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BRIEF REPORT

Amodal completion of unconsciously presented objects

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Abstract In the visual environment, objects often appear behind occluding surfaces, yet they are automatically and effortlessly perceived as complete. Here, we examined whether visually occluded objects that are presented below the threshold of awareness are amodally completed. We used a priming paradigm in which participants responded to consciously perceived targets that were preceded by unconsciously presented primes. In two experiments, we show that discrimination responses to targets were faster when they were preceded by congruent shapes, regardless of whether these shapes were intact and complete or occluded by a horizontal bar. This priming effect was not produced by a partial match in features, since the occluded primes did not facilitate responses to targets that shared local features (Experiment 1) or contained only the object features that remained visible after occlusion (Experiment 2). These results show that objects presented below the threshold of awareness can be amodally completed and provide compelling evidence that unconscious processing occurs to a greater extent than previously considered.

Keywords Visual awareness · Perceptual organization · Priming

As the sun sets over the horizon, we continue to see the sun as round, even though much of it is blocked from the edges of the earth. Indeed, the visual system infers properties of occluded objects in such a robust manner that it becomes difficult to consider alternative interpretations. For example, in Fig. 1, we tend to immediately perceive a single dog behind the tree, with the tail and legs on the left side belonging to the owner of the head on the right. It is very difficult to override this perception and consider the possibility that the tail belongs to another dog hiding behind the tree.

The perception of complete objects behind occluders, referred to as *amodal completion* (Michotte, Thinès, Costall, & Butterworth, 1991), has been considered a complex perceptual correction that occurs only after early stages of visual feature encoding. Corroborating this view, evidence suggests that at short intervals search for a target is not influenced by completion (Rauschenberger, Peterson, Mosca, & Bruno, 2004; Rauschenberger & Yantis, 2001). Furthermore, it takes a longer time for an occluded object to prime the completed object, as compared with a fragment matching the object's visible surface (Sekuler & Palmer, 1992). In contrast, there is also evidence for preattentive amodal completion of objects when occluders remain indiscriminable through inattentional blindness (Moore, Grosjean, & Lleras, 2003). Although the role of attention and the exact timing of perceptual completion have been debated (Guttman, Sekuler, & Kellman, 2003; Joseph & Nakayama, 1999; Plomp & van Leeuwen, 2006; Rauschenberger et al., 2004), the necessity of visual awareness remains largely unexplored.

In the present study, we tested whether visual awareness of occluded objects is necessary for amodal completion. Several studies have shown that complex computations can occur for unconsciously presented stimuli, suggesting that amodal completion may occur for objects that we do not consciously perceive. For example, the perception of simultaneous brightness contrast (Persuh & Ro, 2012), color (Breitmeyer, Ro, & Singhal, 2004), and form (Klotz & Wolff, 1995; Koivisto,

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Fig. 1 An example of amodal completion. The natural interpretation of this image is that the leg and tail protruding on the left of the tree trunk belong to the dog whose head we see on the right of the trunk

Henriksson, Revonsuo, & Railo, 2012; Persuh & Ro, 2013; Ro, Singhal, Breitmeyer, & Garcia, 2009), as well as semantic processing (Abrams, Klinger, & Greenwald, 2002), and cognitive control (Lau & Passingham, 2007; van Gaal, Ridderinkhof, Scholte, & Lamme, 2010), have all been demonstrated to take place outside of awareness of the stimuli. If amodal completion can also occur unconsciously, it would suggest that entire object information, as opposed to fragmented information, is extracted without awareness from natural visual scenes, which are ubiquitous with occluded objects.

To investigate this issue, we used a priming paradigm in which participants responded to targets that were preceded by unconsciously presented (i.e., masked) primes. In two experiments, we tested whether an occluded prime produces more priming for targets that match the completed shape, than for targets that match the visible features of the shape after occlusion.

Experiment 1

In Experiment 1, participants discriminated between full circle and notched circle (pacman) targets preceded by masked primes (Fig. 2). On the basis of previous work demonstrating unconscious priming of shapes (Klotz & Wolff, 1995; Ro et al., 2009), we expected faster and more accurate processing of circle and pacman targets when they were preceded by congruent circle and pacman primes. Importantly, we also measured priming from an occluded prime, which is consciously completed as a circle, even though it is also logically consistent with the possibility of an occluded pacman. We hypothesized that if the occluded shape were unconsciously completed as a circle, it would produce similar priming results as the full circle, giving rise to shorter reaction times (RTs) for circle targets. If, however, the unconsciously presented occluded shape was not completed, it would produce similar RTs for circle and pacman targets, since it shares local features with both targets. In order to ensure that this effect would not be driven by the unoccluded semicircle parts being conceptually more similar to a circle than to a pacman, we included a control condition with semicircle primes.

