal regions of monkey visual cortex (Chelazzi, Duncan, Miller, & Desimone, 1998; Luck et al., 1997), and a magnetoencephalographic study indicates that it is generated primarily in occipito-temporal cortex (Hopf et al., 2000).

We used the N2pc component to test the predictions of the object-substitution hypothesis. First, to test whether masked targets are initially identified by the visual system, we looked for evidence that targets elicited an N2pc component at contralateral scalp sites. In our experimental design, a target could not elicit a lateralized N2pc response unless it had been localized, and localization of the target re-

quired identification of the target. Second, because the N2pc component is a well-established neural correlate of the focusing of attention, the presence of an N2pc component for a masked target would indicate that the target triggered a shift of attention. Moreover, the onset time of the N2pc component would help to establish whether the shift of attention occurred after the target stimulus terminated. Finally, if the target triggered a shift of attention but the target representation was not transferred to higher-level cognitive processes, then we would observe a normal N2pc component but significantly impaired behavioral detection performance.

## EXPERIMENT 1

In the first experiment, observers were asked to detect the presence of target shapes embedded in arrays of distractor shapes. As illustrated in Figures 1b and 1c, the briefly presented search arrays were composed of 20 distractors and two possible target shapes that were surrounded by four dots. The two possible targets were selected at random from a set of three shapes (circle, square, and diamond). On every trial, one of the possible targets was in the left visual field, and the other was in the right visual field. One of the three shapes served as the target for a given block of trials, and the observers made a button press response to indicate whether the target was present or absent.

On *co-termination trials*, the four dots that surrounded each of the two possible targets began and ended simultaneously with the search array; the dots do not interfere with performance under these conditions. On *delayed-offset trials*, the four dots remained visible after the offset of the search array; under these conditions, the dots lead to poor target detection performance.

The design of this experiment reflects the need to ensure that the ERP waveforms are not distorted by differences in sensory stimulation per se. Specifically, the masked objects differed in the two visual fields and were selected at random from the set of three shapes. Because the shape defined as the target varied across blocks of trials, the same physical stimulus array could contain a target on either the left side or the right side. This made it possible to measure the N2pc in a manner that purely reflected the lateralized allocation of attention, uncontaminated by bottom-up sensory effects.

## Method

### Subjects

Ten volunteers between 18 and 35 years of age were paid for their participation. All had normal or corrected-to-normal visual acuity and provided informed consent.

### Stimuli and procedure

The stimuli were presented on a video monitor with a gray background ( $9.9 \text{ cd/m}^2$ ) at a distance of 100 cm. The search arrays were identical on co-termination and delayed-offset trials. Each search array was composed of 20 distractor triangles and two possible target shapes surrounded by four dots. Each shape was  $0.585^\circ \times 0.585^\circ$  and was drawn in white ( $92.46 \text{ cd/m}^2$ ). Each set of four white dots ( $0.065^\circ \times 0.065^\circ$ ) was located at the corners of an imaginary square ( $0.75^\circ \times 0.75^\circ$ ) centered on the possible target shape (see Fig. 1). The shapes were randomly distributed within a  $7.8^\circ \times 5.9^\circ$  area, with the constraints that (a) each hemifield contained one shape that was sur-

rounded by four dots and 10 distractor shapes without dots, and (b) the shapes were separated from each other by at least  $0.97^\circ$  (center to center). The two shapes surrounded by dots were selected at random, without replacement, from the set of three possible target shapes (i.e., the circle, square, and diamond). Consequently, each of the three possible target shapes was present on two thirds of trials. One of these three shapes was designated the target at the beginning of each trial block, and the observers were instructed to press one button for target-present arrays and another button for target-absent arrays. Accuracy and speed were emphasized equally.

Each array was presented for 83 ms. On co-termination trials, the four-dot masks terminated simultaneously with the search array. On delayed-offset trials, the four-dot masks remained visible for 600 ms after the search array disappeared. Co-termination trials were more frequent (62.5%) than the randomly intermixed delayed-offset trials (37.5%) to ensure that the subjects would not find the overall task too difficult and give up. A white fixation point appeared in the center of the monitor 1,200 to 1,400 ms before the onset of the search array and was extinguished 1,200 to 1,400 ms after the offset of the search array, followed by a blank 2,000-ms interstimulus interval. Subjects performed six blocks of 96 trials.

