Research Report

Visual Cognition Influences Early Vision

The Role of Visual Short-Term Memory in Amodal Completion

Hyunkyu Lee and Shaun P. Vecera

University of Iowa

ABSTRACT—*A partly occluded visual object is perceptually filled in behind the occluding surface, a process known as amodal completion or visual interpolation. Previous research focused on the image-based properties that lead to amodal completion. In the present experiments, we examined the role of a higher-level visual process—visual short-term memory (VSTM)—in amodal completion. We measured the degree of amodal completion by asking participants to perform an object-based attention task on occluded objects while maintaining either zero or four items in visual working memory. When no items were stored in VSTM, participants completed the occluded objects; when four items were stored in VSTM, amodal completion was halted (Experiment 1). These results were not caused by the influence of VSTM on object-based attention per se (Experiment 2) or by the specific location of to-be-remembered items (Experiment 3). Items held in VSTM interfere with amodal completion, which suggests that amodal completion may not be an informationally encapsulated process, but rather can be affected by high-level visual processes.*

A partly occluded visual object is perceptually filled in behind the occluding surface, allowing the occluded object to appear as a single object that continues behind the occluder. This filling in is known as *amodal completion* (Kanizsa, 1975; Michotte, Thinés, Costall, & Butterworth, 1991). Amodal completion occurs early in visual processing (Davis & Driver, 1998; Rensink & Enns, 1998), perhaps before basic Gestalt perceptual grouping processes (Palmer, Neff, & Beck, 1996). Further, amodal completion is unmodifiable by observers' knowledge or experience (Kanizsa & Gerbino, 1982), which suggests that completion is determined from stimulus properties (e.g., Kellman, Guttman, & Wickens, 2001; Kellman & Shipley, 1991; Takeichi, Nakazawa, Murakami, & Shimojo, 1995). Amodal completion thus meets many of the criteria for being a modular process (Pylyshyn, 1999).

By using indirect measures of completion, recent studies have solidified the view that completion is unaffected by observers' knowledge. Pratt and Sekuler (2001) examined the effect of past experience on amodal completion by using an object-based attention task to assay completion. Observers saw a preview display containing two rectangles and then an occluder covered the middle portions of the rectangles. Next, a peripheral cue summoned attention to an end of one of the rectangles, and then several shapes appeared inside the visible portions of the rectangles. Observers were asked to report the identity of the largest shape.

Performance on such object-based attention tasks reveals a spatial cuing effect: The fastest responses are to targets appearing at the cued location (Egly, Driver, & Rafal, 1994; Vecera, 1994). In addition, responses are faster to uncued (or invalidly cued) targets appearing at the other end of the cued object than to invalidly cued targets appearing in the other, uncued object, revealing the effects of object-based attentional selection. Object-based attention can select both occluded objects (Behrmann, Zemel, & Mozer, 1998; Moore, Yantis, & Vaughan, 1998; Pratt & Sekuler, 2001) and unoccluded objects (Egly et al., 1994; Vecera, 1994).

Interestingly, object-based attentional effects are present even when the preview display contains four distinct objects that are then partially occluded (Pratt & Sekuler, 2001; see Fig. 1a). Such displays contain T-junctions at the intersections of the rectangles and the occluder. These T-junctions trigger completion, overriding observers' knowledge of the objects prior to the

Address correspondence to Shaun P. Vecera, Department of Psychology, E11 Seashore Hall, University of Iowa, Iowa City, IA 52242-1407; e-mail: shaun-vecera@uiowa.edu.

