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Explicit and Implicit Memory for Rotating Objects

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Although both the object and the observer often move in natural environments, the effect of motion on visual object recognition has not been well documented. The authors examined the effect of a reversal in the direction of rotation on both explicit and implicit memory for novel, 3-dimensional objects. Participants viewed a series of continuously rotating objects and later made either an *old–new* recognition judgment or a *symmetric–asymmetric* decision. For both tasks, memory for rotating objects was impaired when the direction of rotation was reversed at test. These results demonstrate that dynamic information can play a role in visual object recognition and suggest that object representations can encode spatio-temporal information.

An enduring problem in visual cognition addresses how objects are represented internally for purposes of recognition. The apparent ease with which people recognize objects in everyday situations conceals the immense complexity of the underlying mechanisms. Despite numerous studies of object recognition, researchers are still far from a complete understanding of the recognition processes and the underlying representations (for a recent review, see Tarr & Bülthoff, 1998).

Behavioral studies of object recognition have for the most part used static visual stimuli. This tendency is echoed by noting that theories of object recognition are generally accounts of how static objects are recognized. In the real world, however, both the object and the observer often move about in the environment. Once this movement is noted, it then becomes natural to ask, "What are the effects of motion on object recognition?" The lack of investigation of this question is perhaps caused by a belief that shape is an intrinsic attribute of an object, but motion is an external attribute. This line of reasoning suggests that object recognition should not be affected by an object's motion. This belief is also supported by physiological evidence that demonstrates functional specialization in the visual system. For example, under one interpretation, the ventral stream processes shape information, whereas the dorsal stream processes spatial information, including motion (i.e., the *what* vs. *where* distinction; Ungerleider & Mishkin, 1982).

Nonetheless, the perceptual literature has provided some examples in which motion is important for the perception of shape. One such example is the kinetic depth effect (Wallach & O'Connell, 1953), in which motion makes the structure of the object (e.g., a wireframe cube) available to observers. A similar effect is found for biological motion, in which motion makes the perception of biological forms possible, even without any shape information (Johansson, 1973). Perhaps the most forceful argument for the importance of motion in perception comes from Gibson (1979). The theory of ecological optics proposes that visual information resides in the optic array and that invariants are extracted from dynamic optic arrays. According to Gibson, motion is paramount, for "invariants of structure do not exist except in relation to variants" (p. 87); that is, invariants are meaningful only when there is change in the optic array, and hence motion.

Aside from its role in the perception of structure, motion has been shown to play a role in other visual functions. For example, Kozlowski and Cutting (1977) filmed a walking person in the dark with point-lights attached to major joints. When shown such a film, observers can reliably identify the gender of the walker on the basis of pure motion signals in the display. The direction of motion can also bias the identification of ambiguous figures (Bernstein & Cooper, 1997). Finally, research in representational momentum has clearly demonstrated that motion can bias memory for an object's spatial location (Freyd, 1987).

Despite its role in the various functions as mentioned above, motion's role in memory for shape is less clear. A sizable literature exists on the role of motion in memory for faces, a rather special type of shape (see review by O'Toole, Roark, & Abdi, 2002). Faces can exhibit a variety of complex rigid and nonrigid motions, which can provide a rich source of information. For example, using computer-animated synthetic faces, Hill and Johnston (2001) showed that participants could use motion information for identification and gender categorization tasks. Compared with static presentations, motion can also benefit face recognition, especially for familiar faces (reviewed in O'Toole et al., 2002).

The studies on face memory are informative, but it is not clear how they apply to memory for other objects. Two properties associated with faces argue against a quick generalization: (a) Faces seem to involve special processing mechanisms, both psychological and physiological, and (b) Faces possess characteristic (often socially relevant) nonrigid motions, which are uncommon for many other objects.

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In one of the few existing studies, Stone (1998) demonstrated an effect of motion on recognition of 3-D novel objects. In the experiment, participants learned a small set of amoeboid shapes as targets and had to discriminate the targets from similar distractors. Both the targets and the distractors were rotating continuously in depth. Performance improved over blocks of trials when the direction of rotation remained constant. After participants learned to a predefined criterion, the rotation direction was reversed, at which point a significant decrease in performance was observed. Stone (1999) later replicated essentially the same result in another experiment using similar shapes defined by textures of dots, instead of the gray-scale surfaces used in the previous study. He used the term *spatiotemporal signatures* to refer to the temporal or time-varying spatial information contained in a motion sequence and suggested that spatiotemporal signatures are encoded in an object's representation.

