

Visual Representation of Malleable and Rigid Objects That Deform as They Rotate

Zoe Kourtzi and Maggie Shiffrar
Rutgers University

Most studies and theories of object recognition have addressed the perception of rigid objects. Yet, physical objects may also move in a nonrigid manner. A series of priming studies examined the conditions under which observers can recognize novel views of objects moving nonrigidly. Observers were primed with 2 views of a rotating object that were linked by apparent motion or presented statically. The apparent malleability of the rotating prime object varied such that the object appeared to be either malleable or rigid. Novel deformed views of malleable objects were primed when falling within the object's motion path. Priming patterns were significantly more restricted for deformed views of rigid objects. These results suggest that moving malleable objects may be represented as continuous events, whereas rigid objects may not. That is, object representations may be "dynamically remapped" during the analysis of the object's motion.

To interact successfully with objects in the environment, we must be able to recognize them across changes in their orientation. Consistent with the fundamental nature of this requirement, many studies have examined the perception of objects across orientation change. Because nearly all of these studies have focused on objects moving rigidly, models of object recognition emphasize the maintenance of object structure across orientation change. However, nonrigid objects, such as articulated or elastic objects, can change their shape as they move. For example, an automobile tire deforms when it comes in contact with a surface. Importantly, observation of such an event is associated with the perception of a single object changing shape rather than with the perception of multiple static objects of different shapes. How and when can we recognize objects across nonrigid changes in their shape? To examine this question, we begin with an overview of current approaches to the visual recognition of objects that change.

Object Recognition Across Rigid Changes

As an object rotates, either in the frontal plane or in depth, it changes its orientation relative to the observer. Traditional theories

of object recognition attempt to explain the recognition of objects in novel orientations by proposing two primary types of object representations: object-based representations and image-based representations.

Object-based models suggest that objects are represented as structural descriptions of their three-dimensional (3-D) parts and the relations between those parts in a manner that is independent of the object's orientation relative to the observer (Biederman, 1987; Hummel & Biederman, 1992; Marr & Nishihara, 1978). These models propose that novel object views can be recognized when they are structurally similar to previously observed or "known" views of those objects. Such viewpoint-invariant representations are supported by the finding that observers can easily identify objects rotated in depth as long as the object parts and the spatial relations between them remain the same (Biederman & Gerhardstein, 1993).

Image-based models propose that objects are represented as a set of two-dimensional (2-D) views or snapshots taken at specific orientations relative to the observer. These viewpoint-dependent representations are supported by studies showing that recognition performance decreases with increases in the angular separation between novel and "known" views (Jolicoeur, 1985, 1988, 1990; Jolicoeur & Landau, 1984; Rock, DiVita, & Barbeito, 1981; R. N. Shepard & Cooper, 1982; R. N. Shepard & Metzler, 1971; S. Shepard & Metzler, 1988; Tarr & Pinker, 1989). Viewpoint-dependent models suggest that novel object views can be recognized by aligning a novel view to a canonical view (Palmer, Rosch, & Chase, 1981) or the nearest stored object view (Koriat & Norman, 1988, 1989; Tarr & Pinker, 1989). Moreover, recent psychophysical (Bülthoff & Edelman, 1992; Edelman & Weinsshall, 1991; Poggio & Edelman, 1990) and neurophysiological (Logothetis, Pauls, Bülthoff, & Poggio, 1994; Logothetis, Pauls, & Poggio, 1995) studies suggest that we can recognize novel object views by generalizing between "known" views that are spatiotemporally contiguous and share similar image features. This generalization process appears to be restricted to a spatial window

Zoe Kourtzi and Maggie Shiffrar, Department of Psychology, Rutgers University.

Zoe Kourtzi is now at the Department of Brain and Cognitive Science, Massachusetts Institute of Technology, and Max Planck Institute for Biological Cybernetics, Tuebingen, Germany.

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Correspondence concerning this article should be addressed to Zoe Kourtzi, Max Planck Institute for Biological Cybernetics, Spemannstrasse 38, 72076 Tuebingen, Germany. Electronic mail may be sent to zoe.kourtzi@tuebingen.mpg.de.

extending up to approximately 45° from “known” views (Bülhoff & Edelman, 1992).

Object Recognition Across Nonrigid Changes

Taken together, the approaches to object recognition just described suggest that objects can be identified across rigid rotations that yield object views with similar 3-D parts or image features. One of the potential weaknesses of models based on structural similarity is that they cannot easily explain how we recognize objects after they have been nonrigidly deformed. Specifically, object-based models (Hummel & Biederman, 1992) predict that when deformations cause changes in object parts and part configurations, views of such deformed objects will be particularly difficult to recognize. Image-based models predict that we can recognize novel views of deformed objects by generalizing from “known” views only within a limited deformation range that is equivalent to the generalization range possible with rigid rotations in depth (Sklar, Bülhoff, Edelman, & Basri, 1993; Ullman & Basri, 1991). Thus, both models predict that an object cannot be easily recognized after its shape has changed.

Why might an assumption of object rigidity be detrimental to theories of object recognition? The crux of the problem relates to the fact that ordinary solid physical objects are never absolutely rigid (Love, 1944). Instead, solid objects can undergo various changes in their shape depending on their material composition and the applied forces. For example, objects made of malleable materials, such as balls of clay or rubber, are plastic and can deform nonrigidly. Whether or not these plastic objects can be defined as elastic depends on the forces exerted on them. If the applied force is relatively large, then the deformation will be permanent. A smashed egg and a torn sheet of paper will not regain their original shapes. On the other hand, some objects, depending on the magnitude and duration of the force exerted on them, can change their shape and then recover their original shape. For example, stretched rubber bands and wind-blown trees can regain their original shape once they are returned to their unstressed states. Such objects are defined as having the physical property of elasticity. Thus, solid objects undergo structural deformation in a manner that is dictated by the forces exerted on them and their material composition (Love, 1944).

One possible reason for the inherent difficulty with which many classic models address the visual recognition of deformed objects may be their failure to emphasize surfaces. That is, most models define objects as fixed collections of 3-D parts or 2-D image features. Nonrigid deformations, such as bending, stretching, and twisting, change the structure of 3-D parts and 2-D features because they change the distances between the surface points. Models based on structural similarity do not easily tolerate such structural change. On the other hand, deformations can be easily differentiated on the basis of the effect that they have on object surfaces (Hilbert & Cohn-Vossen, 1952; Jansson, 1977; Koenderink & van Doorn, 1986). Furthermore, surface properties play a critical role in numerous visual processes such as image segregation (He & Nakayama, 1994b; Nakayama, Shimojo, & Silverman, 1989), motion perception (Braddick, 1994; He & Nakayama, 1994a, 1994c; Shimojo & Nakayama, 1990; Shimojo, Silverman, & Nakayama, 1989; Trueswell & Hayhoe, 1993), and visual search (Enns & Rensink, 1990; He & Nakayama, 1992). Such results have

led to the suggestion that object representations may be best understood in terms of surface properties (Nakayama, He, & Shimojo, 1995). As J. J. Gibson (1979) put it, “The surface is where most of the action is” (p. 23). It follows that visible surface properties may play a defining role in object recognition.

Surface properties determine how we can manipulate objects within our environment. Malleability is a fundamental physical property that defines how individuals can use objects. For example, as illustrated in Figure 1, malleability allows an object to change its shape continuously when a force is applied to it (Gray & Isaacs, 1975). When a rigid object is subjected to the same range of forces, its shape will change discontinuously. This difference is clearly illustrated when one considers how the shapes of an egg and of a rubber ball change when they are dropped on a rock.

Behavioral evidence supports the hypothesis that individuals use surface malleability to direct their interactions with objects. For example, young children develop both visual and haptic sensitivity to surface elasticity early on and use it to control their manipulation of objects (E. J. Gibson et al., 1987). Moreover, by the age of 1 month, infants discriminate between elastic and inelastic objects and handle them differently (E. J. Gibson & Walker, 1984). Furthermore, infants use deformability in determining whether they can walk on a particular surface (E. J. Gibson et al., 1987). Adults also demonstrate a significant sensitivity to elasticity (e.g., Warren, Kim, & Husney, 1987). Finally, both young children and adults can generalize across deformed versions of a malleable object, but not of a nonmalleable object, and recognize them as the same object (Landau & Leyton, 1999). When considered together, these findings suggest that surface malleability may play an important role in the visual representation of objects.

The goal of the series of experiments described here was to develop an understanding of the visual representation of deforming objects. To that end, Experiment 1 addressed whether the visual system can generalize across changes in the structure of malleable objects. Experiment 2 examined whether rigid objects are represented differently from malleable objects. Experiments 3 and 4 investigated whether the deformations of malleable and rigid objects are represented as continuous events. Experiment 5 examined whether elastic objects are represented differently from nonelastic objects. Finally, Experiment 6 addressed whether processing time might influence the way in which deforming objects are represented.

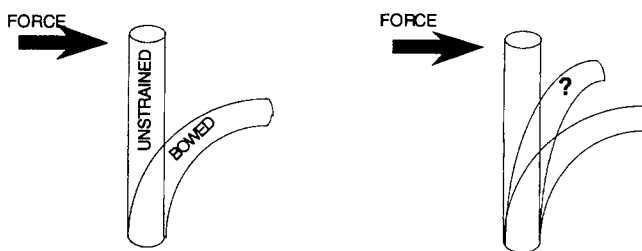


Figure 1. A force is applied to the upper portion of a malleable, elastic tube. As a result of this force, the tube is bowed. When the force is removed, the tube will regain its original or unstrained state. When presented with an unstrained and a bowed version of a malleable object, does the visual system construct intermediate representations of the object?

Experiment 1: Malleable Objects That Deform as They Rotate

Wind-blown plants, locomoting animals, cloth being folded, and bending paper clips are all examples of physical objects that deform as they move. Several studies have demonstrated that nonrigid deformations can be easily recognized (Todd, 1982, 1984). For example, observers can recognize the bending, stretching, and elastic compression of point-defined patterns (Jansson, 1977; Jansson & Johansson, 1973; Jansson & Runeson, 1977; von Fieandt & Gibson, 1959). The relative motions of local elements or point lights are also sufficient for the recognition of human locomotion (Cutting, 1987; Cutting, Proffitt, & Kozlowski, 1978; Johansson, 1973; Kozlowski & Cutting, 1977), human facial expression (Bassili, 1978), and behavioral intentions (Bassili, 1976; Heider & Simmel, 1944). Observers are also able to discriminate well among body motions, hydrodynamic events, and aerodynamic events defined by local elements (Bingham, Schmidt, & Rosenblum, 1995). Taken together, these studies suggest that we can perceive objects moving nonrigidly as unique entities changing shape rather than as multiple discrete snapshots of structurally different objects. The current experiment investigated further the visual representation of moving objects undergoing structural deformation. That is, can the visual system integrate different views of an object that changes its shape as it moves?