Method

Participants

Twenty participants (mean age = 19.1 years, 18–23 years old) completed the experiment for course credit. All participants gave written informed consent, as approved by the Institutional Review Board of the City University of New York, and had normal or corrected-to-normal vision.

Stimuli and procedure

All stimuli were presented with Psychophysics Toolbox on a Sony Trinitron GS220 cathode ray tube monitor cycling at a 100-Hz frame rate. The stimuli were a black fixation cross (0.63°), primes (1.09°) and targets (2.62°), presented on a white background. On each trial, participants saw one of four possible primes, followed by one of two possible targets (Fig. 2a). The targets were either circles or pacmen and served as metacontrast masks to the preceding primes, which took one of four shapes: circles, pacmen, occluded shapes, or control semicircles. All primes contained a horizontal rectangle, which acted as the occluder in the occluded shape condition. In order to produce optimal metacontrast masking, the masks/targets were designed with a cutout, which fit the outer edges of every prime. All prime–target combinations appeared equally likely. When the prime or the target was a pacman, it faced either to the left or to the right with equal probability. When the prime and target were both pacmen, they faced the same direction in order to avoid any incongruency effects produced by different stimulus orientations. The control semicircles were misaligned, with the top semicircle being either to the left or to the right of the bottom semicircle an equal number of times.

In the first part of the experiment, participants were asked to respond to the shape of the target (circle or pacman) as quickly and as accurately as possible. In the second part of the experiment, participants were asked to ignore the target and, instead, identify the shape of the masked prime as accurately as possible, making their best guess if unsure. This prime identification task, in which the stimuli were identical to the main experiment, was included to verify that participants were not conscious of the primes and would be at chance in discriminating them.

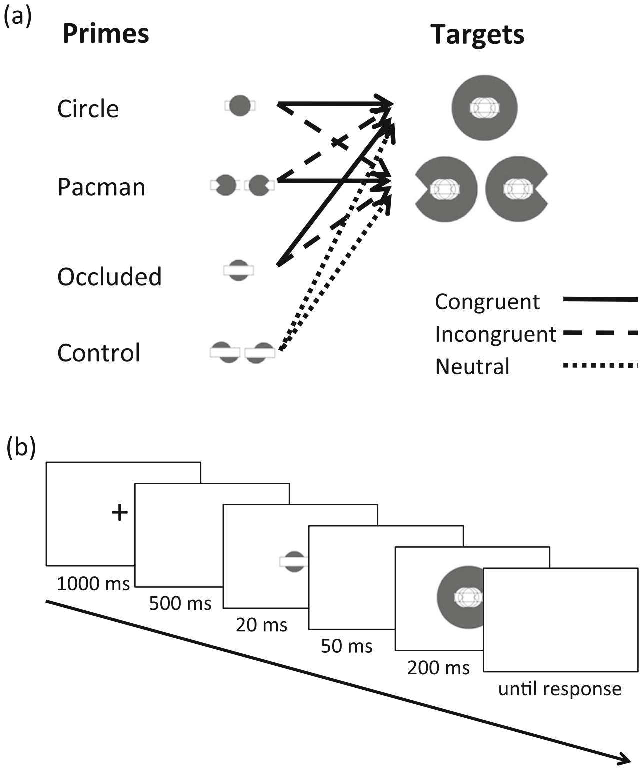

Fig. 2 Stimuli and trial sequence in Experiment 1. **a** Participants responded to pacman and circle targets (right column), which were preceded by four possible primes (left column). Pacman and circle targets were expected to show shorter reaction times and more accurate performance when preceded by congruent (solid lines), as compared with incongruent (dashed lines), primes. Note that the occluded prime was congruent with the circle insomuch as it would be amodally completed. Control primes were expected to have a neutral effect (dotted lines), ruling out the possibility that any effects of the occluded prime would be due to the presence of semicircles. **b** An example sequence for a trial in Experiment 1