We should note that these results, although interesting, were obtained under rather special conditions. One of the important task parameters that often affects performance in object recognition is interstimulus similarity. Experiments using homogeneous stimulus sets tend to produce highly viewpoint-dependent recognition performance, whereas the opposite is true in experiments using heterogeneous stimulus sets (e.g., Edelman, 1995; Tjan & Legge, 1998). It is likely that a highly homogeneous stimulus class invokes subordinate-level recognition, as opposed to basic-level (or entry-level) recognition (Jolicoeur, Gluck, & Kosslyn, 1984; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976)—that level at which initial access to object representations occurs. The stimuli used by Stone (1998, 1999) were amoeboid shapes that were highly similar to each other, and they were presented repeatedly in a continuous recognition task. Under these conditions, participants had to make fine discriminations between targets and distractors. Thus, they were likely engaged in subordinate-level recognition. Furthermore, participants were instructed to memorize the objects intentionally, and they were made aware of the fact that the direction of rotation would reverse during the experiment. It is possible that participants explicitly remembered the rotational direction under these conditions. If explicit memorization of rotation direction is involved during learning, then subsequent change in this attribute might be expected to impair performance. In sum, these experimental parameters seemed to be designed to maximize the likelihood of observing the desired effect.

Given these caveats, it would be useful to know if Stone's (1998, 1999) results hold under more natural conditions. We conducted our initial experiment (Experiment 1) to test the generalizability of the effects observed when the direction of rotation changes. The experiment used a much less homogeneous stimulus set—that is, the stimuli were highly distinct novel objects (see Figure 1 for examples). Moreover, participants were not told to remember the objects intentionally, and they were uninformed about the upcoming reversal in rotation direction. Finally, instead of repeated recognition with a few targets, the task that we adopted was an *old–new* judgment following a study block of many objects. We took these measures to seek converging evidence for spatiotemporal signatures.

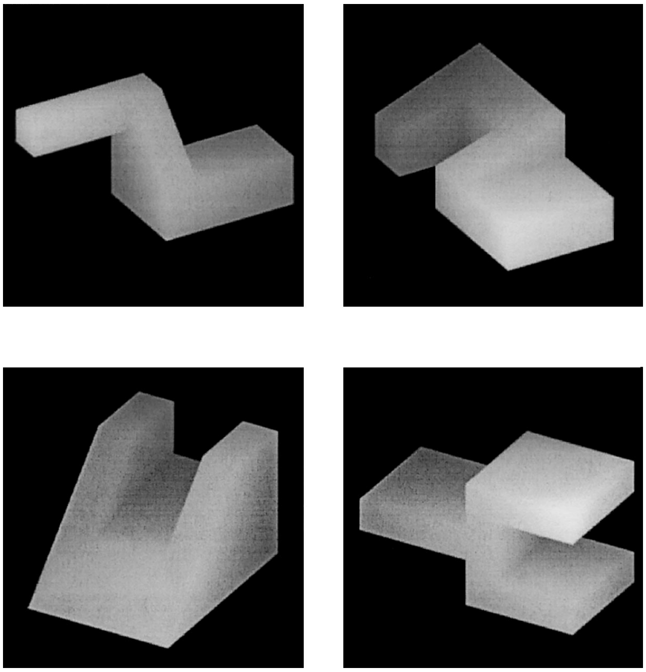

Figure 1. Example stimuli used in the experiments. The top row contains two asymmetric objects, and the bottom row contains two symmetric objects.

Experiment 1

As we mentioned above, the homogeneity of the stimulus set is an important task parameter in object recognition experiments. Whereas Stone (1998, 1999) used highly similar amoeboid shapes, in this experiment we used a set of highly distinct 3-D objects (see Figure 1). There were two blocks in the experiment: a study epoch followed by a memory test. During the study block, participants viewed a series of objects that were rotating continuously in depth and performed an incidental encoding task; that is, they were not informed that a memory test would follow (see the *Method* section). In the test block, participants performed an *old–new* recognition task on studied objects intermixed with nonstudied objects. Half of the studied objects rotated in the original direction, whereas the other half reversed their direction of rotation.

Method

Participants. Twenty-five undergraduate students from Columbia University participated in the experiment for course credit or a payment of $5. One participant was excluded from the data analysis because of computer error.

Materials. The stimuli were composed of 64 objects, half of which were symmetric and the other half asymmetric. The objects contained only flat surfaces and were rendered as solids via depth cuing without an external light source in the scene. Figure 1 shows some examples of the stimuli. Objects were rendered on an Apple Macintosh G3 computer using software written by Taosheng Liu in the C language. They were fit into a window of 300 × 300 pixels at a screen resolution of 1024 × 768 pixels on a 17-in. (43.18-cm) monitor. The screen was placed 1.1 m away from the participant. Thus, the window containing the object had a dimension of 9.4 × 9.4 cm, subtending a visual angle of approximately 4.9°.