A priming paradigm was used to address this question. Priming refers to the facilitated judgment or identification of previously viewed stimuli relative to novel stimuli (Bartram, 1974). Priming is considered to be a sensitive tool for the investigation of object representations because it does not require observers to access representations explicitly (Cooper & Schacter, 1992).

In previous studies, we used a similar priming paradigm to investigate how rigid objects rotating in the frontal plane (Kourtzi & Shiffrar, 1997) and in the depth plane (Kourtzi & Shiffrar, 1999b) are represented. According to an immediate priming paradigm (Sekuler & Palmer, 1992), observers were shown two different views of a prime object that were perceptually linked by apparent motion. After this prime display, observers were asked to match two subsequently presented target objects with each other. The amount of time from the presentation of the target pair until the participant's response was recorded across trials. The results showed that when two different views of a prime object were linked by apparent motion, observers matched the target objects more quickly when the targets had the same structure as the prime object and an orientation that fell within the prime object's path of apparent rotation. Such priming occurred within apparent motion paths extending up to 150° in length. However, under otherwise identical conditions, perception of static views of the prime object did not accelerate judgments of the target objects. Thus, observers more readily represented moving, as compared with static, objects in novel orientations. These results suggest that motion processes play a critical role in the representation of rigid objects across changes in their orientation.

In this experiment, priming was used to examine the implicit representation of malleable objects that deform as they rotate into novel orientations. To that end, participants viewed novel asymmetrical figures from the same category, as shown in Figure 2A. Such stimuli are thought to be represented in a viewpoint-dependent manner (Tarr & Pinker, 1990) and, as such, should not

ordinarily be primed across significant changes in orientation. These stimuli were rotated in the frontal plane because this manipulation changes the relations between the object parts relative to the observer and, as a result, violates the conditions necessary for view invariance (Hummel & Biederman, 1992). As a result, if objects are difficult to recognize after a deformation, then priming should not be found for novel views of the objects used in this experiment.

Method

Participants. Eighty undergraduate students, recruited from the Rutgers University participant pool, took part in this experiment. All had normal or corrected-to-normal vision and were naive to the hypothesis under investigation.

Materials. Stimuli were presented on a 21-in. (53.3-cm) color monitor with a 1,024 × 768 pixel resolution and 60 Hz refresh rate controlled by a PowerMac 7100. The monitor was positioned 95 cm from a chin rest, and the stimuli were drawn within a 12.05 × 4.82 degree of visual angle (DVA) rectangular area on the screen. Participants viewed the stimuli through a circular aperture to minimize framing effects from the monitor.

The stimuli consisted of 40 figures adapted from the asymmetrical characters of Tarr and Pinker (1990). These figures were modified so that they appeared to be 3-D-rendered cylindrical tubes, as shown in Figure 2A. The average vertical and horizontal extent of each figure was 4.5 × 4.5 DVA, and the diameter of each tube was 0.18 DVA.

As described earlier, object deformations are a function of object material and applied force. To create realistic object deformations, it was therefore necessary to deform the stimuli in a manner that was consistent with the material from which they appeared to be constructed. Curvilinear deformations of malleable tubes were selected, because these deformations are well understood (Love, 1944). The malleable appearance of the tubes was created through the use of the "ripple" filter in Adobe PhotoShop 4.0. This filter uses a sinusoidal function (with a 0.30-DVA wavelength and 0.12-DVA amplitude relative to the position of the chin rest) to curve segments smoothly and continuously along their length. This manipulation yielded wavy surfaces that, according to participants in a pilot study, appeared to be malleable. Furthermore, previous studies have suggested that observers perceive novel 2-D objects with wrinkled contours as more malleable and deformable than novel 2-D objects with straight lines and corners (Landau & Leyton, 1999). Because these results implied that curvature is naturally associated with malleability, the use of wavy contours to suggest malleability seemed warranted.

The set of prime objects consisted of 10 asymmetrical 3-D figures. As shown in Figure 2A, the second view of each prime object differed from the first view by a rigid rotation in the frontal plane and a curvilinear deformation. That is, each prime object appeared to deform at the same time as it rotated about its base. The structural deformation of the prime and target objects was created with the "twirl" filter from Adobe PhotoShop 4.0, which deforms straight segments by 90° in polar coordinates. This particular filter was chosen because physical theories of cylindrical forms undergoing curvilinear bending are classically defined in polar coordinates (Love, 1944). The filter was applied to the center of each object figure. As a result, this transformation produced highly dissimilar object views. That is, one view displayed the tubular object in its unstrained or "straight" form, and the other view displayed the object in its bowed or curvilinear form. On the basis of the predictions of most current object recognition models, these views should be particularly difficult to recognize (e.g., Hummel & Biederman, 1992; Sklar et al., 1993). Nonetheless, such a transformation resembles the shape change that malleable objects normally undergo when they are gently bent. Thus, this transformation allowed us to investigate whether the visual system can integrate structurally dissimilar views of malleable objects.

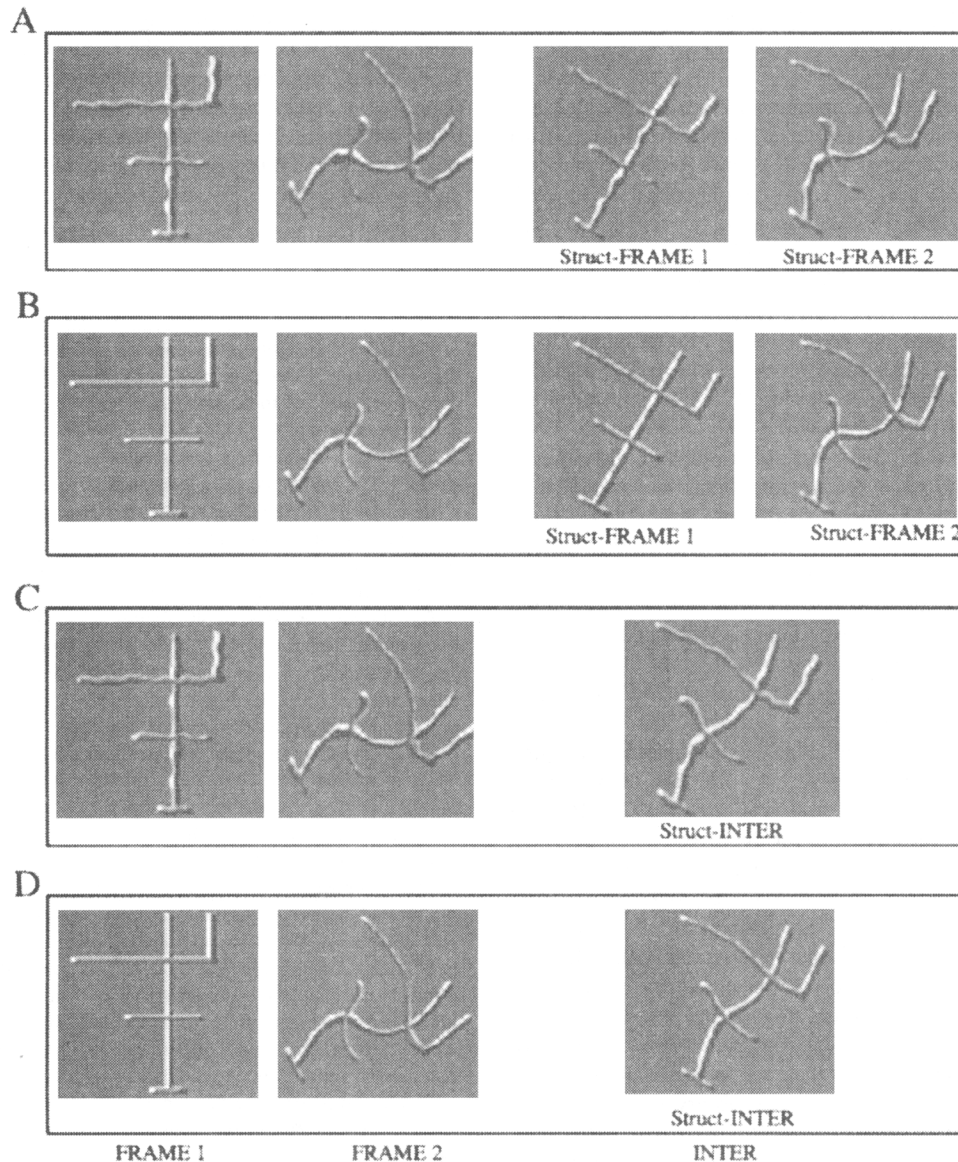


Figure 2. Examples of the asymmetrical figures used. A—Experiment 1, malleable objects; B—Experiment 2, rigid objects; C—Experiment 3, malleable objects; D—Experiment 4, rigid objects. Starting on the left side of each row, the first object illustrates the unstrained version of each class of prime objects. The second object illustrates the strained or bowed version of each class of prime objects. On the right of each row can be found the possible shapes of the target objects. In the first two experiments, the target objects could have the same shape as the prime views (Struct-FRAME 1 or Struct-FRAME 2). In Experiments 3 and 4, the targets had an intermediate shape (Struct-INTER) that was consistent with the implied deformation of the prime object. Any jagged edges appearing on this sample of stimuli are due to the small size of the images required for this figure. The jagged edges were not present in the experimental stimuli.

Procedure. Figure 3 illustrates the experimental procedure. Each trial began with a fixation point presented for 1,500 ms, followed by the first view of the prime object shown for a variable duration (as described subsequently). The second view of the prime object followed for the same duration as the first. A blank screen was then displayed for 500 ms, followed by a pair of target objects presented until the participant responded (with a 3-s maximum). Participants were instructed to observe the prime objects and then to press a key if the two subsequent targets matched each other. Time from target presentation to participant response was

measured in milliseconds. Such a “go–no go” procedure is thought to reduce the variability frequently found with certain priming paradigms (Biederman & Gerhardstein, 1993). Participants were instructed that both reaction time and accuracy were important. Overall feedback (mean reaction time and percentage correct responses) was provided at the end of each block of trials.