Participants sat in a dimly lit room and completed the two parts of the experiment in one session. Responses to circle and pacman targets were made with keyboard presses, using the index and middle fingers of the right hand, with the response assignments counterbalanced across participants. In the target discrimination task, participants completed 288 trials. Each trial (Fig. 2b) began with the presentation of the fixation cross for 1,000 ms, followed by a 500-ms blank interval. The prime was then presented and remained on the screen for 20 ms. The target appeared after a 50-ms blank interval (for a 70-ms stimulus onset asynchrony [SOA]) and remained on the screen for 200 ms. After the 200-ms target presentation, the screen went blank until the participants responded. In the subsequent prime identification task, participants completed half as many trials as in the target identification task (144 trials). Participants were asked to discriminate the prime, as opposed to the target, responding whether it was a circle or a pacman and using the same buttons as before.

Results

For the RT analysis, we excluded trials on which RTs were longer than 1 s or were greater or less than three standard deviations from the individual participant mean (1% of all trials). RTs for correct trials in the target identification task (Fig. 3) were analyzed using a 4 × 2 repeated measures ANOVA, with prime (circle, pacman, occluded, control) and target (circle, pacman) as the within-subjects factors. The results showed no effect of prime, $F(3, 57) = 0.90$, $p = .45$, $\eta_p^2 = .05$, but a main effect of target, $F(1, 19) = 9.96$, $p = .005$, $\eta_p^2 = .33$, with RTs to circles being overall shorter than RTs to pacmen. Importantly, and as predicted, there was also an interaction between prime and target, $F(3, 57) = 14.42$, $p < .001$, $\eta_p^2 = .44$, because the primes differentially affected responses to the different types of targets.

In order to understand this interaction, we performed a one-way ANOVA comparing RTs for the different primes for each target condition separately. There was a significant effect of prime in both the circle target, $F(3, 57) = 12.43$, $p < .001$, $\eta_p^2 = .39$, and the pacman target, $F(3, 57) = 3.23$, $p = .03$, $\eta_p^2 = .14$, conditions. Circle primes produced shorter RTs than did pacman primes for the circle targets, $F(1, 19) = 15.72$, $p = .001$, $\eta_p^2 = .50$, whereas they produced marginally longer RTs than did pacman primes for the pacman target condition, $F(1, 19) = 3.24$, $p = .09$, $\eta_p^2 = .14$. Importantly, occluded primes produced RTs that were similar to the circle primes, that is shorter RTs than pacmen primes in the circle target condition, $F(1, 19) = 22.87$, $p < .001$, $\eta_p^2 = .53$, and longer RTs than pacmen primes in the pacman target condition,

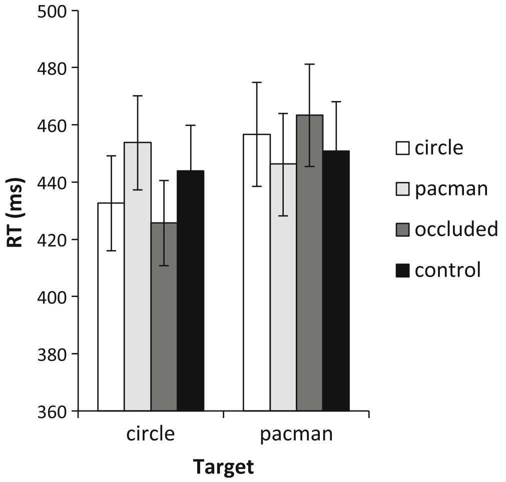

Fig. 3 Reaction time (RT) data for each of the prime and target conditions in Experiment 1. Circle targets were detected faster when they followed congruent circle and occluded primes, as compared with pacman primes. Similarly, pacman targets were facilitated by congruent pacman primes, as compared with circle and occluded primes. These differences were not due to the semicircles contained in the control primes. Error bars indicate one standard error of the mean

$F(1, 19) = 11.41$, $p = .003$, $\eta_p^2 = .38$, suggesting that the occluded stimuli were amodally completed and perceived as circles.