Design and procedure. There were two within-subjects factors in the experiment: rotation direction (original vs. reversed) and object type (symmetric vs. asymmetric). For each participant, the study phase contained 32 objects (16 symmetric and 16 asymmetric) randomly selected from the pool of objects. The objects were shown individually, each in a continuous motion sequence around a vertical axis that passed through the object's center (i.e., rotation in depth). For each participant, half of the studied objects (8 symmetric and 8 asymmetric) were randomly selected and assigned a clockwise (CW) rotation, and the other half were assigned to rotate in a counterclockwise (CCW) direction. For each object, an arbitrary orientation was designated as 0°, and all rotations of that object, including those in the test phase, started from that orientation. The motion sequence lasted for 6 s, during which the object rotated for two complete revolutions (720°), resulting in an angular speed of 120° per second. At the beginning of the experiment, participants were told that they would view a series of rotating objects and that they should decide whether each object could be better used as a tool or for support (cf. "functional encoding" condition; Schacter & Cooper, 1993). The experimenter gave some examples of possible uses as tools, such as cutting, pounding, and scooping, as well as examples of possible uses for support, such as sitting, stepping, and leaning. Participants were also told to examine the object carefully for the full duration for which it was on the screen and to respond only after it had disappeared. At the beginning of each trial, a prompt appeared, and participants pressed the space bar on a keyboard to start a trial. They pressed the *Z* key or the */* key to indicate *tool* or *support*, respectively. The study list of 32 items was shown once in a random order separately determined for each participant.

Immediately after the study phase, participants were given instructions for the *old–new* recognition task; that is, they were told to decide whether they had seen a particular object in the previous study phase. All of the studied objects, along with an equal number of nonstudied objects, were used in the test phase. For the studied objects, half of the CW-rotating objects (four symmetric and four asymmetric) were randomly selected to rotate in the original direction (CW), whereas the other half rotated in the CCW direction. Likewise, half of the CCW-rotating studied objects (four symmetric and four asymmetric) were randomly selected to rotate in the original direction (CCW), and the other half rotated in the CW direction. For nonstudied objects, half of them (eight symmetric and eight asymmetric) were randomly assigned to a CW rotation and the other half to a CCW rotation. All objects in the test phase rotated at the same speed as in the study—120° per second. Participants were told that they should make their judgment regardless of the motion and that they could respond at any time after the object appeared. They were also instructed to respond as accurately and as quickly as possible. Each trial started with a prompt, and participants pressed the space bar on a keyboard to see an object. After they pressed the space bar, a rotating object would appear. Participants were told to press the */* key or the *Z* key for *old* or *new* responses, respectively. The rotating object disappeared as soon as the participant responded or after a 6-s period, whichever came earlier. There were two and four filler objects, constituting practice trials, at the beginning of the study and test phases, respectively. Responses to the fillers were not included in the data analysis. The experiment took approximately 25 min to complete. All participants were told the purpose of the experiment at the end of testing.

Results

In the past, the main dependent measure in this type of recognition experiment has been accuracy (e.g., Schacter, Cooper, & Delaney, 1990). However, in this experiment we also analyzed reaction time (RT) for completeness. The results presented below are based on analyses in which participant was the random variable. The analyses with object as the random variable gave similar results for both dependent measures, unless otherwise noted. In all statistical tests reported in this study, a confidence level of $p < .05$ was used.

Recognition accuracy. An initial analysis did not find any difference between CW- and CCW-rotating objects for both the accuracy and RT measures. Thus, we collapsed across the actual rotation in all subsequent analyses. For each participant, two hit rates were calculated on the basis of the studied objects that rotated in the original direction and the reversed direction, respectively, whereas one false-alarm rate was calculated on the basis of the nonstudied objects. The data are plotted in Figure 2A, showing a decrease in recognition accuracy with rotation reversal for both symmetric and asymmetric objects. The four hit rates were subject to a 2 × 2 repeated measures analysis of variance (ANOVA), with object type (symmetric vs. asymmetric) and rotation direction (original vs. reversed) as factors. Both main effects were significant: for object type, $F(1, 23) = 7.81$, $MSE = 0.03$, and for rotation direction, $F(1, 23) = 6.35$, $MSE = 0.02$, although their interaction was not significant. In the by-object analysis, the object type effect was not significant, $F(1, 62) = 2.36$, $MSE = 0.06$, $p > .10$, but the rotation direction effect was still significant, $F(1, 62) = 4.19$, $MSE = 0.04$.

Recognition latency. For the purpose of RT analyses, we considered only trials in which participants made correct responses. For each participant, we calculated three mean RTs, corresponding to the hit trials when objects rotated in the original direction, the hit trials when objects reversed the direction of rotation, and the correct rejection trials for the nonstudied objects. The latency data are plotted in Figure 2B, which shows that RTs were consistently shorter for symmetric objects than for asymmetric objects. There was also a trend for slower RTs with rotation reversal. To test the statistical significance, we performed a 2 × 2 repeated measures ANOVA on participants' mean RTs on hit trials. A significant effect was found for object type, $F(1, 23) = 24.35$, $MSE = 416{,}597$, but not for rotation direction, $F(1, 23) = 2.11$, $MSE = 205{,}406$, $p > .10$, or for their interaction.