The first view of the prime object had one of five possible orientations relative to the observer: 0° (upright), 90°, 180°, –45°, or –135°. The second view of the prime was a rotated version of the first view. The two

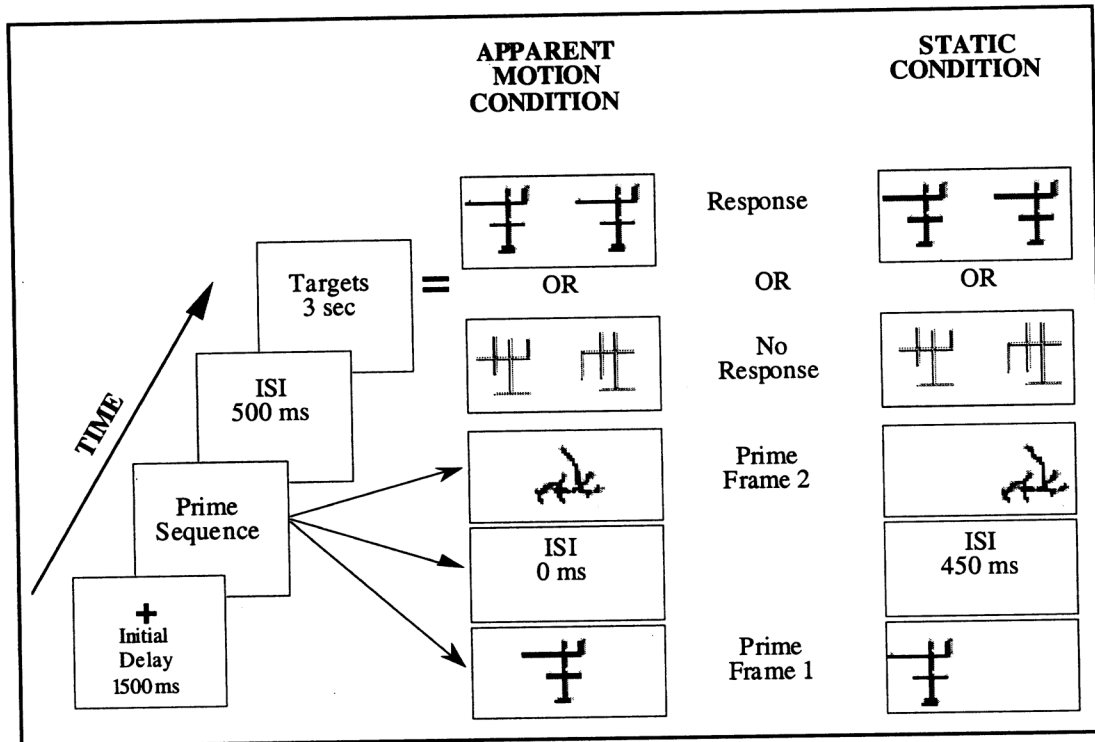


Figure 3. Experimental design for the apparent motion and static conditions. After an initial delay, each trial begins with a prime sequence, followed by a 500-ms interstimulus interval (ISI) and then the presentation of a pair of target figures. Following a go–no go procedure, participants press a button only if the two target figures match each other.

prime views were separated by one of four possible rotation angles: 30°, 60°, 120°, or 150°. Our previous studies (Kourtzi & Shiffrar, 1997) showed that 30° and 60° rotations placed the novel views close enough to the “known” views for priming to be observed under both static and apparent motion conditions. On the other hand, 120° and 150° rotations resulted in priming for novel views only when two views of the prime objects were linked by apparent motion. The second view of the prime was rotated clockwise from the first view of the prime in half of the trials and counterclockwise in the rest. The presentation duration of the two prime views varied with the rotation angle between them such that the optimal apparent motion was achieved. These durations were selected from pilot studies in which participants reported the most compelling motion percepts when each view of the prime object was presented for the duration used by R. N. Shepard and Judd (1976) for the corresponding angle plus a constant of 100 ms. This yielded view durations of 232, 265, 331, and 364 ms for the four rotation angles, respectively. The interstimulus intervals (ISIs) between the two prime views were 0 ms in the apparent motion condition and 450 ms in the static condition. In the apparent motion condition, the first and second prime views were presented so that the prime object appeared to rotate smoothly about its base. In the static condition, the second prime view was displaced 2.41 DVA to the right of the first. This spatiotemporal separation between the two prime views or frames eliminated the perception of apparent motion in the static condition.

In addition to the change in orientation, the two views of the prime differed structurally. During half of the trials, the first view of the prime displayed the unstrained or “straight” form of the tubular object, whereas the second view displayed the object in its bowed or curvilinear form. During the other half of the trials, the first prime view displayed the bowed object, and the second view showed the unstrained object. When shown in motion, these arrangements of views were consistent with the application

of a force to a malleable object. These two trial types were randomly intermixed throughout the experiment.

The target objects were presented in one of three orientations: the first orientation of the prime (Orient–FRAME 1), the second orientation of the prime (Orient–FRAME 2), or the novel, intermediate orientation defined as the bisector of the rotation angle (Orient–INTER). In other words, the orientation of the INTER target equaled the first orientation of the prime plus half of the rotation angle. Table 1 indicates all of the target orientations relative to the prime orientations. Each target object was also presented with the structure of the first prime view (Struct–FRAME 1) or with the structure of the second prime view (Struct–FRAME 2).

The experimental session consisted of six blocks, each containing 40 trials. Each block contained trials with targets at one of the three possible orientations (Orient–FRAME 1, Orient–FRAME 2, or Orient–INTER) and in one of the two possible object structures (Struct–FRAME 1 or Struct–FRAME 2). Each block contained 10 trials in which the two targets were identical to each other and were based on the same figure as the prime, 10 trials in which the targets were identical to each other but were based on a different figure than the prime, and 20 trials in which the targets differed from each other and the prime. Block order was counterbalanced across participants. Stimulus order was randomized within each block.

In a between-subjects design, four groups of 10 participants completed the apparent motion condition, and four groups of 10 participants completed the static condition. Each group of participants observed stimuli at only one rotation angle so that every participant only viewed objects in novel orientations. Before beginning the experimental trials, each participant completed a block of 20 practice trials with objects that differed from those of the experimental trials. Most participants had obtained reaction times less than 1,000 ms by the end of the practice block. Participants having longer reaction times completed a second practice block. In sum,

Table 1
Absolute Orientations of the Two Target Objects as a Function of the Angle of Rotation Separating the Two Views of the Prime Objects

Prime rotation angle	Target orientation		
	Orient-FRAME 1	Orient-FRAME 2	Orient-INTER
30°	0	30	15
	90	120	105
	180	-150	-165
	-45	-15	-30
	-135	-105	-120
60°	0	60	30
	90	150	120
	180	-120	-150
	-45	15	-15
	-135	-75	-105
120°	0	120	60
	90	-150	150
	180	-60	-120
	-45	75	15
	-135	-15	-75
150°	0	150	75
	90	-120	165
	180	-30	-105
	-45	105	30
	-135	15	-60

Note. Orient-FRAME 1 = first orientation of the prime; Orient-FRAME 2 = second orientation of the prime; Orient-INTER = novel, intermediate orientation.

after observing two different views of a nonrigid prime object, participants reported as quickly and accurately as possible whether two simultaneously presented target objects were identical to each other.

Results

In all experiments, only reaction times to correct responses are reported, because all participants exhibited ceiling levels of performance. Priming is reported as a repeated measurement, or as the reaction time difference between trials in which the prime and targets were the same object and trials in which the prime and targets were different objects. The results are reported on the basis of participants and collapsed over all 40 figures, orientation of the first prime frame, structure (unstrained or bowed) of the first prime frame, and rotation direction (clockwise or counterclockwise), because no systematic pattern of differences was observed for these variables. A table showing priming and p values for both the apparent motion and static conditions across rotation angles is presented for each experiment. The p values reported were derived from one-tailed paired t tests used to assess the unidirectional hypothesis that faster reaction times are observed when the targets match the prime than when the targets differ from the prime.

The average reaction time across participants in Experiment 1 was 696 ms ($SD = 140$). Table 2 reports priming and p values for malleable objects in both the apparent motion and static conditions across rotation angles.

To investigate priming for apparently rotating and static malleable objects, we conducted a repeated measures analysis of variance (ANOVA) with priming as the within-measure variable and condition (static or apparent motion), target orientation (Ori-

ent-FRAME 1, Orient-FRAME 2, or Orient-INTER), target structure (Struct-FRAME 1 or Struct-FRAME 2), and rotation angle (30°, 60°, 120°, or 150°) as the independent variables. The results showed significant main effects of priming, $F(1, 432) = 182.42$, $p < .001$; target structure, $F(1, 432) = 32.24$, $p < .001$; and rotation angle, $F(3, 432) = 6.23$; $p < .001$. No significant effects of condition, $F(1, 432) = 0.03$, $p = .852$, or target orientation, $F(2, 432) = 0.48$, $p = .618$, were observed. However, there were significant interactions among condition, target orientation, and target structure, $F(2, 432) = 4.50$, $p < .01$, and between condition and rotation angle, $F(3, 432) = 4.71$, $p < .01$.

These interactions suggest priming differences between rotating and static malleable objects. These differences are further analyzed and illustrated in Figure 4. In the apparent motion condition, targets at novel orientations between the two prime orientations were primed for both small and large rotation angles. In the static condition, significant priming of a novel orientation was observed only for small rotation angles.

Specifically, in the apparent motion condition, a repeated measures ANOVA with priming as the within-measure variable and target orientation, target structure, and rotation angle as the independent variables showed significant main effects of priming, $F(1, 216) = 84.06$, $p < .001$, but no significant effects of target orientation, $F(2, 216) = 1.12$, $p = .332$, or rotation angle, $F(3, 216) = 0.34$, $p = .796$. Interestingly, a significant main effect of target structure, $F(1, 216) = 26.52$, $p < .001$, was observed. Fisher post hoc comparisons showed that the targets were significantly more primed when they had the same structure as the first prime view (Struct-FRAME 1) than when they had the structure of the second prime view (Struct-FRAME 2; $p < .001$).

In the static condition, significant main effects were observed for priming, $F(1, 216) = 99.25$, $p < .001$, and rotation angle, $F(3, 216) = 11.23$, $p < .001$, but not for target orientation, $F(2, 216) = 2.05$, $p > .10$. Fisher post hoc comparisons showed that the small rotation angles (30° and 60°) were significantly more primed ($p < .001$) than the large rotation angles (120° and 150°). A significant main effect of target structure, $F(1, 216) = 7.94$, $p < .01$, was observed. As in the apparent motion condition, Fisher post hoc comparisons showed that the targets were significantly more primed when they had the structure of Frame 1 than that of Frame 2 ($p < .01$).

Taken together, along with the results reported in Table 2, these analyses indicate that rotating malleable objects were primed in all orientations when they had the same structure as Frame 1. However, statically presented malleable objects were only primed, independent of their structure, at orientations falling within a small rotation angle (30° or 60°).