Control (unaligned fragment) primes produced significantly slower responses than circle primes in the circle target condition, $F(1, 19) = 8.24$, $p = .01$, $\eta_p^2 = .25$, but similar responses to circle primes in the pacman target condition, $F(1, 19) = 1$, $p = .33$, $\eta_p^2 = 0$. Control primes also showed significantly slower responses than occluded primes in the circle target condition, $F(1, 19) = 14.81$, $p = .001$, $\eta_p^2 = .43$, and marginally faster responses in the pacman target condition, $F(1, 19) = 3.64$, $p = .07$, $\eta_p^2 = .20$. This suggests that the semicircle fragments, which were present in both the occluded and control prime conditions, do not produce the effects measured with the circle and occluded primes. The accuracy data revealed a similar pattern to the RT results (see the supplementary material).

In order to ensure that the presentation of the primes was below the threshold for awareness, we analyzed accuracy in the prime identification task for each prime condition separately. In the occluded and control prime conditions, we considered a circle response as correct in order to investigate whether participants were more likely to consciously perceive the occluded prime as a circle (Fig. 4). Prime discrimination performance was at chance for the circle ($M = 53\%$, $SD = 15\%$), $t(19) = 1.04$, $p = .31$, the pacman ($M = 48\%$, $SD = 13\%$), $t(19) = -0.62$, $p = .55$, and the occluded prime ($M = 45\%$, $SD = 13\%$), $t(19) = -1.63$, $p = .12$, conditions. Also, in the control misaligned semicircles condition, participants did not show a bias toward one response; they indicated that the prime was a circle on approximately half of the trials ($M = 46\%$, $SD = 14\%$), $t(19) = -1.16$, $p = .26$. Thus, we found, using a conservative objective measure of awareness, that participants remained unaware of the primes for all conditions.

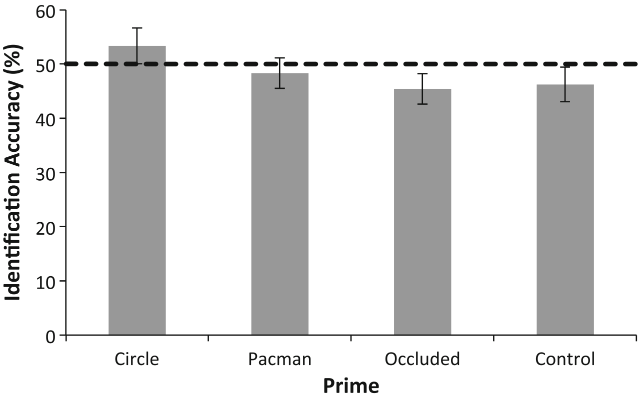

Fig. 4 Prime identification performance in Experiment 1. Participants responded whether the prime was a circle or a pacman. Even though there was no correct response for occluded and control stimuli, we considered a circle response as correct for the purposes of this analysis. Performance was not significantly different from the 50% level expected by chance in the circle and pacman conditions. Also, in the occluded and control conditions, participants' responses were quite evenly distributed, indicating that they could not discriminate the stimuli

Experiment 2

Experiment 1 suggests that unconsciously presented occluded stimuli are perceived as complete shapes. However, it is possible that in Experiment 1 participants may have leaned toward a circle interpretation of the occluded stimulus because they were more familiar with this shape. In a second experiment, we controlled for familiarity by using squares and pairs of horizontally aligned rectangles (i.e., equal signs). We also included a no-prime condition, which allowed us to obtain baseline RTs for the targets without the primes. Moreover, to better control for local feature priming, in this experiment we compared the magnitude of priming from an occluded stimulus to a target that matched the completed shape and to another target that matched only the visible portions of the occluded shape.

The primes were squares that appeared either in front of or behind a horizontal rectangle, or they were equal signs that matched the visible portions of the occluded squares (Fig. 5a). Participants' task was to discriminate between the square and equal sign targets. As before, we expected congruent shape priming, which in this case would mean faster processing of square and equal sign targets when they were preceded by congruent full square and equal sign primes, respectively. Importantly, we hypothesized that if the occluded prime were unconsciously completed as a square, it would produce similar priming results as the full square, giving rise to shorter RTs for square targets. However, if the unconsciously presented occluded prime were not completed, we should observe priming for the equal sign target, which matched the visible portions of the occluded prime.

Method

Participants

Sixteen participants (mean age = 23.1 years, 18–45 years old) completed the experiment for course credit. All participants gave written informed consent, as approved by the Institutional Review Board of the City University of New York, and had normal or corrected-to-normal vision.