### Recording and analysis

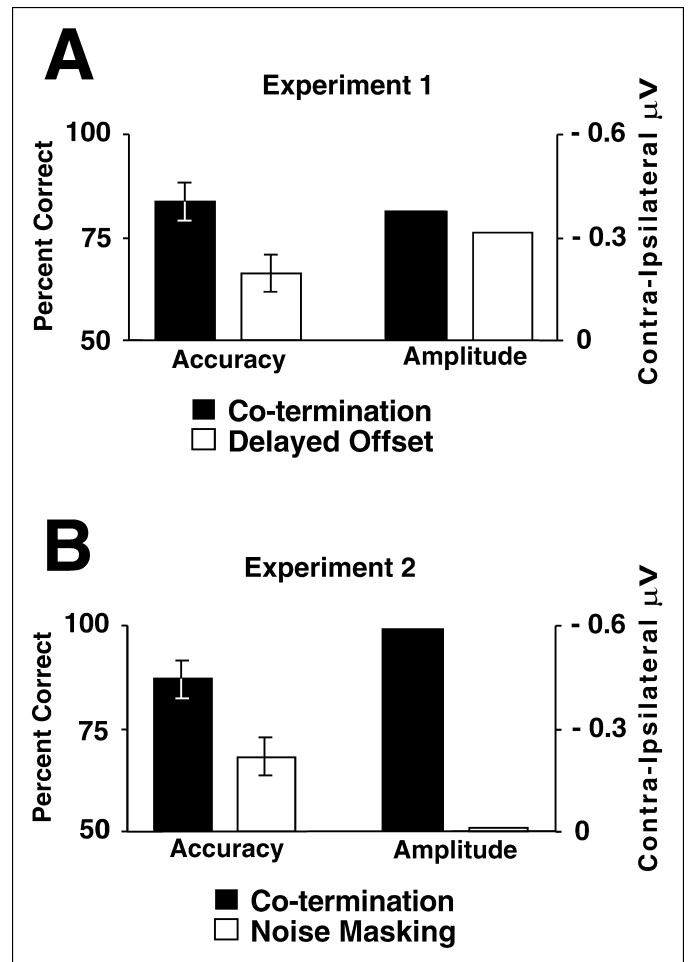
The electroencephalogram (EEG) and electro-oculogram (EOG) were recorded with a bandpass of 0.01 to 80 Hz using our standard methods (Vogel, Luck, & Shapiro, 1998). Trials with blinks or clear eye movements (typically  $1^\circ$  or more), muscle artifacts, or amplifier saturation were excluded from the averages. Four subjects were replaced because of excessive ocular artifacts (i.e., more than 25% of trials rejected). In the remaining subjects, ocular artifacts led to the rejection of an average of 7.1% of trials, with a single-subject maximum of 14.8%. Averaged horizontal EOG waveforms indicated that any residual eye movements were less than  $0.2^\circ$  on average and led to a propagated voltage of less than  $0.1 \mu\text{V}$  at posterior scalp sites.

The N2pc component was quantified as the mean amplitude between 200 and 375 ms poststimulus, relative to a 200-ms prestimulus baseline period at lateral posterior electrode sites (International 10/20 system sites O1, O2, T5, and T6, and nonstandard sites OL and OR, located halfway between O1 and T5 and halfway between O2 and T6, respectively). All  $p$  values were adjusted with the Greenhouse-Geisser epsilon correction for nonsphericity (Jennings & Wood, 1976). The data were collapsed across the three target shapes.

### Results and Discussion

As illustrated in Figure 2a, target detection was significantly less accurate on delayed-offset trials than on co-termination trials (66.2% vs. 83.6%, respectively),  $F(1, 9) = 19.82, p < .01$ . The  $A'$  measure of sensitivity (Macmillan & Creelman, 1991) exhibited the same pattern of results (.772 vs. .887, respectively),  $F(1, 9) = 16.37, p < .01$ . These findings demonstrate that significant masking did occur on delayed-offset trials.<sup>1</sup>

1. The representation of the four dots may have not entirely replaced the representation of the target on all trials, so although behavioral performance was impaired by the masking, performance was still significantly greater than chance. This pattern of findings has often been observed in previous studies of object-substitution masking (e.g., Di Lollo et al., 2000).