Discussion

The results of this experiment suggest that motion processes can readily link deformed views of objects that appear to be malleable. Specifically, when two structurally different views of a rotating, malleable object were presented under conditions of apparent motion, priming was observed for both the first view and the second view of the prime object. Moreover, when the two prime views were perceptually linked by apparent motion, priming across all rotation angles was observed for the novel view falling in between the two prime views whenever it had the same structure

Table 2
Experiment 1: Amount of Priming (in Milliseconds) for Malleable Objects Across Rotation Angles for All Possible Target Orientations in Struct-FRAME 1 and Struct-FRAME 2 for the Apparent Motion Condition and the Static Condition

Structure and rotation angle	Orient-FRAME 1	<i>p</i>	Orient-INTER	<i>p</i>	Orient-FRAME 2	<i>p</i>
Apparent motion condition						
Struct-FRAME 1						
30°	83.2	.002	152.0	.001	76.2	.036
60°	82.1	.009	78.7	.004	63.5	.025
120°	67.8	.003	83.5	.026	95.9	.007
150°	92.5	.026	91.2	.011	69.9	.006
Struct-FRAME 2						
30°	-1.2	.476	13.5	.294	68.3	.035
60°	0.6	.489	-12.9	.373	82.0	.010
120°	36.2	.152	-2.7	.460	35.4	.010
150°	16.4	.297	4.06	.455	51.0	.010
Static condition						
Struct-FRAME 1						
30°	110.9	.000	111.2	.001	104.8	.009
60°	103.9	.000	63.0	.003	113.5	.000
120°	100.9	.000	8.4	.347	18.2	.236
150°	91.8	.004	21.6	.326	26.0	.249
Struct-FRAME 2						
30°	62.8	.005	81.6	.013	95.2	.012
60°	75.4	.000	81.2	.033	74.4	.003
120°	30.0	.250	20.6	.082	-33.4	.044
150°	9.07	.365	13.3	.281	-20.4	.216

Note. Orient-FRAME 1 = first orientation of the prime; Orient-INTER = novel, intermediate orientation; Orient-FRAME 2 = second orientation of the prime; Struct-FRAME 1 = structure of the first prime view; Struct-FRAME 2 = structure of the second prime view.

as the first prime view (either bowed or unstrained). This result suggests that the visual system can recognize a novel view of an object even after the object has changed its shape.

However, when two structurally different views of a malleable object were perceived statically, novel views of that object were primed only when their orientation differed by a small rotation from the orientation of one of the prime views. When the two static prime views were separated by a large rotation angle, no priming was found when the target objects were displayed in a novel orientation. These results suggest that when orientation change is relatively small, the visual system can generalize across simultaneous changes in object orientation and shape without relying on motion processes (Bülthoff & Edelman, 1992; Sklar et al., 1993). However, robust generalization across simultaneous changes in object orientation and structure may require the recruitment of motion processes.

One could argue that these differences observed between moving and static objects are due to the different spatiotemporal parameters used in the motion and static conditions in this experiment. That is, the two prime frames in the static condition were separated in space and time to eliminate the perception of motion. However, previous results suggest that the observed priming effects are due to the perception of motion rather than to these spatiotemporal differences. Specifically, presentation of a dim gray band that connects two static figures (Shepard's path-guided apparent motion technique) facilitates the perception of apparent motion and results in priming effects similar to the motion condi-

tion (Kourtzi & Shiffrar, 1997). Similarly, placing an occluder between two statically presented views of an object rotated in depth facilitates the perception of rotation in depth and results in priming effects similar to the motion condition (Kourtzi & Shiffrar, 1999b).

Finally, it is important to note that, in the apparent motion condition, the target judgments were significantly more primed when target objects had the same structure as the first, as compared with the second, view of the prime object. The targets were also primed when they had both the structure and orientation of the second view of the prime. On the other hand, target judgments were not primed when the targets had the structure of Frame 2 and the orientation of Frame 1 or the intermediate orientation. However, in the static condition, targets were primed, independent of their structure, when their orientations differed by only a small amount from the orientation of either prime view. Such results suggest two hypotheses. First, for static objects, generalization across orientation and form may be restricted to small changes. Second, for rotating objects, generalization is possible across much larger changes in orientation. Moreover, generalization across shape change may be asymmetric, because the continuous representation of deforming objects may unfold in a specific spatial direction (Freyd, 1987). This possibility was directly examined in Experiments 3-5.

When considered together, the results of the current experiment suggest that motion processes can facilitate the linkage of structurally different views of malleable objects. If these priming results

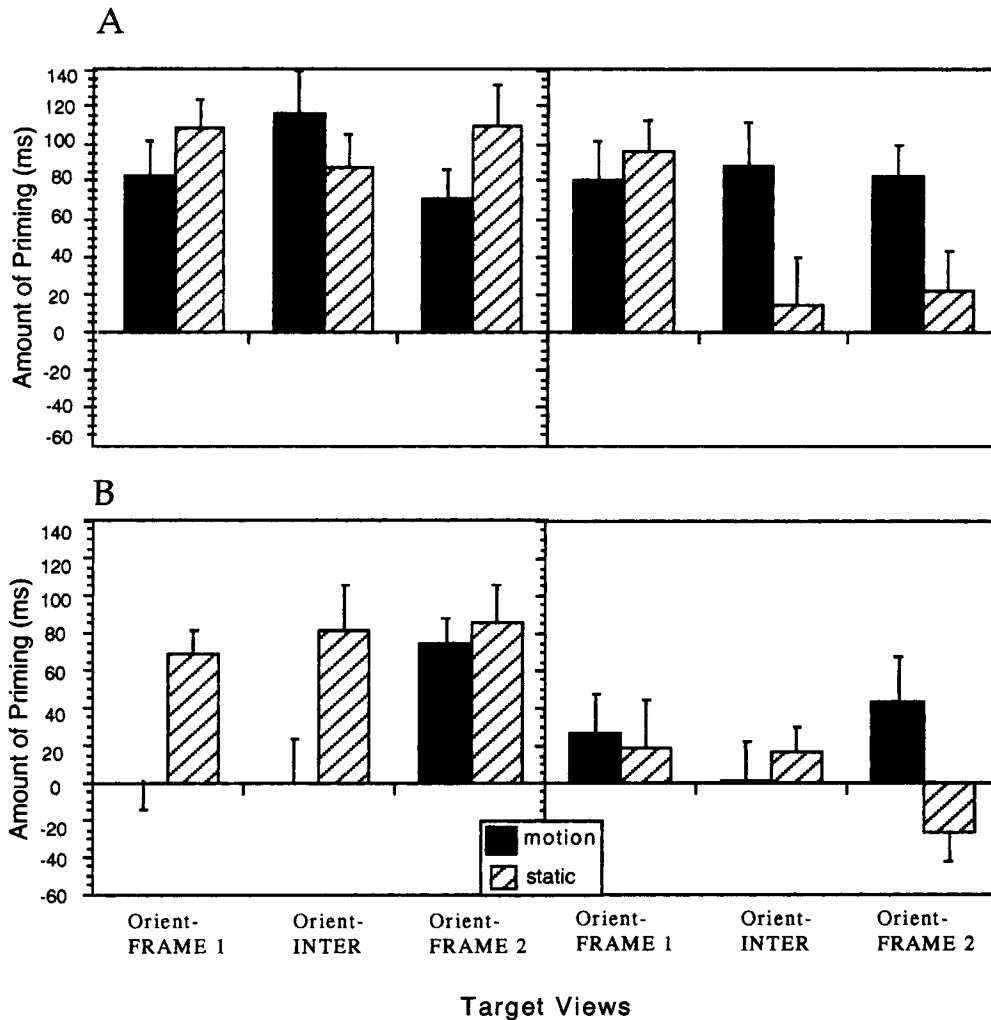


Figure 4. Experiment 1: Magnitude of priming for targets in the apparent motion condition (solid bars) and the static condition (hatched bars). The upper graph (A) indicates priming when the target objects have the same shape as the first view of the prime object (Struct-FRAME 1). The lower graph (B) indicates priming when the target objects have the same shape as the second view of the prime object (Struct-FRAME 2). Each pair of bars indicates priming at a different target orientation (Orient-FRAME 1, Orient-FRAME 2, or Orient-INTER). Data from the small rotation angles (30° and 60°) are shown on the left side, and data from the large rotation angles (120° and 150°) are shown on the right. INTER = intermediate. Error bars indicate standard errors on the amount of priming averaged across participants.

are truly a function of apparent object malleability, then these findings should not be replicated with rigid objects. This prediction was tested in the following experiment.

Experiment 2: Rigid Objects That Deform as They Rotate

When rigid objects, such as rocks and bricks, undergo visible changes in their structure, these changes are discontinuous. For example, the shape of a clay pot will change abruptly and irreversibly when it hits the floor. Conversely, a rubber ball can undergo continuous and reversible shape changes. This difference raises the following question: Are malleable and rigid objects that change their shape represented similarly by the visual system?

Several studies have supported the hypothesis that structural object properties are fundamental to object perception and, presumably, object representation. Some understanding of the relationship between object solidity and possible object transformations is evidenced in infants as young as 5 months of age (Baillargeon, 1986; Baillargeon, Spelke, & Wasserman, 1985). In adults, object rigidity influences the interpretation of object motion (Ishiguchi, 1990; Shiffrar & Freyd, 1990, 1993). Finally, both children and adults categorize deformed versions of malleable but not nonmalleable objects as the same object (Landau & Leyton, 1999). These results suggest that surface properties, such as malleability, may influence the representation of visual objects. To test whether malleable and rigid objects are similarly represented, we

conducted a modified version of Experiment 1 with stimuli that did not appear to be malleable.

Method

Participants. Eighty undergraduate students, recruited from the Rutgers participant pool, took part in this experiment, based on a between-subjects design. All had normal or corrected-to-normal vision and were naive to the hypothesis under investigation. None had participated in the previous experiment.

Materials and procedure. The stimuli consisted of the same 40 asymmetrical figures of Tarr and Pinker (1990) that had been used in Experiment 1. However, in this experiment, the "ripple" filter was not applied to the stimuli. As a result, all of the figures appeared to be rigid metal tubes, as shown in Figure 2B. In all other respects, the stimuli were identical to those used in Experiment 1. Thus, the prime objects deformed in a curvilinear manner that was inconsistent with their apparent rigid composition.

The procedure was identical to that used in Experiment 1. Participants viewed a prime object in two different orientations and then reported whether two subsequently represented target objects matched each other. Reaction time was recorded. Following a between-subjects design, four groups of 10 participants took part in the apparent motion condition (in which the two views of the prime object were perceptually linked by apparent motion), and four groups of 10 participants took part in the static condition (in which the two prime views appeared to be static). Each group observed the prime object at orientations separated by only one of four possible rotation angles: 30°, 60°, 120°, or 150°.

Results

The average reaction time across participants was 773 ms ($SD = 200$). Table 3 reports priming and p values for nonmalleable objects in both the apparent motion and static conditions across rotation angles.

To investigate priming for moving and static rigid objects, we conducted a repeated measures ANOVA with priming as the within-measure variable and condition, target orientation, target structure, and rotation angle as the independent variables. The results showed significant main effects of priming, $F(1, 432) = 73.23$, $p < .001$; condition, $F(1, 432) = 8.62$, $p < .01$; target structure, $F(1, 432) = 17.94$, $p < .001$; and rotation angle, $F(3, 432) = 18.31$; $p < .001$, but no significant effect of target orientation, $F(2, 432) = 1.11$, $p = .315$. However, significant interactions were found between target orientation and target structure, $F(2, 432) = 4.94$, $p < .01$, and between condition and rotation angle, $F(3, 432) = 4.6$, $p < .01$.