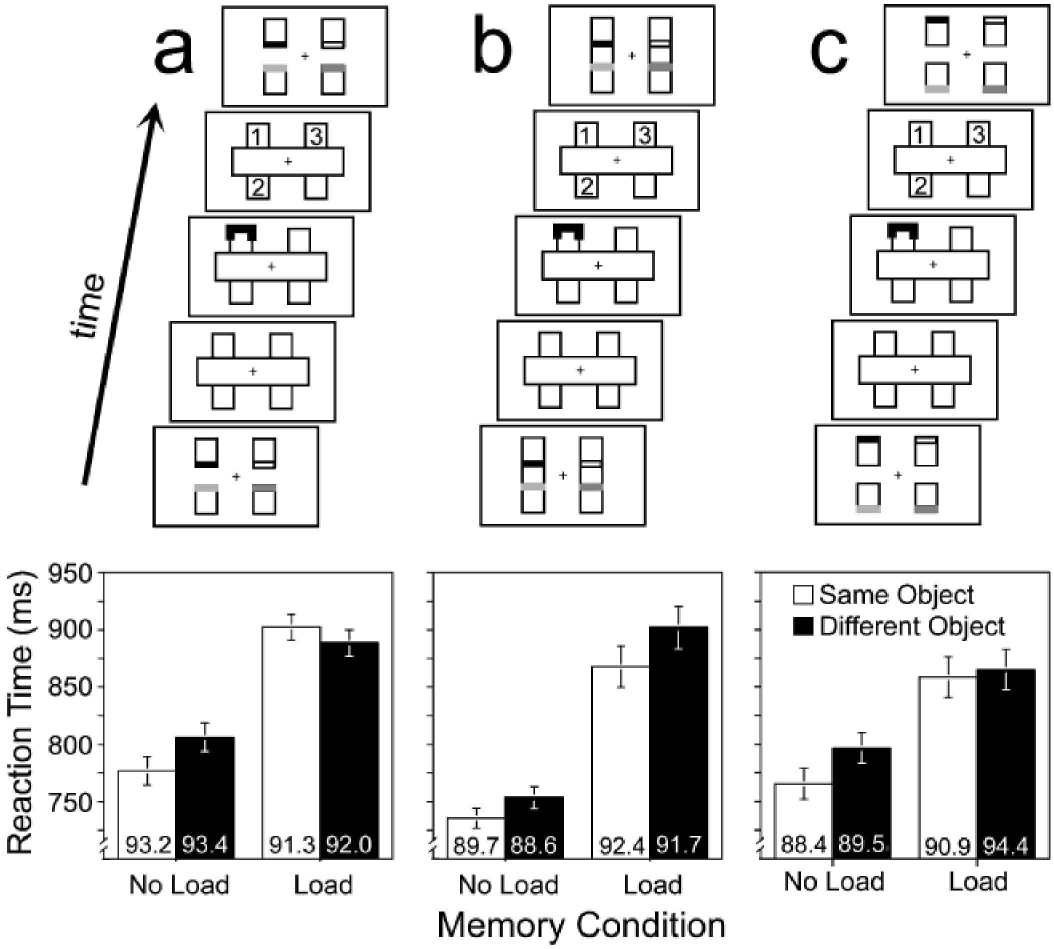

Fig. 1. Order of events and results from invalidly cued trials in Experiments 1 (a), 2 (b), and 3 (c). On each trial, either four (Experiments 1 and 3) or two (Experiment 2) rectangles with color patches were displayed before being partially occluded. Then, one end of one of the rectangles was cued (shown here in black), before a target and distractors appeared in the rectangles. The numbers indicate the locations of different kinds of targets, given a cue in the upper left rectangle, as shown here. A target at Location 1 would be a valid target, a target at Location 2 would be an invalid same-object target, and a target at Location 3 would be an invalid different-object target. In the load condition, observers were tested on their memory for the color patches (top display in each panel) after they completed the object-based attention task. After the color patches appeared in Experiment 3 (c), the rectangles were presented without the patches (not shown) for an additional 500 ms before the occluder appeared. The graphs show reaction time as a function of condition, with the percentage correct shown in each bar. Error bars are within-subjects 95% confidence intervals for the same-object versus different-objects comparisons.

occluder's appearance. That is, even though observers know that there were initially four rectangles, they perceive two objects as a result of amodal completion.

But is amodal completion always stimulus driven? An alternative view is that the operation of high-level visual processes, such as a visual short-term memory (VSTM) or a task-relevant goal, participates in amodal completion. If this is the case, completion would be either slowed or blocked when VSTM is occupied with objects irrelevant to completion. In the following experiments, we developed a direct test of the role of higher cognitive processes in amodal completion processes. We propose that VSTM is a natural process to affect completion because VSTM represents visual objects across temporal delays that exceed iconic memory (Irwin & Andrews, 1996; Luck & Vogel, 1997; Pashler, 1988; Phillips, 1974; Vogel, Woodman, & Luck, 2001). VSTM might maintain the previously visible portions of occluded objects, thereby allowing occluded objects to be completed and perceived as a connected "unit."