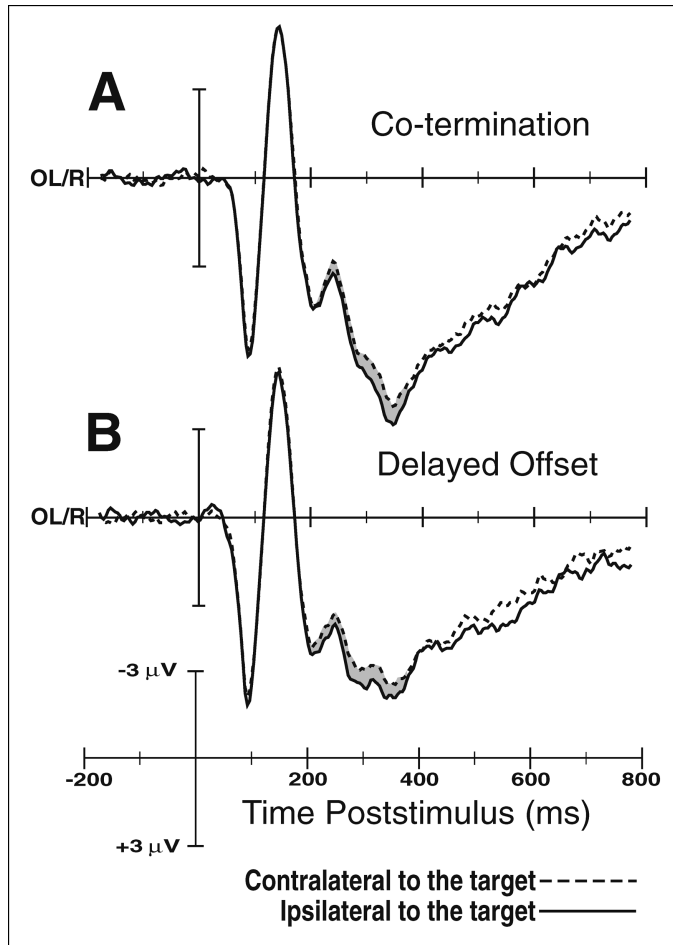


**Fig. 2.** Behavioral and N2pc amplitude data from Experiments 1 (a) and 2 (b). Each graph shows mean accuracy (percentage correct) at detecting the target shapes (left) and electrical activity contralateral minus ipsilateral to the target location during the N2pc measurement window (right). Error bars represent the 95% within-subjects confidence intervals (as recommended by Loftus & Loftus, 1988).

Figure 3 shows grand-average waveforms elicited by target-present arrays from a pair of lateral, posterior electrode sites (OL and OR). (Unless otherwise indicated, the figures and analyses presented in this article include trials with both correct and incorrect behavioral responses.) Target objects on co-termination and delayed-offset trials elicited approximately equivalent N2pc components. That is, the hemisphere contralateral to the target object was more negative than the ipsilateral hemisphere, beginning approximately 200 ms poststimulus, and this effect did not differ appreciably across masking conditions.

To verify this observation statistically, we conducted a 2 (trial type: co-termination vs. delayed-offset)  $\times$  2 (contralaterality: target ipsilateral vs. contralateral to the electrode site)  $\times$  3 (anterior-posterior electrode position: O1/O2 vs. OL/OR vs. T5/T6) analysis of variance (ANOVA) on the data from target-present trials. The N2pc component is defined by the difference in amplitude between the contralateral and ipsilateral sites (Luck et al., 1997; Luck & Hillyard, 1994b). In this