Discussion

Results from Experiment 1 showed that when a continuously rotating object had its direction reversed during subsequent testing, memory was impaired. A small but significant drop in the hit rate was exhibited with rotation reversal. A parallel trend of slower response latencies was also observed, although the effect failed to reach statistical significance.

These results are consistent with those obtained by Stone (1998, 1999) and lend support to the idea of spatiotemporal signatures. However, there are several key differences between the present experiment and those of Stone. One concerns the stimuli: Whereas Stone used highly similar amoeboid shapes, we used highly distinct 3-D objects. Stone also used a continuous recognition task in which four target shapes were repeatedly tested over blocks, whereas the present experiment had only one learning episode and one test episode with many more objects. Finally, participants in Stone's experiments were told to memorize the object (intentional encoding) and were aware that rotation reversal would occur during the experiment. In the present experiment, participants performed an incidental encoding task and were not told anything about rotation reversal. Basically, rotation direction was an irrelevant feature for the tasks in both encoding and retrieval. These procedural differences notwithstanding, similar results were obtained—rotation reversal impaired recognition. The demonstrated generalizability of results strengthens the original argument for spatiotemporal signatures.

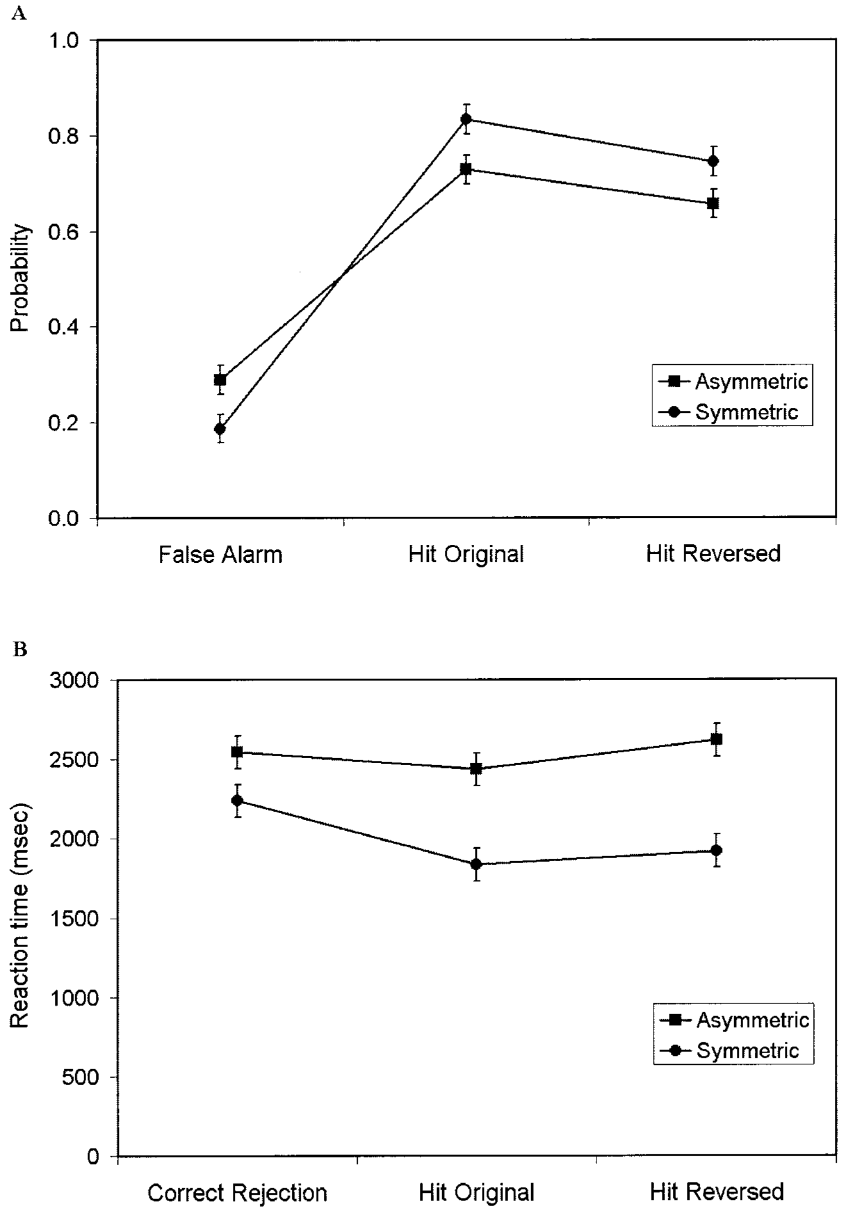

Figure 2. Results of Experiment 1. Panel A plots, separately for symmetric and asymmetric objects, the mean probability of the hit rate for studied objects rotating in the original direction (Hit Original) and for studied objects rotating in the reversed direction (Hit Reversed), as well as the false-alarm rate for nonstudied objects (False Alarm). Panel B plots the mean reaction time for the three conditions as in Panel A. The standard error of the mean was calculated using the interaction term of the analysis of variance (Loftus & Masson, 1994) and plotted as error bars. msec = milliseconds.