Stimuli and procedure

The stimuli were a black fixation cross, primes, targets and pattern masks presented on a light gray background. The primes were a black square (0.94°) in front of or occluded by a gray rectangle (1.50) or an equal sign (two 0.94 × 0.2° black bars that matched the visible portions of the occluded square), or there was no prime. The primes were followed by one of two targets, a square or an equal sign (1.50°). On half of the trials, the primes were masked using two pattern masks, which were 4 × 4 grids, in which cells (0.34°) randomly assumed either the black color of the prime or the gray color of the occluder or

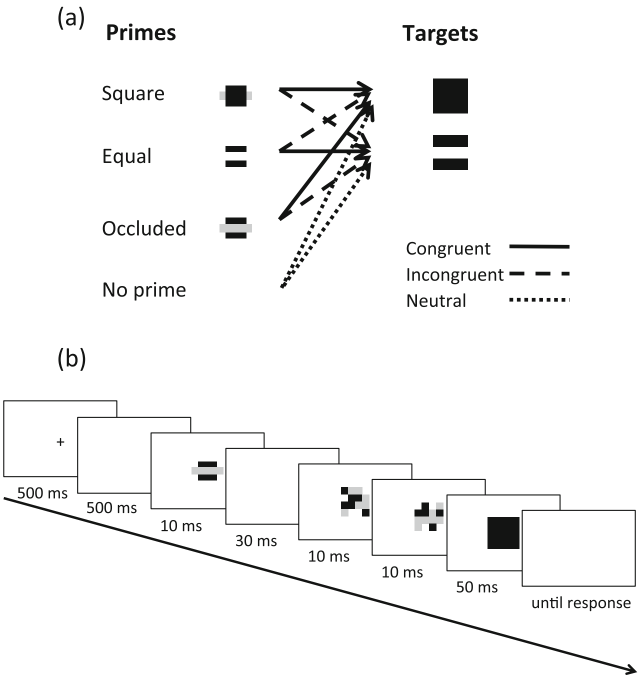

Fig. 5 Stimuli and trial sequence for Experiment 2. **a** Participants discriminated between square and equal sign targets (right column). These targets were preceded by three possible primes or a no prime blank screen (left column). Square and equal sign primes were expected to produce shorter reaction times (RTs) for congruent square and equal sign targets, respectively. We also hypothesized that the occluded primes would be completed and would give rise to shorter RTs for square, as compared with equal sign targets, which matched the occluded prime's visible surface. All conditions were compared with the no-prime control baseline. **b** An example sequence for a masked trial in Experiment 2

remained the background color (with 33% probability) if they were located in the grid's periphery to produce an irregular global mask shape. The mask was used to further reduce visibility of the primes, which were already difficult to detect given the short presentation durations and the brief SOA between primes and targets. All prime, target, and masking conditions appeared with equal probability and in random order.

In the first part of the experiment, participants were asked to respond to the shape of the target (square or equal sign) as quickly and as accurately as possible. In the second part of the experiment, participants were asked to ignore the target and, instead, identify the shape of the masked prime. We asked participants to respond whether the primes were squares, equal signs, or occluded squares (which we called *hidden squares*) in a three-alternative forced choice task.

Participants sat in a dimly lit room and completed the two parts of the experiment in one session. For the target identification task (first part of the experiment), participants completed 256 experimental trials. Each trial (Fig. 5b) began with the presentation of the fixation cross for 500 ms, followed by a 500-ms blank interval. The prime was then presented and remained on the screen for 10 ms. On half of the trials, two successive masks appeared after a 30-ms blank interval, and each remained on the screen for 10 ms (on the other half of the trials, there were no masks, and instead, a blank screen was presented for the same duration). Next, the target appeared for 50 ms and was followed by a blank screen that remained on until participants responded. In the prime identification task (second part of the experiment), participants completed 96 experimental trials. The stimuli in the prime identification task were identical to those in the main experiment; however, participants were asked to discriminate whether the prime was a square, an equal sign, or a hidden square, as accurately as possible, making their best guess if unsure. For the square and equal sign responses in both tasks, participants made keyboard presses, using their index and middle fingers, counterbalanced across participants, whereas for the hidden square response, they pressed an additional button, using their ring finger.