## Dissociations During Substitution Masking



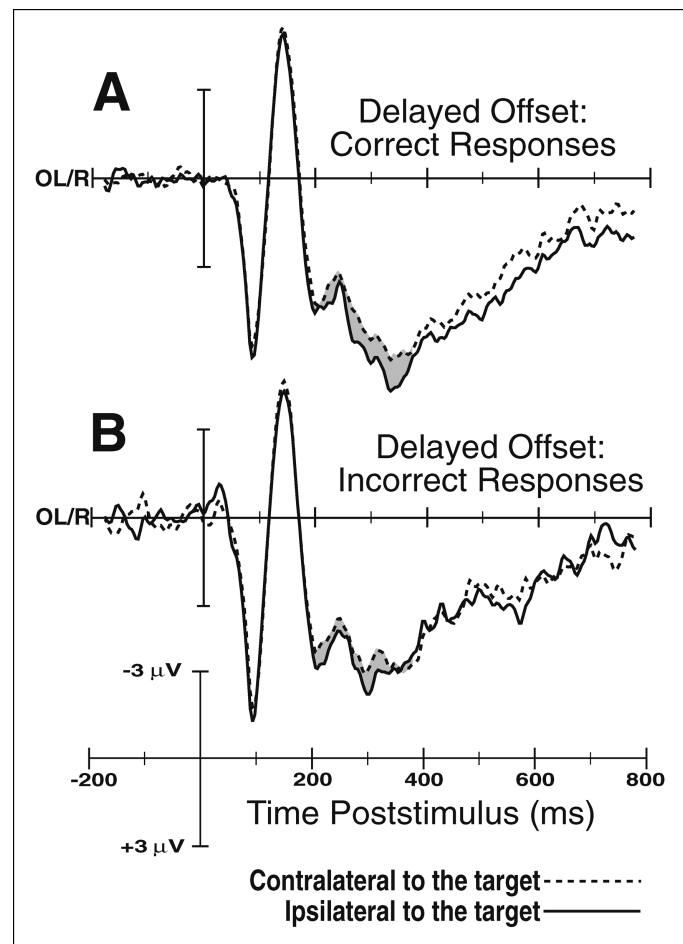
**Fig. 3.** Grand-average event-related potential (ERP) waveforms across all 10 subjects at sites OL and OR on target-present trials in Experiment 1. Results are shown separately for co-termination trials (a) and delayed-offset trials (b) and for activity contralateral to and ipsilateral to the target. In this and all subsequent figures, the ERP waveforms were digitally low-pass filtered by convolving the ERP waveforms with a gaussian impulse response function ( $SD = 6$  ms, 50% amplitude cutoff at 30 Hz).

ANOVA, the N2pc component was reflected by the main effect of contralaterality,  $F(1, 9) = 13.03$ ,  $p < .01$ . Any modulations of the N2pc component would have been reflected by interactions between this factor and other factors, but none of the other factors interacted significantly with contralaterality. In particular, the interaction between trial type and contralaterality did not approach significance ( $p > .75$ ), supporting the observation that masking did not influence N2pc amplitude. Separate two-way ANOVAs for the co-termination and delayed-offset trials indicated that N2pc amplitude was significantly greater than zero for both trial types,  $F(1, 9) = 5.55$ ,  $p < .05$ , and  $F(1, 9) = 12.17$ ,  $p < .01$ , respectively.

These findings demonstrate that significant and approximately equivalent N2pc components were elicited by the targets in the two conditions, even though overt target detection accuracy was highly impaired on the delayed-offset trials. The finding of a lateralized re-

sponse to the targets indicates that on both trial types, the brain was able to determine which side of the array contained the target, which implies that the target was detected by the visual system even though the observers could not accurately report it.

This conclusion was further supported by separately examining the ERPs from delayed-offset trials in which responses were correct versus incorrect. Figure 4 shows that a significant N2pc component was elicited even when the observers reported that no target was present. It should be noted that performance on co-termination trials was far from perfect, so some of the errors in this task were presumably genuine perceptual errors. Consequently, we expected N2pc amplitude on the delayed-offset trials to be somewhat smaller on error trials than on correct trials, because error trials contain a mixture of postperceptual errors that are due to masking and perceptual errors that are not due to masking. An ANOVA comparing correct and incorrect delayed-offset trials yielded a significant effect of contralaterality,  $F(1, 9) = 48.41$ ,  $p < .001$ , but no significant effect of trial type (correct vs. incorrect) or interaction between contralaterality and trial type (both  $ps > .25$ ). Moreover, N2pc amplitude was significantly greater than zero on both



**Fig. 4.** Grand-average event-related potential waveforms across all 10 subjects at sites OL and OR on delayed-offset trials in Experiment 1. Results are shown separately for trials on which subjects responded correctly (a) and incorrectly (b).

correct trials and error trials,  $F(1, 9) = 18.38, p < .01$ , and  $F(1, 9) = 4.94, p < .05$ , respectively.<sup>2</sup>

These results provide strong evidence that targets masked in this manner are detected by the visual system even if they cannot be accurately reported. This conclusion does not depend on any assumptions about the nature of the lateralized brain activity (e.g., whether it is attention related or arises from a particular brain area). The mere presence of lateralized brain activity is sufficient to indicate that the target was located and hence must have been detected. By making the reasonable assumption that the lateralized activity is the same attention-related N2pc component that has been observed in previous experiments (an assumption consistent with the observed onset time and scalp distribution), it is possible to further conclude that the observers shifted attention to the location of the target equivalently on the two trial types. Thus, as predicted by the object-substitution hypothesis (Di Lollo et al., 2000), targets on the delayed-offset trials were identified and triggered a shift of attention even though they could not be accurately reported.