Another procedural difference worth noting is that rotations in the current experiment were always around the vertical axis, whereas the rotation axis changed constantly in Stone's (1998, 1999) experiments, producing a tumbled motion. With a fixed axis, the gross profile of an object tends to be more invariant as compared with a changing axis, and such invariance could be beneficial for recognition.[1] To the extent that participants used such a strategy focusing on the profiles, any effect of rotation reversal would be diminished. Thus, the observed effect in this experiment could have been greater had a nonfixed axis of rotation been used.

We also observed a faster RT for symmetric than for asymmetric objects. This difference in RT might be due to the structural redundancy of symmetric objects. Presumably, the processing of symmetric objects is more efficient because the two halves of a

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[1] We thank an anonymous reviewer for pointing this out.

symmetric object are identical via reflection, so that processing one half of the object can facilitate processing the other half. Asymmetric objects, however, do not have such structural redundancy and thus may require more processing.

Experiment 1 provides converging evidence for the importance of dynamic information in object recognition. Even under conditions that favor everyday object recognition, rotation reversal is still effective. Thus, it seems that the rotation direction (or, more generally, the spatiotemporal signature) of a moving object is encoded in its memory representation. The implications of such a conclusion are further considered in the General Discussion.

Experiment 2

An important distinction in the field of memory research is that between explicit and implicit memory. Explicit memory requires deliberate retrieval of past information, as commonly tested by recall and recognition, whereas implicit memory does not require conscious recollection and is usually manifested as a facilitation in performance from study to test, also called priming (for reviews, see Roediger & McDermott, 1993; Schacter, 1987). Experiment 1, as well as Stone's (1998, 1999) experiments, tested explicit memory with an *old–new* recognition task and demonstrated an effect of spatiotemporal signatures. Experiment 2 explored the notion of spatiotemporal signatures in the domain of implicit memory.

In previous studies, Cooper, Schacter, and their colleagues have shown that explicit and implicit memory for visual objects can be dissociated by a number of experimental variables (for a summary, see Cooper & Schacter, 1992). These variables include the encoding task during study (Schacter et al., 1990), study-to-test transformation of object attributes (Cooper, Schacter, Ballesteros, & Moore, 1992), and participant population (Schacter, Cooper, Tharan, & Rubens, 1991). Among these variables, the study-to-test transformation of object attributes has particular relevance to the current reported research (Cooper et al., 1992). For example, with a size change from study to test, *old–new* recognition was impaired, whereas priming was preserved. A left–right reflection (parity) change from study to test produced similar effects. Analogous findings to these attribute changes have also been obtained with familiar objects in a naming task (Biederman & Cooper, 1992). Such results suggest that explicit and implicit memory tasks may make use of different aspects of representations and may rely on different retrieval processes. In particular, Cooper and Schacter (1992) proposed that an episodic memory system underlies *old–new* recognition whereas a structural description system underlies priming.

A general argument from Cooper and Schacter's (1992) research is that a more complete understanding of object representation can be gained by using both explicit and implicit memory tests. These two types of memory tasks probe different aspects of the representation, and they complement each other. In the context of the study-to-test transformation of object attributes, it is meaningful to ask whether a change in the direction of rotation (an object attribute) affects priming. Experiment 2 tested the effect of rotation reversal on priming in a *symmetric–asymmetric* object decision task. Results from this experiment may allow one to infer whether the representations used in implicit memory encode an object's direction of rotation and, more generally, are characterized by spatiotemporal signatures.

The experimental procedure was similar to that used in Experiment 1, except that the task in the test phase was changed from an *old–new* recognition to a *symmetric–asymmetric* decision task; that is, participants had to decide whether an object was symmetric or asymmetric. This task has been used in other studies of implicit memory in which significant priming effects have been observed (e.g., Liu & Cooper, 2001; Srinivas & Schwoebel, 1998).

Method

Participants. Twenty-four undergraduate students at Columbia University served as participants in this experiment. They participated in the experiment in exchange for course credit or for a payment of $5.

Materials. The stimuli were the same 64 objects that were used in Experiment 1.

Design and procedure. The design and the procedure were identical to those of Experiment 1. The only difference was in the test task—a *symmetric–asymmetric* object decision—which is described below. At the beginning of the test phase, participants were told to decide whether an object was symmetric about one or more planes. The concept of symmetry was explained in terms of mirror reflection, and several examples of symmetric and asymmetric objects were shown on paper. After instruction, no participants expressed uncertainty about the distinction between symmetric and asymmetric objects. Participants were instructed to press the */* key if the object was symmetric and the *Z* key if it was asymmetric. They were also told that they should respond as accurately and as quickly as possible and that the rotating object would disappear after a response was made or after a certain interval (6 s), whichever came first. All other aspects of the procedure were identical to those of Experiment 1.