Results

For the RT analysis, we excluded trials on which RTs were longer than 1 s or were greater or less than three standard deviations from the individual participant mean (3% of all trials). RTs for the correct trials in the target identification task (Fig. 6, Table 1) were analyzed using a 4 × 2 × 2 repeated measures ANOVA, with prime (square, equal sign, occluded, none), target (square, equal sign), and masking (mask, no mask) as the within-subjects factors. The results showed a significant effect of prime, $F(3, 45) = 11.35$, $p < .001$, $\eta_p^2 = .43$, with the equal sign prime producing longer RTs than the other two primes and the no-prime conditions. The main effects of target, $F(1, 15) = 2.01$, $p = .17$, $\eta_p^2 = .12$, and masking, $F(1, 15) = 0.12$, $p = .73$, $\eta_p^2 = 0$, were not significant. Importantly, and as predicted, there was an interaction between prime and target,

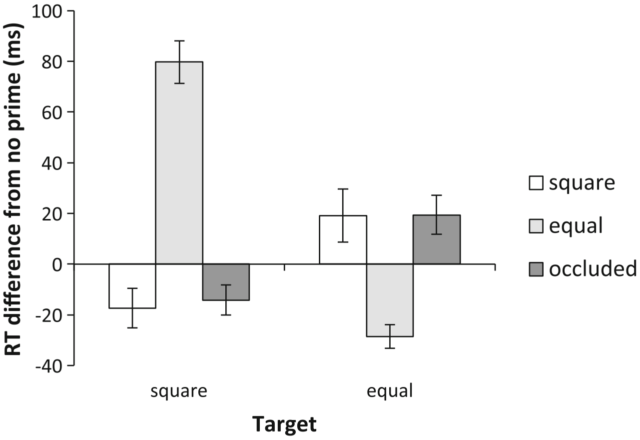

Fig. 6 Priming effects for Experiment 2. Priming for each prime and target condition (collapsed across masking conditions) are expressed as a difference from the no-prime control. Reaction times (RTs) to square targets were shorter after congruent square and occluded primes, as opposed to equal sign primes. Conversely, equal sign targets were responded to faster after equal sign primes, as compared with square and occluded primes. Error bars indicate one standard error of the mean

Table 1 Reaction time data for each prime, target, and mask condition in Experiment 2 (with standard errors of the means in parentheses)

	Target			
	Square		Equal	
Prime	*Masked*	*Unmasked*	*Masked*	*Unmasked*
Square	478 (23)	465 (22)	514 (21)	497 (17)
Equal	544 (15)	593 (22)	461 (17)	455 (24)
Occluded	475 (22)	475 (22)	507 (20)	504 (21)
None	488 (20)	490 (19)	488 (19)	485 (18)

$F(3, 45) = 62.46$, $p < .001$, $\eta_p^2 = .81$, because the primes differentially affected responses to the different targets.

This interaction was, in part, due to congruent shape priming; RTs to the square and equal sign targets were shorter when they were preceded by congruent square and equal sign primes, as compared with incongruent equal sign and square primes [for square targets, $F(1, 15) = 157.66$, $p < .001$, $\eta_p^2 = .92$; for equal sign targets, $F(1, 15) = 20.66$, $p < .001$, $\eta_p^2 = .58$]. More importantly, the results also showed occluded shape priming; the occluded square prime showed similar priming to the full square prime, producing shorter RTs than did equal sign primes in the square target condition, $F(1, 15) = 157.48$, $p < .001$, $\eta_p^2 = .92$, but longer RTs than did equal sign primes in the equal sign target condition, $F(1, 15) = 26.29$, $p < .001$, $\eta_p^2 = .64$. The latter result is important in that it shows that the occluded prime was perceived as a whole square rather than the equal-sign/occluded-square features that were physically presented. In other words, the priming effect from the occluded stimulus was larger for the square target stimulus even though the physical features of the primes that were presented more closely matched the equal sign target stimulus.

There was also a two-way interaction between masking and prime, $F(3, 45) = 5.07$, $p = .004$, $\eta_p^2 = .25$, and a triple interaction between prime, target, and masking, $F(3, 45) = 4.57$, $p = .007$, $\eta_p^2 = .24$, suggesting there was more priming from the equal sign prime to the equal sign target in the unmasked, as compared with the masked, condition (Table 1).