In addition to supporting the object-substitution hypothesis, these results provide a clear example of dissociations among perception, attention, and awareness. That is, the N2pc results indicate that the visual system was able to detect and direct attention to the target just as well whether it was masked or not, whereas the behavioral responses demonstrate that awareness of the target was substantially impaired on the delayed-offset trials.<sup>3</sup>

## EXPERIMENT 2

It is possible that the pattern of ERP effects observed in Experiment 1 was not due to the characteristics of object-substitution masking per se, but would have been observed with any type of mask, even a mask that impaired the perception of the target. That is, the relationship between N2pc amplitude and target perceptibility might be nonlinear, such that moderate decreases in perceptibility do not lead to decreases in N2pc amplitude. To demonstrate that N2pc amplitude is sensitive to moderate decreases in perceptibility and that we had sufficient statistical power to detect changes in N2pc amplitude in Experiment 1, we conducted an additional experiment in which we used masks consisting of simultaneously presented visual noise, which directly interfere with sensory processing.

Experiment 2 was identical to Experiment 1, except that the delayed-offset trials were replaced by *noise-masking trials* in which the two possible target shapes in each stimulus array were accompanied by simultaneous visual noise that physically obscured the shape contours (see Fig. 1d). The contrast of the noise was adjusted so that the noise produced the same degree of behavioral impairment as the delayed-offset masks in Experiment 1. Because the masks used in Experiment 2 directly interfered with object identification, we predicted

2. The N2pc appeared to end earlier when the observers made target-absent responses than when they made target-present responses, which may indicate that the late phase of the N2pc requires overt detection of the target. However, this possibility does not affect our conclusions in any way.

3. We are not claiming that this is a demonstration of perception without awareness, because masked targets were detected on a substantial proportion of trials. It is extremely difficult to demonstrate that an observer has no awareness of a target, and it may therefore be more fruitful to look for dissociations in the *degree* of perception and awareness rather than dissociations in the *presence* of perception and awareness.

that no N2pc component would be elicited by the masked targets, in contrast to the significant N2pc observed for targets masked by object substitution in Experiment 1.

## Method

A new group of 10 volunteers was recruited. The stimuli and procedure of Experiment 2 were identical to those of Experiment 1 with the following exceptions. The co-termination condition was exactly repeated, but the delayed-offset trials were replaced by noise-masking trials in which each of the two possible target items was obscured by an array of 23 white dots ( $0.065^\circ \times 0.065^\circ$ ) placed randomly within a  $0.75^\circ \times 0.75^\circ$  region centered over the masked object. The masks co-terminated with the search arrays. Accuracy on the noise-masking trials was titrated to match, as closely as possible, the accuracy observed on delayed-offset trials in Experiment 1. Between trial blocks, the luminance of the mask was decreased by 3% (making the mask less visible) if performance was below 60% correct or increased by 3% (making the mask more visible) if performance was above 72% correct.