These interactions indicate important priming similarities between apparently rotating and static rigid objects that deform. These differences are further analyzed and illustrated in Figure 5. More specifically, in the apparent motion condition, a repeated measures ANOVA with priming as the within-measure variable and target orientation, target structure, and rotation angle as the independent variables showed significant main effects of priming, $F(1, 216) = 17.61$, $p < .001$; target structure, $F(1, 216) = 11.42$, $p < .001$; and rotation angle, $F(3, 216) = 2.71$, $p < .05$. No

Table 3
Experiment 2: Amount of Priming (in Milliseconds) for Rigid Objects Across Rotation Angles for All Possible Target Orientations in Struct-FRAME 1 and Struct-FRAME 2 for the Apparent Motion Condition and the Static Condition

Structure and rotation angle	Orient-FRAME 1	p	Orient-INTER	p	Orient-FRAME 2	p
Apparent motion condition						
Struct-FRAME 1						
30°	57.3	.018	77.7	.000	26.1	.214
60°	72.2	.002	106.5	.005	24.0	.256
120°	46.0	.020	15.1	.291	26.4	.213
150°	45.6	.021	14.2	.233	-9.7	.404
Struct-FRAME 2						
30°	25.2	.205	31.7	.081	14.4	.193
60°	6.8	.430	7.2	.436	16.3	.274
120°	-49.2	.052	1.6	.471	-11.1	.302
150°	14.7	.294	16.4	.173	-19.3	.196
Static condition						
Struct-FRAME 1						
30°	107.6	.000	82.9	.034	96.1	.002
60°	117.9	.001	114.2	.000	99.6	.006
120°	79.8	.019	-4.1	.455	18.7	.224
150°	101.2	.022	-7.5	.328	-32.3	.119
Struct-FRAME 2						
30°	73.3	.004	81.4	.015	89.5	.020
60°	75.7	.025	62.3	.028	128.4	.000
120°	4.6	.448	-59.7	.103	-3.9	.434
150°	-75.2	.053	0.7	.491	-4.2	.356

Note. Orient-FRAME 1 = first orientation of the prime; Orient-INTER = novel, intermediate orientation; Orient-FRAME 2 = second orientation of the prime; Struct-FRAME 1 = structure of the first prime view; Struct-FRAME 2 = structure of the second prime view.

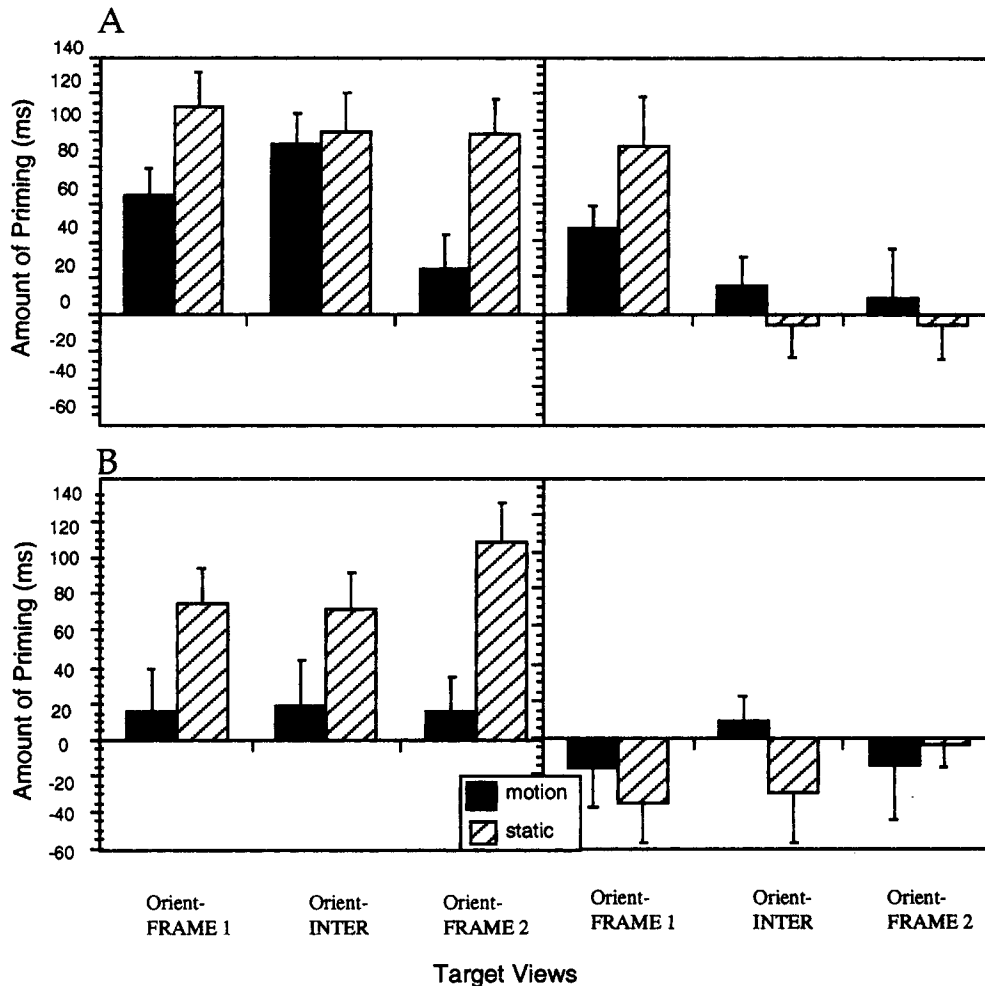


Figure 5. Experiment 2: Magnitude of priming for targets having the structure of the first (A; Struct-FRAME 1) or second (B; Struct-FRAME 2) prime frame across variations in target orientation and rotation angle. Orient-FRAME 1 = first orientation of the prime; Orient-INTER = novel, intermediate orientation; Orient-FRAME 2 = second orientation of the prime. Error bars indicate standard errors on the amount of priming averaged across participants.

significant effect of target orientation, $F(2, 216) = 1.93, p = .15$, was observed. Fisher post hoc comparisons showed that the targets were significantly more primed when they had the structure of Frame 1 than that of Frame 2 ($p < .001$) and when the two views of the prime object were separated by a small rotation angle (30° or 60°) than by a large rotation angle (120° or 150° ; $p < .05$).

Similarly, in the static condition, significant main effects of priming, $F(1, 216) = 58.01, p < .001$; target structure, $F(1, 216) = 7.09, p < .01$; and rotation angle, $F(3, 216) = 18.32, p < .001$, were observed. Again, no significant effect of target orientation, $F(2, 216) = 1.50, p = .218$, was observed. Fisher post hoc comparisons showed that, once again, the targets were significantly more primed when they had the structure of Frame 1 than that of Frame 2 ($p < .01$) and when the two views of the prime object were separated by a small rotation angle (30° or 60°) than by a large rotation angle (120° or 150° ; $p < .001$).

Taken together with the results reported in Table 3, these analyses indicate that, for small rotation angles of rigid prime objects,

novel views were primed only when they had the same structure as the first view of the prime. For large rotation angles, both moving and static objects were primed only when they were presented at the same orientation and structure as the first prime view.

Discussion

The results of this experiment, when combined with those of Experiment 1, indicate an intriguing pattern of similarities and differences in the visual representation of malleable and rigid objects. Similarities in the representation of objects that appear to be malleable or rigid were most prevalent when the prime views were perceptually static. That is, in the static condition of Experiment 2, deformed views of rigid objects were primed in much the same way as the malleable objects from Experiment 1. Specifically, when the orientations of the target and prime figures differed by only a small rotation, priming was observed for the two "known" views of the prime figure and for the novel view oriented

between the prime views. This held true when the target figures had the same structure as the first or second prime view (that is, either bowed or unstrained). Priming across large rotation angles was observed for the first view of the prime object only when object shape was unchanged. Consistent with previous studies (Bülhoff & Edelman, 1992; Sklar et al., 1993), these results suggest that the visual system can generalize across small changes in object orientation and shape. These results do not suggest any significant differences in the visual representation of malleable and rigid objects under static viewing conditions.

On the other hand, differences in the representation of malleable and rigid objects are suggested when motion processes come into play. For example, unlike malleable objects, deformed views of rigid objects do not appear to have been perceptually linked across long paths of apparent rotation. More specifically, when observers viewed rigid objects in apparent motion (Experiment 2), priming was not observed for novel orientations when the rotating prime object changed its orientation by a large angle. Conversely, when observers viewed malleable objects in apparent rotation (Experiment 1), novel orientations were significantly primed under otherwise identical conditions. This pattern of results suggests that the two structurally different views of the rigid prime objects may have been represented as two separate objects rather than as a single deforming object. If so, then motion processes may not readily facilitate the linkage of structurally differing views of rigid objects.

Taken together, the results of Experiments 1 and 2 suggest that surface malleability may significantly influence the visual representation of deforming objects. When objects appear to be malleable, the visual system may generalize rapidly across changes in their shape. On the other hand, when changes in object shape are incongruent with the apparent composition of that object's surface material, then such generalization may be relatively retarded.

Experiment 3: Continuous Deformation of Malleable Objects?

It has been suggested that objects are represented in an inherently dynamic manner such that changes can be continuously taken into account (Freyd, 1987). Consistent with this theory, structurally dissimilar shapes appear to deform gradually, rather than discontinuously, when they are perceptually linked by apparent motion (Kolers & Pomerantz, 1971; Ohmura, 1986). Malleable objects, when subjected to forces that are not too large, physically deform in a smooth and continuous manner. Conversely, rigid objects undergo visible deformations that are discontinuous. The goal of Experiments 3 and 4 was to begin investigating whether the deformations of malleable and rigid objects are represented continuously. Malleable objects were used in Experiment 3, and rigid objects were used in Experiment 4. In both cases, priming was examined for novel object views having a novel shape halfway between the shape of the first and second views of the prime object (Struct-INTER). This manipulation allowed us to address the following question: When the visual system is presented with two structurally different views of a malleable object, does it construct structurally intermediate representations of that object? In other words, are the structural transformations of a deforming malleable object represented continuously?

Method

Participants. Eighty undergraduate students, recruited from the Rutgers participant pool, took part in this experiment. All had normal or corrected-to-normal vision and were naive to the hypothesis under investigation. None had participated in either of the previous experiments.