Results

Because the by-participant and by-object analyses yielded similar results, only the former are presented here, and we note wherever the latter gave different results. Because participants had a long exposure duration (6 s) to make a decision, accuracy was expected to be high—perhaps at the ceiling level. Thus, RT was the main measure of interest in this experiment.

Decision accuracy. Again, an initial analysis did not reveal any difference between the CW- and CCW-rotating objects; therefore, subsequent data analyses were collapsed across the actual rotation direction. For each participant, the percent correct rates in all conditions were calculated, and the means are plotted in Figure 3A. As we expected, accuracy was high in all conditions (around 90%). A 2 × 2 repeated measures ANOVA with object type (symmetric vs. asymmetric) and rotation direction (original vs. reversed) was performed on the accuracy scores for studied objects. Only the main effect of object type was significant, $F(1, 23) = 5.81$, $MSE = 0.01$. However, the object type effect was not significant in the by-object analysis, $F(1, 62) = 1.05$, $MSE = 0.05$, $p > .10$.

Decision latency. Only trials with correct responses were entered into the RT analysis. To evaluate the effect of motion on performance, we thought it seemed reasonable to limit analyses to trials in which a response was made during the motion sequence. In other words, responses made after the object had disappeared ceased to be influenced by the dynamic information. Thus, trials with an RT greater than 6 s—the maximal duration of the motion sequence—were excluded. This criterion excluded 38 trials in total (2.8% of the correct trials).

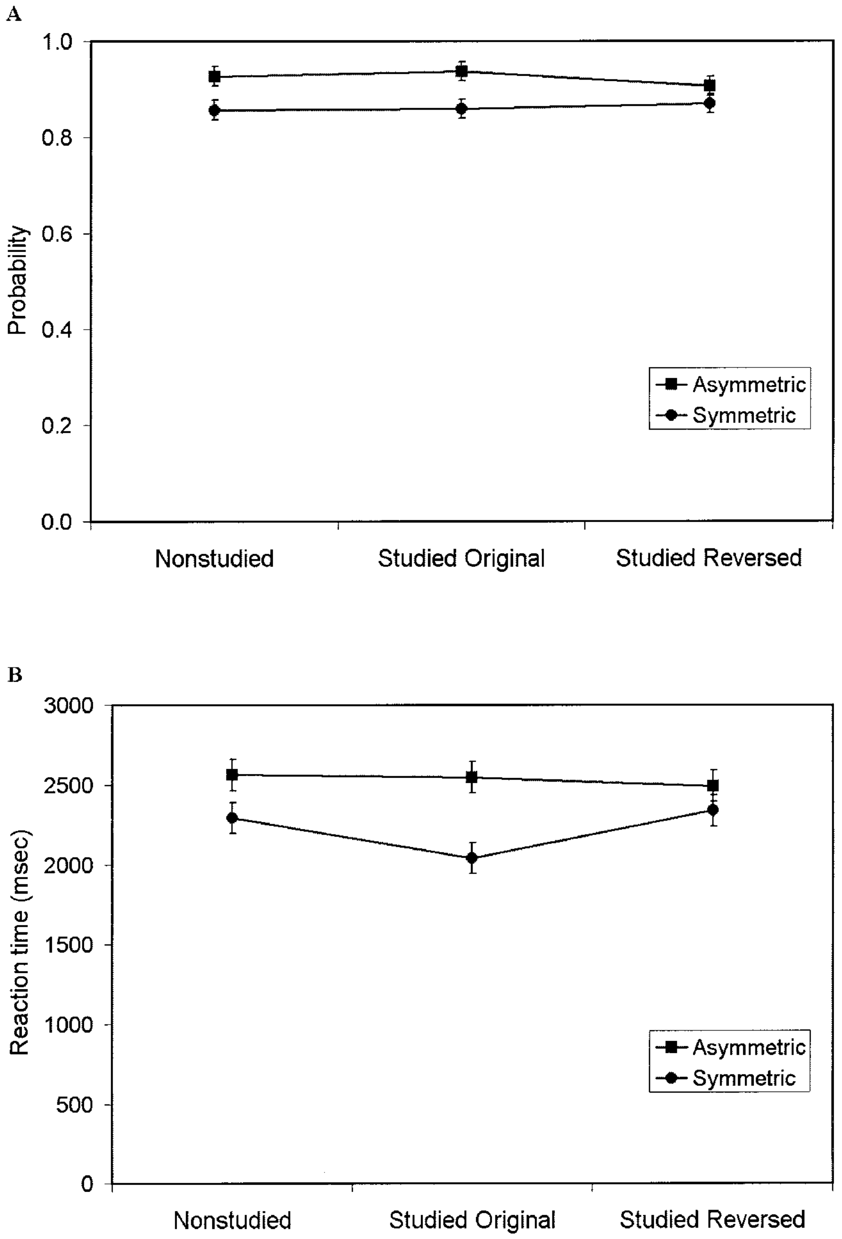

Figure 3. Results of Experiment 2. Panel A plots, separately for symmetric and asymmetric objects, the mean probability of correct response for studied objects rotating in the original direction (Studied Original), studied objects rotating in the reversed direction (Studied Reversed), and nonstudied objects (Nonstudied). Panel B plots the mean reaction time for the three conditions as in Panel A. The standard error of the mean was calculated using the interaction term of the analysis of variance (Loftus & Masson, 1994) and plotted as error bars. msec = milliseconds.