We used a dual-task procedure to examine the role of VSTM in amodal completion. Observers performed an object-based attention task in which four objects appeared in a preview display (Fig. 1a). Four color patches appeared inside the ends of the rectangles; on some trials, observers had to remember these colors using VSTM (the *load* condition), and on other trials, observers could ignore the colors (the *no-load* condition). If amodal completion is computed using bottom-up properties only, then completion, indexed by object-based attention, would not be expected to be affected when the ends of the rectangles were being held as separate objects in VSTM. In contrast, if VSTM influences amodal completion by maintaining the previously visible portions of occluded objects, then remembering the ends of the rectangles as separate objects in VSTM would be expected to slow or abolish amodal completion. We included the no-load condition for purposes of comparison, so that we could determine whether any effects in the load condition went beyond those due to the mere presence of the color patches.

METHOD

Participants

Twenty University of Iowa undergraduates with normal or corrected vision participated in each experiment.

Stimuli

In Experiments 1 and 3, displays contained four outlined rectangles measuring 1.4° by 3.9° of visual angle from a viewing distance of 60 cm. The rectangles were oriented either horizontally or vertically; the far edge of each rectangle was 4.4° from the central fixation cross (Figs. 1a and 1c). In Experiment 2, displays contained two large rectangles formed by connecting the edges of the four preview rectangles used in the other experiments (Fig. 1b).

The occluder was a gray rectangle measuring 1.9° by 10.5°. The memory items were four color patches measuring 1.2° by 0.46°. They were selected randomly from a set of six colors (red, blue, violet, green, yellow, and brown). The color patches were located under the occluder in Experiments 1 and 2 (Figs. 1a and 1b) and at the outermost ends of the rectangles in Experiment 3 (Fig. 1c).

The peripheral cue involved brightening the end of one rectangle with a line that was 0.1° thick. Next, four stimuli—three small circles or squares (0.4° in diameter) and one large circle or square (0.9° in diameter)—were presented, with one shape centered at each of the four outer ends of the rectangles. The target was the large stimulus. Circles and squares appeared equally often.

Procedure

Trials began with a 500-ms digit array, which was used for an articulatory suppression task to eliminate verbal encoding of the color patches (Besner, Davies, & Daniels, 1981). A fixation cross appeared (500 ms), followed by the rectangles and color patches (1,000 ms). In Experiments 1 and 2, the occluder then appeared (500 ms), followed by the cue (50 ms). In Experiment 3, the rectangles appeared for an additional 500 ms without the color patches before the occluder appeared. A pilot study revealed that with the stimuli used in this experiment, when the occluder immediately followed the offset of the color patches, the color patches appeared to move toward the occluder.

Following the cue, a target and three distractors were presented (50 ms). Observers pressed the "n" key for a circle target and the "m" key for a square target. There was no limit on response time; the rectangles and occluder were shown until the observer responded. Feedback was given after each response. In the load condition, the memory-test array appeared after the feedback. On half of the trials, this array was identical to the original memory array; on the other half, one item was replaced with a new randomly selected color. Observers made an unspeeded response, indicating whether there was or was not a change in the array.

The load and no-load conditions were blocked, and the order of the two blocks was counterbalanced across participants. There were 160 trials in each block: 60% valid trials, 20% invalid same-object trials (i.e., the target was in the cued rectangle but at the opposite end), and 20% invalid different-object trials (i.e., the target was not in the cued rectangle). In the load condition, observers were instructed to remember the colors until the end of the trial. In the no-load condition, observers were told to disregard the color patches. Observers received breaks every 40 trials and received 10 unanalyzed practice trials at the beginning of each block.