Materials and procedure. The same set of malleable-appearing figures from Experiment 1 was used in this experiment. The only difference between the stimuli was in the magnitude of the deformation of the target objects. In this experiment, the targets never had exactly the same shape as the prime views. Instead, all of the target figures had shapes that were intermediate between the shapes of the first and second prime views (or Struct-INTER). In other words, as before, the two views of the prime object were always consistent with the deformation of a malleable object. Unlike in the previous experiments, the target objects were constructed so that they had a form that would have been viewed if the deformation of the prime object had been displayed continuously. Thus, the shape of the target objects was consistent with the structural deformations of the prime objects. The target objects were deformed by only half as much as the bowed view of each prime object. This was accomplished by deforming the target objects with the PhotoShop "twirl" filter adjusted to 45° of curvature. As in the previous two experiments, each prime object was presented in a manner that was consistent with the application of a force (that is, as first unstrained and then bowed by 90° of polar curvature or as first bowed by 90° of polar curvature and then unstrained) as the prime object rotated about its base. The target objects were presented in one of three possible orientations, that is, in either of the "known" or previously seen orientations of the prime object (Orient-FRAME 1 or Orient-FRAME 2) or in a novel, intermediate orientation (Orient-INTER). Again, as illustrated in Figure 2C, the structure of the target figure was always novel and always consistent with an intermediate stage of the deformation implied by the two structurally different views of the prime object (Struct-INTER). In all other respects, the procedure in this experiment was identical to that of Experiment 1.

Results

The average reaction time across participants was 836 ms ($SD = 187$). The top panel of Table 4 reports priming and p values for malleable objects in both the apparent motion and static conditions across rotation angles.

A repeated measures ANOVA with priming as the within-measure variable and condition, target orientation, and rotation angle as the independent variables indicated significant main effects of priming, $F(1, 456) = 168.08, p < .001$, and condition, $F(1, 456) = 10.31, p < .001$, but no significant effect of target orientation, $F(2, 456) = 2.33, p = .09$, or rotation angle, $F(3, 456) = 0.47, p = .703$. Priming differences between the apparent motion and static conditions are summarized in Figure 6A. In the apparent motion condition, targets at novel orientations between the two prime views were primed for both small and large rotation angles. In the static condition, significant priming of a novel target view was observed only for small rotation angles.

Specifically, in the apparent motion condition, a repeated measures ANOVA with priming as the within-measure variable and target orientation and rotation angle as the independent variables showed significant main effects of priming, $F(1, 228) = 110.84, p < .001$, but no main effect of target orientation, $F(2, 228) = 0.92, p = .399$, or rotation angle, $F(3, 228) = 0.20, p = .894$. Moreover, no main effects of target orientation were observed at either the small (30° or 60°) rotation angles, $F(2, 117) = 0.27, p = .761$, or the large (120° or 150°) rotation angles, $F(2, 117) = 0.85, p = .427$.

Table 4
Amount of Priming (in Milliseconds) Across Rotation Angles for All Possible Target Orientations in the Apparent Motion Condition and the Static Condition for Malleable Objects (Experiment 3), Rigid Objects (Experiment 4), and Rigid Objects Deforming Elastically (Experiment 5)

Condition and rotation angle	Orient-FRAME 1	<i>p</i>	Orient-INTER	<i>p</i>	Orient-FRAME 2	<i>p</i>
Malleable objects						
Apparent motion condition						
30°	77.3	.011	59.8	.009	93.2	.002
60°	76.0	.000	73.4	.000	78.9	.019
120°	77.4	.002	46.9	.000	65.8	.001
150°	66.5	.011	58.9	.000	91.0	.000
Static condition						
30°	32.8	.022	88.1	.000	49.6	.022
60°	22.3	.034	32.1	.029	37.1	.011
120°	53.9	.005	13.2	.290	74.1	.003
150°	39.2	.016	3.5	.432	75.2	.001
Rigid objects						
Apparent motion condition						
30°	58.6	.021	41.8	.040	18.9	.227
60°	37.6	.016	37.9	.006	-10.2	.309
120°	29.7	.051	-13.3	.256	16.0	.263
150°	33.5	.034	19.9	.177	-6.8	.382
Static condition						
30°	58.9	.008	54.6	.004	45.9	.048
60°	50.3	.001	54.4	.015	50.8	.012
120°	77.1	.000	5.6	.388	68.7	.000
150°	45.9	.005	10.8	.231	70.8	.002
Kinematic elasticity						
Apparent motion condition						
60°	61.9	.001	74.9	.004	53.6	.001
120°	31.2	.021	30.7	.000	48.4	.004
Static condition						
60°	52.2	.010	49.3	.001	43.7	.006
120°	48.1	.004	7.6	.331	47.5	.007

Note. Orient-FRAME 1 = first orientation of the prime; Orient-INTER = novel, intermediate orientation; Orient-FRAME 2 = second orientation of the prime.

In the static condition, significant main effects of priming, $F(1, 228) = 57.94$, $p < .001$, but no main effect of target orientation, $F(2, 228) = 1.80$, $p = .154$, or rotation angle, $F(3, 228) = 0.96$, $p = .408$, were observed. However, a main effect of target orientation was observed for large (120° or 150°) rotation angles, $F(2, 117) = 4.95$, $p < .01$, but not for small (30° or 60°) rotation angles, $F(2, 117) = 1.64$, $p = .202$. Fisher post hoc comparisons showed that Orient-INTER was significantly less primed than Orient-FRAME 2 ($p < .01$).

Taken together with the results reported in the top panel of Table 4, these analyses indicate that novel views presented between prime views of rotating malleable objects were primed across all rotation angles. However, novel views of statically presented malleable objects were primed only for small rotation angles.

Discussion

The results of this experiment are consistent with the hypothesis that malleable objects can be continuously represented as they

deform. In other words, the visual system may continuously update representations of the structure of deforming objects even when object views are presented discontinuously. More specifically, in the static condition, the target figures were always primed when they were presented in the same orientation as either the first or the second view of the prime. Priming was also observed for the novel orientation between those of the two prime views but only when the angle of rotation was small. Conversely, in the apparent motion condition, when the deformed views of the prime objects were perceptually linked by apparent motion, priming was observed for both the "known" and the novel orientations across all rotation angles. It is important to recall that these target figures never had exactly the same structure of the prime object, because the structure of the target figures was intermediate to that of the two views of the deforming prime object. Thus, contrary to the predictions of classic theories of object recognition, priming was found for target figures that differed in both shape and orientation from previously seen prime figures. Thus, these results provide further evidence that the visual system can integrate different views of non-rigidly

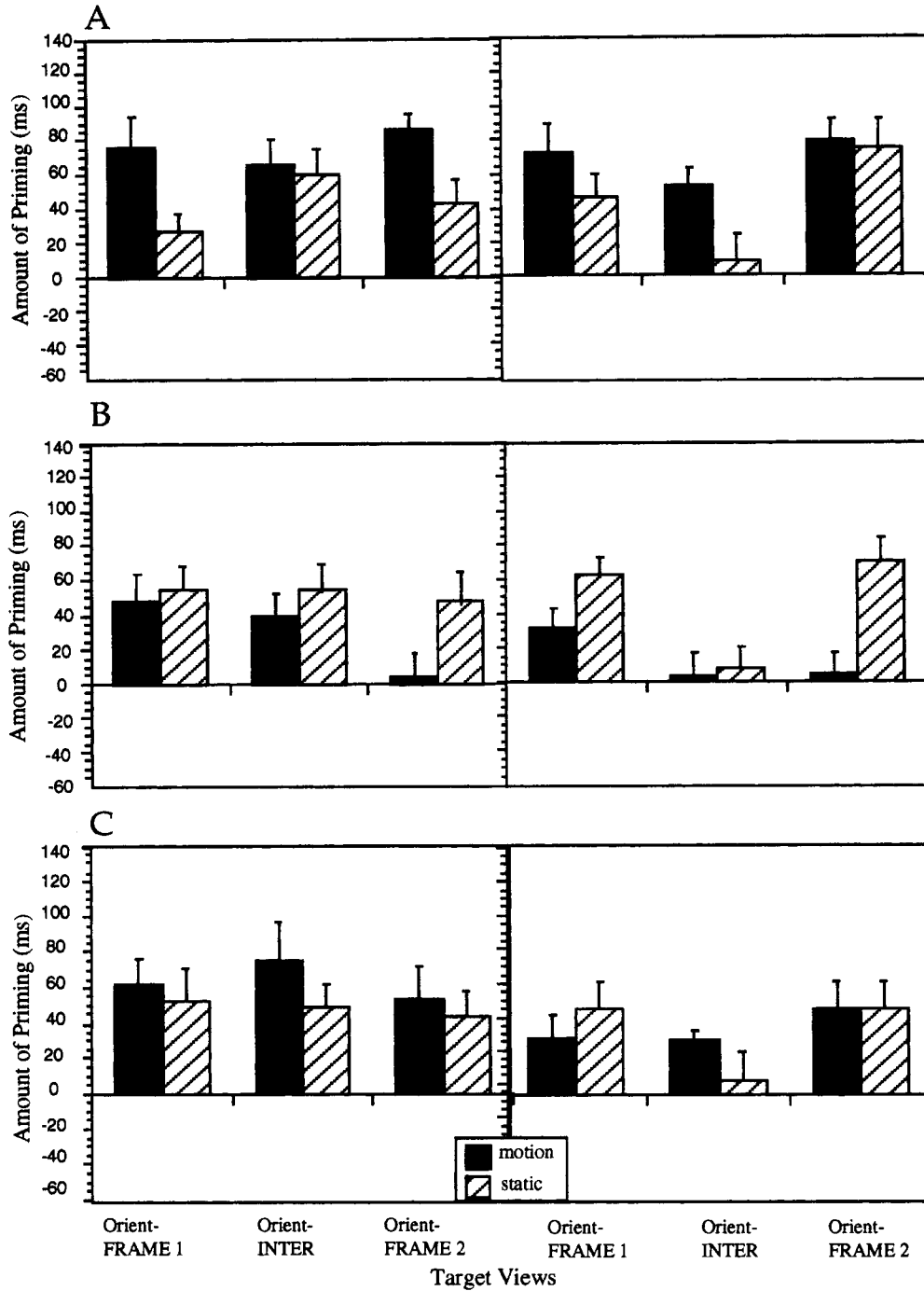


Figure 6. Magnitude of priming for target orientations in the apparent motion (solid bars) and static (hatched bars) conditions at small rotation angles (left side) and large rotation angles (right side). A: Malleable objects (Experiment 3). B: Rigid objects (Experiment 4). C: Rigid objects with a kinematic elasticity cue (Experiment 5). The target shape was always Struct-INTER (shape intermediate between the shapes of the first and second prime views). Orient-FRAME 1 = first orientation of the prime; Orient-INTER = novel, intermediate orientation; Orient-FRAME 2 = second orientation of the prime. Error bars indicate standard errors on the amount of priming averaged across participants.

moving objects. Such integration may play an important role in our ability to recognize moving, malleable objects that have changed their shape.