Importantly, the prime–target congruency effects were observed even when we analyzed the trials from the masked condition alone. In the square target condition, RTs were shortest with square, $F(1,15) = 39.78$, $p < .001$, $\eta_p^2 = .73$, and occluded, $F(1, 15) = 36.98$, $p < .001$, $\eta_p^2 = .70$, primes, as compared with equal sign primes. The opposite was the case for equal sign targets, which showed longer RTs for square, $F(1, 15) = 13.11$, $p = .003$, $\eta_p^2 = .47$, and occluded, $F(1, 15) = 12.17$, $p = .003$, $\eta_p^2 = .45$, primes, as compared with equal sign primes. The accuracy data showed a similar pattern to the RT data (supplementary material), although the effects were less reliable, possibly because of the participants' highly accurate overall performance.

In order to ensure that the presentation of the primes was below the threshold for awareness, we analyzed accuracy in the prime identification task. The no-prime trials were excluded from this analysis, since there was no correct response in this case. Overall, prime identification was above the 33% accuracy level expected by chance for both the masked (M = 41.49%, SD = 7.55%), $t(15) = 4.50$, $p < .001$, and the unmasked (M = 50.35%, SD = 12.13%), $t(15) = 5.72$, $p < .001$, conditions. However, follow-up analyses showed that this above-chance discrimination performance was due to the fact that participants could sometimes see the occluding bar and were, therefore, able to accurately discriminate whether the stimulus was one of the two that contained the bar (the square and occluded primes) or whether it was the equal sign, which did not contain any bar (see supplementary material).

Discussion

In the present study, we asked whether amodal completion can occur even for stimuli that are outside of our awareness. We measured the effects of invisible shape primes on visible shape target discriminations. The results showed a similar priming pattern for occluded and unoccluded primes, indicating that occluded primes were amodally completed, even though they were unconsciously presented. These results shed light both on the mechanisms of amodal completion and on the complexity of processing that is possible in the absence of awareness.

In contrast to several previous reports that suggest that amodal completion requires lengthy processing times (Chen, Liu, Chen, & Fang, 2009; Guttman et al., 2003; Sekuler & Palmer, 1992), our results suggest that amodal completion occurs even for very briefly presented stimuli. Thus, our findings are in agreement with studies showing that amodal completion can occur quickly (Murray, Sekuler, & Bennett, 2001), and that it can influence early stages of visual processing. For example, Shimojo, Silverman, and Nakayama (1989) showed that occlusion can affect motion perception: The presence of an occluding surface along the edge of a barber pole stimulus interferes with the usual perception of vertical movement perpendicular to the edge, creating instead the perception of bars that disappear behind the occluding surface. Also, He and Nakayama (1994) found that completion affects visual search in a way that renders precompletion textures inaccessible to search. Moreover, Moore and colleagues (2003) showed that the speed of object discrimination is influenced by occlusion even if participants do not attend to and are unable to discriminate the identity of occluders in an inattentional blindness task. Consistent with these behavioral effects, studies of the neural correlates of amodal completion suggest that occluded stimuli are represented as early as V1 (Sugita, 1999), and that they activate the shape-selective Lateral Occipital Complex (LOC)

(Kourtzi & Kanwisher, 2001; Malach et al., 1995) even when briefly presented (Lerner, Harel, & Malach, 2004).

More importantly, our results suggest that amodal completion occurs for stimuli presented below the threshold for awareness. The phenomenon of amodal completion describes the subjective experience of an inferred object behind an occluder, and here we show that this inference can be made even without a conscious experience of the object per se. This finding is particularly important in that it suggests that the visual system can extract object information from natural scenes, in which many objects appear occluded and may not be consciously perceived. Our results thus add to a growing body of evidence suggesting that complex computations, such as context effects (Persuh & Ro, 2012) and cognitive control (Lau & Passingham, 2007; Rahnev, Huang, & Lau, 2012; van Gaal et al., 2010), can occur without any awareness of the stimuli. One interesting remaining question is whether unconscious amodal completion would occur not only for objects that are highly learned, such as the circles and squares in the present experiment, but also for novel shapes that are completed only on the basis of the visual interpolation of their boundaries (Kellman & Shipley, 1991).

In summary, the results of the present study show that amodal completion occurs even for stimuli that are not consciously represented. This suggests that such complex perceptual operations necessary for object recognition may be taking place for more objects than those that reach our awareness, which likely facilitates accurate gist perception at short exposures. These findings further suggest that entire objects are reconstructed at early levels of encoding and that amodal completion occurs within shorter temporal intervals than previously suspected. Thus, our study provides direct evidence for some of the mechanisms by which objects that are outside of our awareness are encoded, challenging the traditional view that conscious and unconscious perception are fundamentally different.

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