RESULTS AND DISCUSSION

In the no-load condition, only trials in which responses to the target discrimination task were correct were analyzed; in the load condition, only trials in which responses to both the target discrimination task and the memory task were correct were analyzed. Reaction times (RTs) less than 150 ms or greater than 2,000 ms were excluded from the analyses (less than 1% of trials). Valid trials were not analyzed because they are not theoretically relevant. However, data from the valid trials and accuracy data for the VSTM task appear in Table 1. Mean RTs were analyzed with within-subjects analysis of variance, with object (same object, different object) and memory load (load, no load) as factors.

Experiment 1

Figure 1a shows the mean RTs from invalid trials in the object attention task. There was no main effect of object condition, $F(1, 19) = 1.8$, n.s. There was a significant main effect for memory condition, $F(1, 19) = 8.0$, $p < .05$, with faster RTs in no-load blocks (794 ms) than in load blocks (894 ms). There was also a significant interaction between object and memory conditions, $F(1, 19) = 7.1$, $p < .05$. The accuracy data revealed no significant effects but were consistent with the RTs.

We explored the effect of VSTM on amodal completion with planned comparisons between the invalid same-object and invalid different-object conditions. In the no-load condition, invalid same-object trials produced faster RTs (778 ms) than did invalid different-object trials (809 ms), $t(19) = 2.8$, $p < .05$,

TABLE 1

Mean Reaction Times (RTs; in Milliseconds) and Percentage Correct on the Object-Based Attention and Visual Short-Term Memory (VSTM) Tasks

	Object-based attention task (validly cued trials only)				
	No-load condition		Load condition		VSTM accuracy
Experiment	RT	Accuracy	RT	Accuracy	(across all cuing conditions)
1	683.5 (23.4)	93.8% (0.93)	816.1 (29.4)	93.5% (1.0)	80.4% (1.9)
2	663.1 (21.6)	93.2% (1.4)	800.3 (28.9)	93.3% (1.5)	77.8% (2.1)
3	684.0 (28.7)	93.3% (1.4)	784.7 (39.3)	93.5% (1.1)	78.5% (2.1)

Note. Standard errors are in parentheses.

indicating that the four rectangles were completed into two larger rectangles. In the load condition, however, there was no statistical difference between invalid same-object trials (900 ms) and invalid different-object trials (888 ms), $t(19) = 1.1$, n.s. Finally, the correlations between the object effect and accuracy in the VSTM task were not significant, but this could be because of the small variability in the VSTM task (see Table 1).

These results demonstrate that previous knowledge of objects can influence amodal completion, if portions of the objects are encoded and actively maintained in VSTM. When the ends of the rectangles were stored in VSTM, this memory information was incompatible with the possible interpretation of larger completed rectangles when the occluder appeared. Because of the task relevance of the colored patches, the visual system was prevented (or substantially delayed) from reinterpreting the small rectangles as two larger, amodally completed rectangles. This finding suggests that completion is not driven by stimulus information only.

One concern, however, is that the VSTM load may have interfered with object-based attention, rather than amodal completion processes. To address this possibility, in Experiment 2 we connected the four preview rectangles to form two rectangles (Fig. 1b). If the VSTM task affects object-based attention, then we would replicate the findings of Experiment 1. However, if the VSTM task affects amodal completion, then we would observe an object effect in the load condition.

Experiment 2

The mean RTs from Experiment 2 appear in Figure 1b. There were main effects of object condition, $F(1, 19) = 6.7$, $p < .05$, and memory condition, $F(1, 19) = 22.5$, $p < .001$. The interaction between object and memory conditions was not significant, $F(1, 19) < 1$.

As in Experiment 1, we tested the effect of VSTM on amodal completion using planned comparisons. In contrast to the results of Experiment 1, there were significant object effects in both the no-load and the load conditions: In the no-load condition, the relevant RTs were 736 ms versus 754 ms, $t(19) = 2.2$, $p < .05$; in the load condition, the relevant RTs were 868 ms versus 902 ms, $t(19) = 2.0$, $p = .06$. (This marginal result was caused by increased variability in the load condition, due to 1 participant who showed a small object effect in that condition. When this participant was excluded from the analysis, the object effect remained significant in the no-load condition and became significant at the .05 level in the load condition.)