It is interesting that “known” orientations were primed even when the structure of the target objects differed from the structure of prime views. This finding might suggest that form information and motion information are not bound tightly together for each specific view of an object that deforms as it rotates. On the other hand, this effect may have resulted from a linkage and generalization across view-based object representations based on their image similarity (Sklar et al., 1993; Ullman & Basri, 1991). It is possible that we can generalize across images of malleable objects that are proximal within some deformation space (Sklar et al., 1993). Such a generalization process might yield functionally continuous representations of deforming objects. The following experiment was conducted to examine this possibility and to determine whether rigid objects undergoing structural deformation are represented in the same continuous fashion as malleable objects.

Experiment 4: Continuous Deformation of Rigid Objects?

The deformations of malleable objects appear to be continuously represented by the visual system. Are the deformations of rigid objects similarly represented even though, in the physical world, rigid objects undergo discontinuous shape change? In other words, does apparent surface malleability influence the way in which objects are visually represented? To address this question, Experiment 3 was replicated with rigid objects.

Method

Participants. Eighty undergraduate students, recruited from the Rutgers participant pool, took part in this experiment. All had normal or corrected-to-normal vision and were naive to the hypothesis under investigation. None had participated in any of the previous experiments.

Materials and procedure. The stimuli consisted of the same set of rigid objects used in Experiment 2. The procedure was the same as that of Experiment 3. That is, the deformation applied to the target objects was half the magnitude (45° curvature) of the deformation applied to the prime object (90° curvature). Thus, the target objects were presented in the “known” orientations (Orient-FRAME 1 and Orient-FRAME 2) and in a novel orientation (Orient-INTER), and they always had a novel, half-deformed structure (Struct-INTER), as illustrated in Figure 2D. As before, following a between-subjects design, four groups of 10 participants were presented with objects in the apparent motion condition, and four groups of 10 participants completed the static condition. Each group observed stimuli at only one rotation angle: 30° , 60° , 120° , or 150° .

Results

The average reaction time across participants was 814 ms ($SD = 185$). The middle panel of Table 4 reports priming and p values for rigid objects in both the apparent motion and static conditions across rotation angles.

A repeated measures ANOVA with priming as the within-measure variable and condition, target orientation, and rotation angle as the independent variables indicated significant main effects of priming, $F(1, 456) = 72.84$, $p < .001$, and condition, $F(1, 456) = 10.74$, $p < .001$, but no significant effect of target orientation, $F(2, 456) = 2.63$, $p = .07$, or rotation angle, $F(3,$

$456) = 0.89$, $p = .446$. Priming differences between the apparent motion and static conditions are summarized in Figure 6B. In both the apparent motion and static conditions, priming for the novel view between the prime views was observed only for small rotation angles. Interestingly, in the apparent motion condition, no priming for targets at the orientations of the second prime view was observed.

Specifically, in the apparent motion condition, a repeated measures ANOVA with priming as the within-measure variable and target orientation and rotation angle as the independent variables showed a significant main effect of priming, $F(1, 228) = 13.12$, $p < .001$, but no main effect of target orientation, $F(2, 228) = 2.80$, $p = .06$, or rotation angle, $F(3, 228) = 1.09$, $p = .351$. No main effect of target orientation was observed either for small rotation angles, $F(2, 117) = 2.41$, $p = .09$, or for large rotation angles, $F(2, 117) = 1.22$, $p = .302$. However, Fisher post hoc comparisons showed that Orient-FRAME 1 was significantly more primed than Orient-FRAME 2 ($p < .05$).

Similarly, in the static condition, a significant main effect of priming, $F(1, 228) = 73.21$, $p < .001$, but no main effect of target orientation, $F(2, 228) = 2.40$, $p = .08$, or rotation angle, $F(3, 228) = 0.17$, $p = .396$, was observed. However, a main effect of target orientation was observed for large rotation angles, $F(2, 117) = 6.72$, $p < .001$, but not for small rotation angles, $F(2, 117) = 0.05$, $p = .946$. Fisher post hoc comparisons showed that, for large rotation angles, Orient-INTER was significantly less primed than Orient-FRAME 1 and Orient-FRAME 2 ($p < .01$).

Taken together with the results reported in the middle panel of Table 4, these analyses indicate that, at small rotation angles, priming was found for rigid objects in the apparent motion and static conditions at the novel orientations between the prime views. However, in neither case was priming found at the novel orientation when the prime views differed by a large rotation angle.

Discussion

The results of this experiment suggest that deforming, rigid objects may not be represented in the same continuous fashion as malleable objects. More specifically, priming patterns in the static conditions of Experiments 3 and 4 were very similar. This finding supports the hypothesis that, under static viewing conditions, apparent surface malleability does not significantly influence the representation of deforming objects. Observers can represent a novel view of a deformed, rigid object as long as the orientation of the novel view differs minimally from the orientations of the previously seen views.

However, under conditions of apparent motion, surface malleability can play an important role in the perception of deformed objects that rotate. More precisely, the results of Experiment 3 indicate that the representation of deformed objects was facilitated when the deformation of the object was consistent with the object's apparent surface malleability. In Experiment 4, judgments concerning novel views of deformed objects were not facilitated when the object's curvilinear deformation was inconsistent with the object's rigid appearance. Importantly, in Experiment 4, no priming was found when target objects were presented in the novel, intermediate orientations within long paths of apparent rotation. Furthermore, no priming was observed for targets presented in the orientation of the second view of the prime object. On

the other hand, when malleable-appearing objects were used in exactly the same paradigm (Experiment 3), significant priming was found in all of these conditions. Thus, the results of Experiment 4 indicate that the visual system may represent rigid objects, which normally undergo discontinuous changes in their shape, in a discontinuous fashion. In other words, this experiment provides additional evidence that non-ecologically valid transformations, such as smooth deformations of rigid objects, are represented in a fundamentally different manner than ecologically valid transformations (R. N. Shepard, 1984, 1994). Moreover, when considered along with the results of Experiment 3, these findings suggest that the visual system is particularly sensitive to the relationship between surface malleability and structural deformation.

In summary, the results of Experiments 1–4 suggest that surface malleability can constrain the visual representation of rotating objects that deform. Specifically, deformed views of malleable objects, which can undergo smooth changes in their shape, can be integrated by apparent motion such that novel views can be represented within the object's path of rotation even when the path is long. However, deformed views of rigid objects can be recognized only by generalizing a small distance from previously seen views. These results are consistent with recent studies suggesting that object structure affects visual processes such as the perception of nonrigid object transformations (Massironi & Bruno, 1997) and object categorization (Landau & Leyton, 1999).

Experiment 5: Kinematic Cues to Elasticity

The previous experiments suggest that the apparent malleability of an object can strongly influence the way in which that object is represented and, as a result, the conditions under which the object can be recognized across changes in its shape or orientation. The malleable and rigid objects used in the previous experiments differed only in the static structural cues used to indicate their material composition. Yet, dynamic and kinematic cues are also indicators of an object's composition and may therefore affect object representation (Koenderink & van Doorn, 1979). For example, object elasticity is kinematically suggested whenever an object deforms and then returns to its initial shape. Indeed, such an event is consistent with the temporary application of a force against an elastic body (Gray & Isaacs, 1975).

Previous research supports the hypothesis that observers can use kinematic cues to determine an object's elastic content. For example, kinematic information is sufficient to produce the "rubber pencil" illusion (Ishiguchi, 1988; Pomerantz, 1983). Furthermore, observers can determine a ball's elasticity from its bounce kinematics (Warren, Kim, & Husney, 1987) as well as the elasticity of a support surface from the kinematics of human movement on that surface (Stoffregen & Flynn, 1994).

Will the addition of a kinematic cue to elasticity change the way in which otherwise rigid objects are represented? The current experiment addressed this question by creating a competition between static and kinematic cues to object malleability.

Method

Participants. Forty undergraduate students, recruited from the Rutgers participant pool, took part in this experiment. All had normal or corrected-to-normal vision and were naive to the hypothesis under investigation. None had participated in any of the previous experiments.

Materials and procedure. The stimuli and the procedure were the same as those of Experiment 4. That is, participants viewed a rigid prime object and then judged whether two subsequently presented target objects matched each other. Unlike in Experiment 4, however, in this experiment the first view of the prime was shown twice. Thus, the deforming prime object was seen three times in the following sequence: Frame 1, Frame 2, and Frame 1. In this way, a kinematic cue was added that clearly suggested that the prime object was in fact capable of elastic deformation. Only two rotation angles were used: 60° (representative of small rotations) and 120° (representative of large rotations). The targets were all presented half deformed (Struct-INTER), as in Experiment 4. Two groups of 10 participants were presented with objects in apparent motion, and two groups of 10 participants were presented with static object views. Each group was presented with objects at only one of the two rotation angles.

Results

The average reaction time across participants was 720 ms ($SD = 171$). The bottom panel of Table 4 reports priming and p values for non-malleable objects deforming elastically in both the apparent motion and static conditions across rotation angles.

A repeated measures ANOVA with priming as the within-measure variable and condition, target orientation, and rotation angle as the independent variables indicated significant main effects of priming, $F(1, 108) = 109.00, p < .001$, and rotation angle, $F(3, 108) = 5.41, p < .05$, but no significant effect of condition, $F(1, 108) = 0.99, p = .312$, or target orientation, $F(2, 108) = 0.34, p = .710$. Priming differences between the apparent motion and static conditions are summarized in Figure 6C. In the apparent motion condition, priming was observed for both "known" and novel target orientations across all rotation angles. In the static condition, targets were primed at novel orientations only for small rotation angles. More specifically, in the apparent motion condition, a repeated measures ANOVA with priming as the within-measure variable and target orientation and rotation angle as the independent variables showed significant main effects of priming, $F(1, 54) = 67.75, p < .001$, and rotation angle, $F(3, 54) = 4.83, p < .05$, but no main effect of target orientation, $F(2, 54) = 0.09, p = .909$. In the static condition, there was a significant main effect of priming, $F(1, 54) = 43.91, p < .001$, but no main effect of target orientation, $F(2, 54) = 1.12, p = .336$, or rotation angle, $F(3, 54) = 1.24, p = .271$. Taken together with the results reported in the bottom panel of Table 4, these analyses indicate that novel views of rigid objects deforming elastically were primed across all rotation angles only under conditions of apparent motion.

Discussion

The addition of a kinematic cue to object malleability appears to change the way in which otherwise rigid-appearing objects are represented. Specifically, when rigid objects were sequentially displayed as unstressed, bowed, and then again as unstressed, priming patterns resembled those of malleable objects (Experiment 3). In the apparent motion condition, priming was observed for the "known" orientations of the prime as well as for the novel, intermediate orientations across both large and small rotation angles. This priming pattern replicates that observed for malleable objects (Experiment 3) and differs in important ways from the priming pattern observed for rigid objects (Experiment 4). Views of rigid objects lacking kinematic cues to elasticity (Experiment 4) showed

no priming for the second orientation of the prime object or for the novel orientation at the large rotation angle. Thus, when three views of an otherwise rigid object were kinematically consistent with the application and removal of a force to an elastic surface, priming patterns resembling those of Experiment 3 were found. Taken together, these results suggest that kinematic cues to elasticity can significantly alter the representation of deforming objects. That is, deformed views of objects that appear to have a nonmalleable composition but move in an elastic manner can be integrated by apparent motion processes and represented as unique.