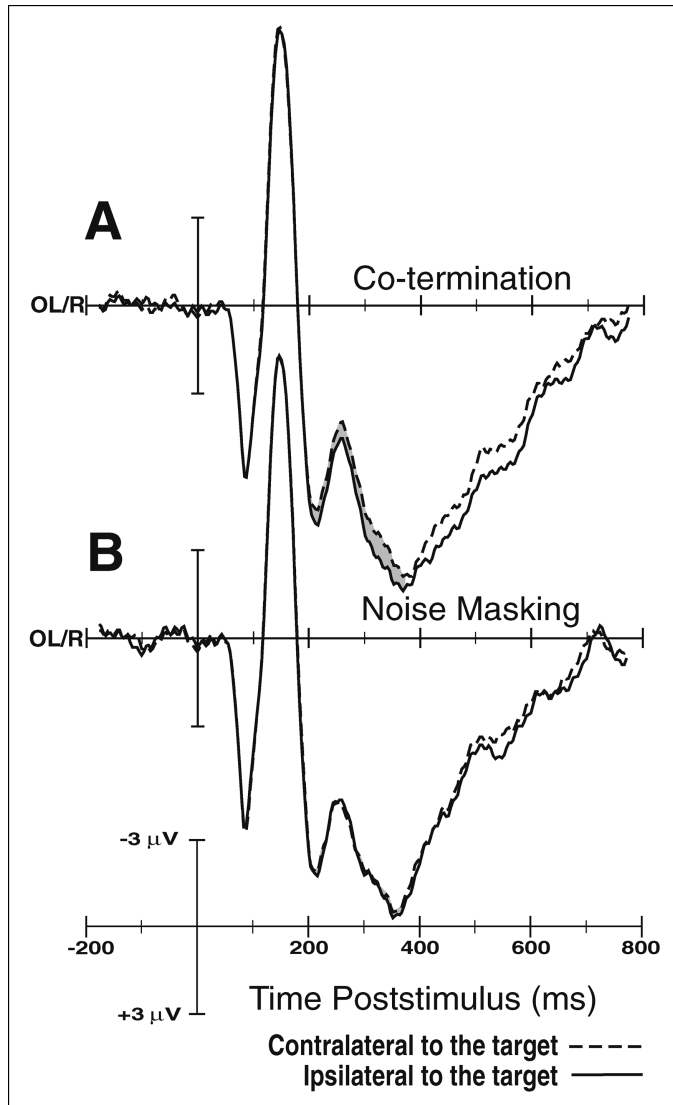
## Results and Discussion

As illustrated in Figure 2b, subjects were significantly less accurate on the noise-masking trials than on the co-termination trials (68.1% vs. 86.7%, respectively),  $F(1, 9) = 29.59, p < .001$ .  $A'$  showed the same pattern as the accuracy data (.731 vs. .902, respectively),  $F(1, 9) = 48.19, p < .001$ . The size of the noise masking effect in this experiment was quite similar to the size of the object-substitution masking effect in Experiment 1.

The ERP waveforms are presented in Figure 5. Targets on co-termination trials elicited an N2pc component beginning approximately 200 ms poststimulus, just as in Experiment 1. In contrast, no lateralized N2pc effects were observed on noise-masking trials. The data were analyzed as in Experiment 1. The only significant effect involving the contralaterality factor was an interaction between trial type and contralaterality,  $F(2, 18) = 8.59, p < 0.05$ , corresponding to the decreased N2pc on the noise-masking trials compared with the co-termination trials. N2pc amplitude was significantly greater than zero on co-termination trials,  $F(1, 9) = 19.71, p < .01$ , but not on noise-masking trials ( $F < 1$ ).

Noise masking eliminated the N2pc component in this experiment, whereas a substantial N2pc was observed for object-substitution masking in Experiment 1 (see the right side of Fig. 2 for a graphical summary of these findings). To provide statistical support for this dissociation, we conducted an ANOVA comparing the noise-masking trials from Experiment 2 with the delayed-offset trials from Experiment 1. The factors were mask type (substitution masking vs. noise masking), contralaterality, and electrode site. We found a significant two-way interaction between mask type and contralaterality,  $F(1, 18) = 3.71, p < .05$ , supporting the observation that N2pc amplitude was suppressed by noise masking compared with object-substitution masking.

These results validate the conclusions drawn from Experiment 1 by demonstrating that the N2pc component is eliminated by masks that interfere with sensory processing. The effects of noise masking and object-substitution masking on behavioral performance were approximately equal, and yet the N2pc component was eliminated by the simultaneous-noise masks and not by the object-substitution masks.



**Fig. 5.** Grand-average event-related potential waveforms across all 10 subjects at sites OL and OR on target-present trials in Experiment 2. Results are shown separately for co-termination trials (a) and noise-masking trials (b).

Thus, Experiment 2 demonstrates that the N2pc component is sensitive to sensory masking, and the finding of no difference between the delayed-offset and co-termination trials of Experiment 1 provides strong evidence that the target was identified and triggered a shift of attention on the delayed-offset trials.

### GENERAL DISCUSSION

In this study, we sought to determine how four small dots can substantially interfere with target detection simply by remaining visible after the target terminates. Di Lollo, Enns, and their colleagues have posited that the initial perceptual processing of the target shape is unaffected by the four dots, but overt detection performance is impaired because the target-plus-mask representation is replaced by the mask-alone representation before the target can be reported (e.g., Di Lollo et

al., 2000; Enns & Di Lollo, 1997, 2000). This hypothesis leads to three specific predictions that were confirmed by the present results.

First, the object-substitution masking hypothesis predicts that targets masked by four dots are initially accurately identified by the visual system. Our results were consistent with this prediction, in that we found brain activity that was lateralized with respect to the location of the target, indicating that the target must have been identified. Second, this hypothesis predicts that attention will be shifted to the target location, but that the target-plus-mask information is replaced by mask-only information before attention reaches the target. Given that the target-plus-mask display was replaced by the mask-alone display after 83 ms and that activity in occipito-temporal areas lags behind the stimulus by 60 to 100 ms (Schmolsky et al., 1998), feedforward information about the target-plus-mask stimulus was probably replaced by feedforward information about the mask-alone stimulus just at the time attention was directed to the location of the target (ca. 200 ms). Third, the hypothesis predicts that although the target is detected and triggers a shift of attention, information about the target is not reliably transferred to higher-level cognitive processes. In the present study, this prediction was confirmed by the observation of significantly impaired behavioral performance in the target detection task on delayed-offset trials.