These results suggest that VSTM affects completion processes, not object-based attention. Previously visible portions of occluded objects appear to have been entered into VSTM in the load condition, and ongoing maintenance of this stored information prevented completion (Experiment 1) or assisted completion (Experiment 2).

Although our results suggest that VSTM influences amodal completion, the results could have been due to subjects' attending to the location of to-be-remembered color patches. Because the color patches were adjacent to one another near the separated ends of the four rectangles in Experiment 1, attention may have been constricted around this location before the occluder appeared. When the occluder appeared, the collinear segments that terminated at the occluder might have fallen outside of the attended region, which could have delayed or prevented completion in the load condition (see Lavie & Driver, 1996, for relevant results).

We addressed this attentional-distribution account in Experiment 3 by presenting the color patches at the outer ends of four preview rectangles. We expected that if VSTM affects completion generally, we would replicate the results of Experiment 1. However, if the "breadth" of attention influences completion, then observers would complete the four rectangles in the load condition because attention would be directed globally across the display, allowing the collinear segments of the rectangles to be attended.

Experiment 3

The mean RTs from Experiment 3 appear in Figure 1c. There were main effects of object condition, $F(1, 19) = 4.1$, $p = .05$, and memory condition, $F(1, 19) = 8.6$, $p < .01$. The interaction between object and memory conditions was not significant, $F(1, 19) = 1.1$, n.s. Most important, however, the pattern of object effects was similar to that in Experiment 1: There was a robust object effect in the no-load condition, with faster responses to same-object trials (765 ms) than to different-object trials (797 ms), $t(19) = 2.4$, $p < .05$; there was no object effect in the load condition, with similar RTs on same-object trials (859 ms) and different-objects trials (865 ms), $t(19) < 1$. These results suggest that the reduction of amodal completion in Experiment 1 was not due to an attentional strategy based on the specific location of the color patches.

GENERAL DISCUSSION

Theories of amodal completion have implicitly or explicitly proposed that completion is based on image information such as T-junctions (e.g., Kanizsa, 1975; Kellman & Shipley, 1991; Rock, 1983; Takeichi et al., 1995). However, we have demonstrated that high-level visual processes such as VSTM participate in amodal completion. Completion did not occur automatically when portions of four separate, but aligned, objects were stored in VSTM. Completion occurred when the colored portions did not need to be remembered. These results were due to neither the VSTM task affecting object-based attention nor an attentional restriction based on the location of the color patches.

Our results are important because they indicate that VSTM affects amodal completion. Of course, local, image-based features remain important for completion because such features provide the input to completion processes. But our results demonstrate that information in VSTM can override image-based cues that otherwise trigger completion in no- or low-load situations. Although previous experience can produce new perceptual groups that permit completion (Zemel, Behrmann, Mozer, & Bavelier, 2002), our study is the first to demonstrate that ongoing cognitive processes can both affect and override completion.

One natural question concerns the VSTM processes that affect completion. Many researchers agree that there are distinct VSTM subsystems for spatial and nonspatial (object) information (e.g., Baddeley & Logie, 1999; Logie, 1995). Our results demonstrate that memory for objects can affect completion, but we would not rule out the possibility that memory for locations can also affect completion. Investigating the role of memory for locations might require new measures of completion, however, because object-based attention tasks may depend on spatial attention (Vecera, 1994). Because a spatial memory load can affect spatial attention (Woodman & Luck, 2004), a spatial load might disrupt object-based attention generally.

Finally, our results suggest why some studies have failed to find an influence of higher-level processes on completion (e.g., Pratt & Sekuler, 2001). Because VSTM capacity is typically small (three to four objects; Irwin & Andrews, 1996; Luck & Vogel, 1997), amodal completion will reduce memory storage requirements. This "memory economy" is readily apparent in our experiments: Completing the four preview objects into two larger rectangles changed the storage requirement in VSTM from four to two, thereby reducing memory demands. When the four objects had to be remembered, memory economy no longer prevailed, and completion into two rectangles was blocked. A similar economy may apply to other visual operations that involve missing visual information (e.g., modal completion) or that require information to be integrated across a wide spatial range within a scene (e.g., perceptual organization).

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