For each participant, the mean RT time in each condition was calculated. The averaged RTs across participants are plotted in Figure 3B, which shows that RTs for asymmetric objects were equivalent in the three conditions. For symmetric objects, RTs for the studied–original objects were shorter than RTs for the nonstudied and studied–reversed objects, which did not differ significantly from each other. A faster RT for the studied than nonstudied objects constitutes the priming effect. Priming effects were evaluated via paired *t* tests between studied and nonstudied objects. The only significant priming effect was that for the studied–original symmetric objects, $M = 253$ ms, $t(23) = 3.16$; none of the other priming effects were significant by *t* tests. The statistical significance was further assessed in a 2×2 repeated measures ANOVA on the studied objects, with object type and rotation direction as factors. There was a significant main effect of object type, $F(1, 23) = 5.65$, $MSE = 465{,}929$, and a marginally significant effect of rotation direction, $F(1, 23) = 3.69$, $MSE = 95{,}570$, $p = .07$. Moreover, the Object Type × Rotation Direction interaction was also significant, $F(1, 23) = 5.92$, $MSE = 125{,}488$, suggesting that rotation reversal had differential effects on symmetric and asymmetric objects.

Discussion

For symmetric objects, significant priming was observed for the studied–original items, whereas priming was absent for the studied–reversed items. For asymmetric objects, priming was not observed, regardless of motion direction. The absence of priming for asymmetric objects is a persistent feature in results obtained on the *symmetric–asymmetric* object decision task (e.g., Kersteen-Tucker, 1991; Liu & Cooper, 2001; Srinivas & Schwoebel, 1998). It is not clear why asymmetric objects did not show priming in this task (for a hypothetical explanation, see Liu & Cooper, 2001). The most relevant point for the present study is that rotation reversal abolished the priming effect for symmetric objects.

The results suggest that at least some form of spatiotemporal information (that relates to the direction of rotation) is important for the representations underlying priming. Because direction of rotation has also been shown to affect explicit *old–new* recognition (Experiment 1), it seems to be encoded in the representations supporting both explicit and implicit memory tasks. It is interesting to consider these results in the framework of distinct memory systems proposed by Cooper and Schacter (1992). In a series of studies, Cooper and colleagues showed that *old–new* recognition and priming were differentially sensitive to changes in stimulus attributes (Cooper, Hilton, Schacter, Frost, & Liu, 1997; Cooper & Schacter, 1992; Cooper et al., 1992). They found that a change in a number of stimulus attributes, such as size, reflection, and scale, reduced *old–new* recognition, although it had no effect on priming. In contrast, a change in some other attributes, such as picture–plane orientation, impaired performance on both types of memory tasks. These results suggest that the representation computed by the structural description system is usually invariant over global changes, whereas the representation computed by the episodic system is generally sensitive to such changes. However, certain aspects of the stimulus must be encoded by both systems for interaction between systems to occur. It seems that both the episodic system and the structural description system can encode some form of dynamic information in their representations.

General Discussion

In two experiments, we tested the effect of rotation reversal on explicit and implicit memory of continuously rotating objects. We observed a detrimental effect of rotation reversal on both forms of memory. Our results extend the research on object representation and recognition into the domain of dynamic information. These results are discussed in more detail below.

Spatiotemporal Signatures and Object Recognition

Spatiotemporal signatures refer to the dynamic spatial information in a motion sequence. Until recently, researchers have generally studied motion in its pure form through the use of displays containing dots and textures (e.g., Anstis, 1986). These displays do not have any apparent structure and, hence, lack spatial information. Although such displays have been instrumental in studies of visual motion processing, people do not usually perceive pure motion in everyday situations. Motion is almost invariably attached to some object. Spatiotemporal signature is thus a more general concept and arguably one with more ecological validity.

Stone (1998, 1999) used a rotation reversal manipulation to demonstrate an effect of spatiotemporal signatures. However, the conditions in Stone's studies were rather specialized, and the goal of Experiment 1 was to test whether the same results held under other circumstances. With several key differences between experimental procedures, the results from Experiment 1 showed similar effects: *old–new* recognition was impaired with rotation reversal. Thus, Experiment 1 provides converging evidence for the notion of spatiotemporal signatures.