The present experiments add to the growing number of studies suggesting that object identities can be computed by the visual system without being transferred to working memory, awareness, and other higher-level cognitive systems. There are several different ways in which identification, attention, and higher-level processes have been dissociated in the past. For example, in the classic perception-without-awareness literature, stimuli that are attended but perceptually degraded (e.g., by very brief durations) are shown to lead to near-chance performance in explicit detection or discrimination tasks, but are later shown to influence behavior implicitly (e.g., Jacoby & Whitehouse, 1989; Kunst-Wilson & Zajonc, 1980). Such findings may be explained by positing that the higher-level processes that are necessary for explicit reports exhibit thresholdlike behavior, disregarding weak inputs entirely, but that the processes that lead to implicit effects do not exhibit these thresholds.

Another variety of dissociation has been observed in the *attentional blink* paradigm, in which an observer tries to identify two targets embedded in a stream of rapidly presented foveal items. If the second target is presented 200 to 500 ms after the first target, explicit discrimination of the second target item is severely impaired. However, several studies have demonstrated that the second target is fully identified, making contact with semantic information and influencing implicit measures of performance (Luck, Vogel, & Shapiro, 1996; Maki, Frigen, & Paulson, 1997). The impairment in explicit report of the second target occurs because higher-level processes are still engaged with the first target when the second target appears, and the perceptual representation of the second target is overwritten by the next item in the stimulus stream before it can be transferred into working memory (Giesbrecht & Di Lollo, 1998; Vogel & Luck, 2002). The present results are conceptually similar to these attentional blink findings in that the representation of the target item in the object-substitution masking paradigm is overwritten by the representation of the masks when higher-level processes are not available soon enough at the target location.

Along with previous behavioral studies of object-substitution masking (Di Lollo et al., 2000; Enns & Di Lollo, 1997, 2000; Jiang & Chun, 2001; Neill et al., 2002), the present study indicates that this va-

riety of masking is fundamentally different from other masking paradigms, in which impaired performance reflects primarily an inability to form an accurate perceptual representation. This contrast is particularly clear when the present results are compared with those of a recent study of metacontrast masking (Jáskowski, van der Lubbe, Schlotterbeck, & Verleger, 2002). Whereas we have demonstrated that targets masked by object substitution elicit an N2pc, this prior study demonstrated that primes masked by metacontrast do not elicit an N2pc (although they may influence the allocation of attention to subsequent targets). Thus, object-substitution masking truly represents a new form of masking, one that is consistent with a role of iterative processing in maintaining consistency between one's internal representation of the world and one's continually changing sensory inputs from the world.

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## REFERENCES

- Breitmeyer, B.G. (1984). *Visual masking: An integrative approach*. New York: Oxford University Press.
- Chelazzi, L., Duncan, J., Miller, E.K., & Desimone, R. (1998). Responses of neurons in inferior temporal cortex during memory-guided visual search. *Journal of Neurophysiology*, *80*, 2918–2940.
- Di Lollo, V., Enns, J.T., & Rensink, R.A. (2000). Competition for consciousness among visual events: The psychophysics of reentrant visual processes. *Journal of Experimental Psychology: General*, *129*, 481–507.
- Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology*, *99*, 225–234.
- Enns, J.T., & Di Lollo, V. (1997). Object substitution: A new form of masking in unattended visual locations. *Psychological Science*, *8*, 135–139.
- Enns, J.T., & Di Lollo, V. (2000). What's new in visual masking? *Trends in Cognitive Sciences*, *4*, 345–352.
- Giesbrecht, B.L., & Di Lollo, V. (1998). Beyond the attentional blink: Visual masking by object substitution. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1454–1466.
- Hillyard, S.A., & Picton, T.W. (1987). Electrophysiology of cognition. In F. Plum (Ed.), *Handbook of physiology: Section 1. The nervous system: Vol. 5. Higher functions of the brain, Part 2* (pp. 519–584). Bethesda, MD: Waverly Press.
- Hopf, J.-M., Luck, S.J., Girelli, M., Hagner, T., Mangun, G.R., Scheich, H., & Heinze, H.J. (2000). Neural sources of focused attention in visual search. *Cerebral Cortex*, *10*, 1233–1241.
- Jacoby, L.L., & Whitehouse, K. (1989). An illusion of memory: False recognition influenced by unconscious perception. *Journal of Experimental Psychology: General*, *118*, 126–135.
- Jáskowski, P., van der Lubbe, R.H.J., Schlotterbeck, E., & Verleger, R. (2002). Traces left on visual selective attention by stimuli that are not consciously identified. *Psychological Science*, *13*, 48–54.
- Jennings, J.R., & Wood, C.C. (1976). The e-adjustment procedure for repeated-measures analyses of variance. *Psychophysiology*, *13*, 277–278.
- Jiang, Y., & Chun, M. (2001). Asymmetric object substitution masking. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 895–918.
- Kahneman, D. (1968). Method, findings, and theory in studies of visual masking. *Psychological Bulletin*, *70*, 404–425.
- Kunst-Wilson, W.R., & Zajonc, R.B. (1980). Affective discrimination of stimuli that cannot be recognized. *Science*, *207*, 557–558.
- Lamme, V.A.F., & Roelfsema, P.R. (2000). The distinct modes of vision offered by feed-forward and recurrent processing. *Trends in Neurosciences*, *23*, 571–579.
- Lleras, A., & Moore, C.M. (2003). When the target becomes the mask: Using apparent motion to isolate the object-level component of object-substitution masking. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 106–120.
- Loftus, G.R., & Loftus, E.F. (1988). *Essence of statistics* (2nd ed.). New York: Random House.
- Luck, S.J., & Ford, M.A. (1998). On the role of selective attention in visual perception. *Proceedings of the National Academy of Sciences, USA*, *95*, 825–830.
- Luck, S.J., Girelli, M., McDermott, M.T., & Ford, M.A. (1997). Bridging the gap between monkey neurophysiology and human perception: An ambiguity resolution theory of visual selective attention. *Cognitive Psychology*, *33*, 64–87.
- Luck, S.J., & Hillyard, S.A. (1994a). Electrophysiological correlates of feature analysis during visual search. *Psychophysiology*, *31*, 291–308.
- Luck, S.J., & Hillyard, S.A. (1994b). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 1000–1014.
- Luck, S.J., Vogel, E.K., & Shapiro, K.L. (1996). Word meanings can be accessed but not reported during the attentional blink. *Nature*, *382*, 616–618.
- Macmillan, N.A., & Creelman, C.D. (1991). *Detection theory: A user's guide*. New York: Cambridge University Press.
- Maki, W.S., Frigen, K., & Paulson, K. (1997). Associative priming by targets and distractors during rapid serial visual presentation: Does word meaning survive the attentional blink? *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 1014–1034.
- Neill, W.T., Hutchinson, K.A., & Graves, D.F. (2002). Masking by object substitution: Dissociation of masking and cuing effects. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 682–694.
- Rugg, M.D., & Coles, M.G.H. (1995). The ERP and cognitive psychology: Conceptual issues. In M.D. Rugg & M.G.H. Coles (Eds.), *Electrophysiology of mind* (pp. 27–39). New York: Oxford University Press.
- Schmolesky, M.T., Wang, Y.-C., Hanes, D.P., Thompson, K.G., Leutgeb, S., Schall, J.D., & Leventhal, A.G. (1998). Signal timing across the macaque visual system. *Journal of Neurophysiology*, *79*, 3272–3278.
- Treisman, A., & Souther, J. (1985). Search asymmetry: A diagnostic for preattentive processing of separable features. *Journal of Experimental Psychology: General*, *114*, 285–310.
- Turvey, M.T. (1973). On peripheral and central processes in vision: Inferences from an information-processing analysis of masking with patterned stimuli. *Psychological Review*, *81*, 1–52.
- Vogel, E.K., & Luck, S.J. (2002). Delayed working memory consolidation during the attentional blink. *Psychonomic Bulletin & Review*, *9*, 739–743.
- Vogel, E.K., Luck, S.J., & Shapiro, K.L. (1998). Electrophysiological evidence for a post-perceptual locus of suppression during the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1656–1674.
- Wauschkuhn, B., Verleger, R., Wascher, E., Klostermann, W., Burk, M., Heide, W., & Kompf, D. (1998). Lateralised human cortical activity for shifting visuospatial attention and initiating saccades. *Journal of Neurophysiology*, *80*, 2900–2910.
- Woodman, G.F., & Luck, S.J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature*, *400*, 867–869.

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