In Experiment 1, participants were not given any instruction about rotation direction in either study or test. Thus, the direction of motion was basically irrelevant to participants' task. Still, an effect was found when the motion reversed its direction at test. These results seem to provide stronger support for spatiotemporal signatures than Stone's (1998, 1999) results. Although the direction of motion was made irrelevant in the tasks as specified by the experimenter, it would be interesting to know whether participants remembered an individual object's rotation directions and whether memory for direction affects memory for shape. Memory for the direction of motion was the focus of a recent study by Price and Gilden (2000). In their experiments, participants first viewed a small number of two-dimensional shapes in motion. During test, the same objects were shown, moving in either the original direction or the opposite direction (e.g., leftward vs. rightward, CW vs. CCW). Participants were asked whether the object moved in the original direction. It was found that memory for translation and looming or zooming direction was highly veridical, whereas memory for rotation direction was apparently absent. However, Price and Gilden did not test memory for shape. It would be interesting to explore the relation between memory for motion and memory for shape. Different models can be constructed regarding these relations. In particular, it can be asked whether memory for motion direction aids memory for shape. Future model development and experimentation could provide insight on how these two sources of information interact in memory.

Results from Experiment 1 and from Stone's (1998, 1999) experiments suggest the possibility that object representations can include spatiotemporal information. Theories of object recognition, such as the structural description theories (e.g., Biederman, 1985; Marr & Nishihara, 1978) and view-based theories (e.g., Bülthoff & Edelman, 1992; Tarr & Pinker, 1989), have for the most part been accounts of recognition of static objects. The present findings argue for a temporal dimension in the representation as well. Exactly what form this spatiotemporal representation would assume is not clear. The present findings are also neutral regarding the form of spatial representations for object structure, which is the focus of much ongoing research and debate (e.g., structural descriptions vs. multiple views). Nevertheless, these results reveal a new aspect of object representation and pose a challenge for theory development.

Consistent with the behavioral results reported here, recent neuroimaging work has found evidence for motion-shape interaction in the brain. For example, the motion-sensitive area in the human cortex, the middle temporal area and the medial superior temporal area, was shown to also have an object-selective response (Kourtzi, Bülthoff, Erb, & Grodd, 2002). Another study found a complex pattern of both motion and form selectivity in the lateral temporal cortex (Beauchamp, Lee, Haxby, & Martin, 2002). These results underscore the highly interactive nature of neural computation and provide constraints for biologically realistic models of object recognition.

Spatiotemporal Signatures in Object Priming

The above discussion focuses on explicit memory for visual objects as measured by *old–new* recognition. Priming, a form of implicit memory, was measured in Experiment 2. Priming is important because it seems to be supported by different forms of representations than those supporting explicit *old–new* recognition (see Cooper & Schacter, 1992). In Cooper and Schacter's theoretical framework, a presemantic, structural description system is responsible for priming, whereas an episodic memory system accounts for *old–new* recognition (but also see Carrasco & Seamon, 1996; Ratcliff & McKoon, 1995; Williams & Tarr, 1997).

Experiment 2 showed that rotation reversal abolished priming on a *symmetric–asymmetric* task. The parallel effects of rotation reversal on priming and *old–new* recognition suggest that spatiotemporal information is important for representations underlying both tasks. Considered from Cooper and Schacter's (1992) memory system perspective, the results suggest that both the structural description system and the episodic system can encode spatiotemporal information. In their earlier theorizing, Cooper and Schacter actually alluded to the possibility that the structural description system is sensitive to spatiotemporal information. They wrote, "The structural description system supports the ability to anticipate the changing structure of objects as the objects or the observers move about in space" (Cooper & Schacter, 1992, p. 145). It seems that such an anticipating function can be served by a system that encodes spatiotemporal information. Although this view of the structural description system is consistent with the original formulation of Cooper and Schacter, it also calls for a modification. Cooper and Schacter conjectured that the representation computed by the structural description system is an axis-based, 3-D representation, much like that in Marr and Nishihara's (1978) theory. However, as discussed before, this type of axis-based representation is a static one, one that cannot encode dynamic information. To account for the present findings, Cooper and Schacter's notion of the structural description system must be extended to incorporate a temporal dimension in its representation. The question then arises concerning how to construct dynamic representations using structural descriptions. This is an outstanding question, and it also has implications for structural description theories of object recognition in general (e.g., Biederman, 1985; Marr & Nishihara, 1978). Adapting static structural descriptions to encode spatiotemporal signatures may be a new direction for theoretical development in object recognition research.

Conclusion

The present studies show that a change in the direction of rotation impairs both explicit and implicit memory for visual objects. The results suggest that spatiotemporal information can be encoded in representations underlying both explicit and implicit memory. These data add a new dimension to object representation: the encoding of dynamic information. We further argue that theories of object representation and recognition should consider the interaction between motion and shape as demonstrated here.

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