A possible confound in this experiment is that the kinematic cue to elasticity required the presentation of three different views of the prime object. Because each view was shown for the same durations used in Experiment 4, this manipulation yielded prime display durations that were longer than those of Experiment 4. Thus, the enhanced priming found in this experiment may have actually resulted from the use of longer presentation times rather than from the addition of a kinematic cue to elasticity. The following control experiment tested this possibility.

Experiment 6: Duration Control

Display duration can influence motion perception. For example, longer frame durations can improve direction discrimination performance in random dot kinematograms for large displacements independently of the number of steps in the motion sequence (Snowden & Braddick, 1990). Also, longer display durations can promote the perception of physically possible paths of apparent biological motion (Shiffrar & Freyd, 1990, 1993). The current experiment tested whether an increase in the duration of a prime display enhances priming for malleable and rigid objects that deform as they rotate.

Method

Participants. Forty undergraduate students, recruited from the Rutgers participant pool, took part in this experiment. All had normal or corrected-to-normal vision and were naive to the hypothesis under investigation. None had participated in any of the previous experiments.

Materials and procedure. The stimuli were the malleable objects from Experiment 3 and the rigid objects from Experiment 4. Only the apparent motion condition was tested, because the static conditions in Experiments 4 and 5 produced similar patterns of priming. Rotation angles of 60° and 120° were tested. The procedure was the same as in the motion condition of Experiment 4 except that the durations of Frame 1 and Frame 2 were increased for the prime objects. In this way, each prime object was presented for the same duration as each of the prime objects in Experiment 5. As a result, the durations of Frame 1 and Frame 2 for prime objects at 60° and 120° rotation angles were 398 and 497 ms, respectively. This manipulation allowed us to control for prime duration. All of the targets were presented half deformed (Struct-INTER). Two groups of 10 participants were presented with malleable objects in apparent motion, and two groups of 10 participants were presented with rigid objects in apparent motion.

Results

For rigid objects, the average reaction time across participants was 734 ms ($SD = 174$). For malleable objects, the average reaction time across participants was 811 ms ($SD = 201$). Table 5

Table 5

Experiment 6: Amount of Priming (in Milliseconds) Across Rotation Angles for All Possible Target Orientations for Rigid Objects and Malleable Objects

Object type and rotation angle	Orient-FRAME 1	<i>p</i>	Orient-INTER	<i>p</i>	Orient-FRAME 2	<i>p</i>
Rigid objects						
60°	41.2	.002	25.2	.008	44.4	.003
120°	56.6	.002	5.4	.398	59.1	.017
Malleable objects						
60°	72.3	.000	56.7	.005	61.2	.000
120°	28.7	.001	25.1	.002	37.1	.042

Note. Orient-FRAME 1 = first orientation of the prime; Orient-INTER = novel, intermediate orientation; Orient-FRAME 2 = second orientation of the prime.

reports priming and *p* values for both rigid and malleable objects across rotation angles.

Rigid versus malleable objects. As illustrated in Figure 7, the novel views of the rigid rotating objects were primed only at the small rotation angles. The same novel views of the malleable objects were primed across both the small and the large rotation angles. Specifically, for rigid objects, a repeated measures ANOVA with priming as the within-measure variable and target orientation and rotation angle as the independent variables indicated significant main effects of priming, $F(1, 54) = 25.24$, $p < .001$, and target orientation, $F(2, 54) = 3.23$, $p < .05$, but no significant effect of rotation angle, $F(1, 54) = 0.070$, $p = .793$. Significant priming was observed when the targets were presented at Orient-FRAME 1, $F(1, 19) = 28.10$, $p < .001$, and Orient-FRAME 2, $F(1, 19) = 15.32$, $p < .001$, but not at Orient-INTER, $F(1, 19) = 2.07$, $p = .165$. Fisher post hoc comparisons showed that Orient-FRAME 1 and Orient-FRAME 2 were significantly more primed than Orient-INTER ($p < .05$).

For malleable objects, significant main effects were observed for priming, $F(1, 54) = 65.51$, $p < .001$, and rotation angle, $F(1, 54) = 8.24$, $p < .01$, but not for target orientation, $F(2, 54) = 0.27$, $p = .765$. Significant priming was observed at Orient-FRAME 1, $F(1, 19) = 26.54$, $p < .001$; Orient-FRAME 2, $F(1, 19) = 17.60$, $p < .001$; and Orient-INTER, $F(1, 19) = 17.12$, $p < .001$. When considered along with the results reported in Table 5, these analyses provide additional evidence for significant priming differences between malleable and rigid objects that deform as they rotate.

Cross-experiment comparisons. This final analysis compared priming patterns for malleable objects with two prime views (Experiment 3), rigid objects with two prime views (Experiment 4), rigid objects with three prime views (Experiment 5), and rigid and malleable objects displayed for two long presentations (Experiment 6) under conditions of apparent motion. In all of these conditions, target objects never had exactly the same shape as either prime view but could have a shape intermediate to the two prime views and consistent with an elastic deformation (Struct-INTER). A one-way ANOVA with priming as the dependent variable and object type (rigid objects, malleable objects, rigid objects with a kinematic elasticity cue, rigid

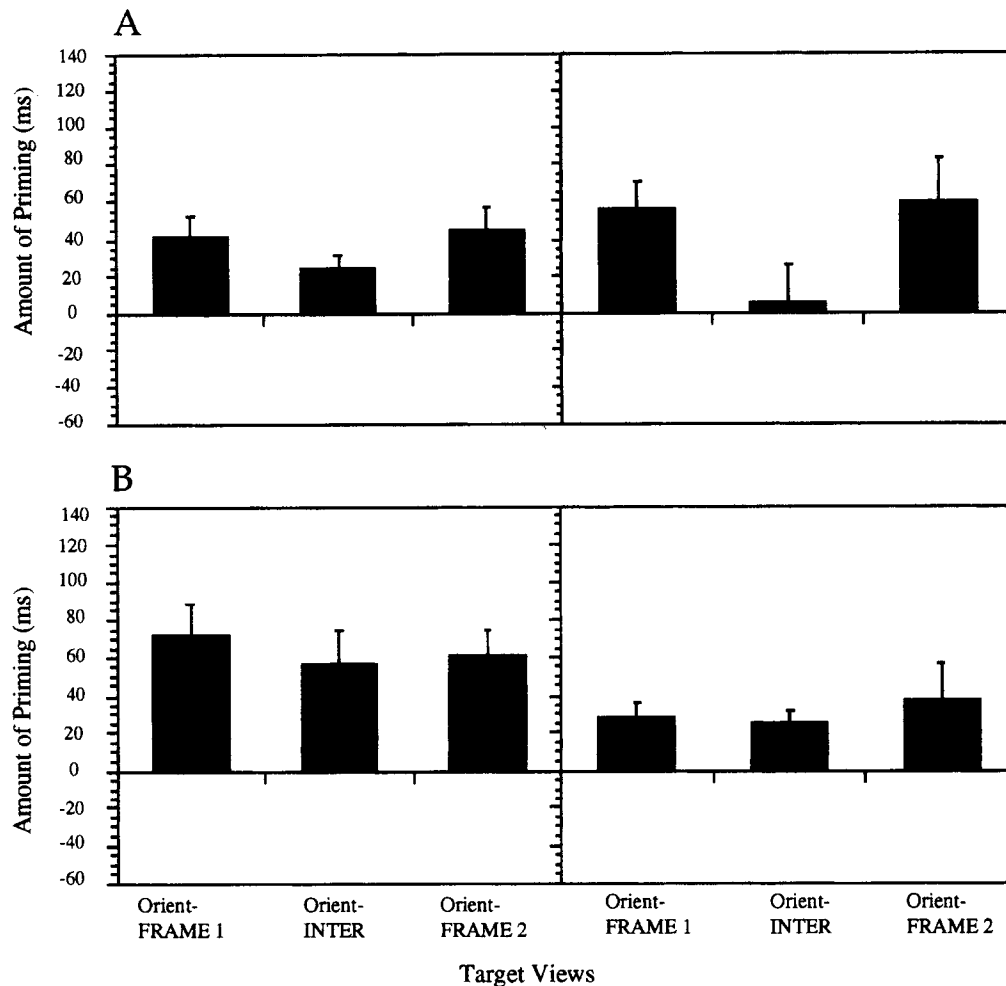


Figure 7. Experiment 6: Priming magnitude for target orientations in the apparent motion condition for rigid (A) and malleable (B) objects at 60° (left) or 120° (right) rotation angles. Orient-FRAME 1 = first orientation of the prime; Orient-INTER = novel, intermediate orientation; Orient-FRAME 2 = second orientation of the prime. Error bars indicate standard errors on the amount of priming averaged across participants.

objects at long presentations, or malleable objects at long presentations), rotation angle (60° or 120°) and target orientation as the independent variables showed main effects of object type, $F(4, 390) = 7.33, p < .001$, and rotation angle, $F(1, 390) = 3.94, p < .05$, but no main effect of target orientation, $F(2, 390) = 1.23, p = .309$. Fisher post hoc comparisons showed that rigid objects were significantly less primed than malleable objects ($p < .001$), malleable objects at long presentations ($p < .01$), and rigid objects with a kinematic elasticity cue ($p < .001$). Also, malleable objects were significantly more primed than rigid objects at long durations ($p < .01$) but did not significantly differ from malleable objects at long presentations ($p = .06$) or from rigid objects with a kinematic cue to elasticity ($p = .110$).

Discussion

The current results suggest that although longer presentation durations can facilitate the integration of structurally dissimilar

object views (Kolars & Pomerantz, 1971; Ohmura, 1986), they do not appear to be sufficient for the construction of continuous representations of deforming objects. Specifically, at long presentation durations, priming was observed across all rotation angles when the targets were presented in the same orientation as the first or the second view of the rigid prime object. In contrast, the second orientation of the rigid prime object was not primed when view durations were relatively short (Experiment 4). Importantly, however, in the current experiment, no priming was found for the novel orientation of the rigid prime object at long rotations. Thus, the priming effects observed for malleable objects in this experiment replicated the priming pattern found with malleable objects displayed for shorter durations (Experiment 3).

Taken together, these results suggest that extended durations do not appear to facilitate the priming of novel orientations within long paths of apparent rotation. Thus, providing the visual system with more time for processing is neither sufficient nor necessary for the continuous representation of deforming objects.

General Discussion

Although our physical environment contains a plethora of objects that move nonrigidly, traditional models of object recognition shed little light on the mechanisms by which observers represent or perceive such objects. The goal of the current series of experiments was to develop an understanding of the visual representation of objects that change their shape as they move. The methodological approach taken was motivated by the fact that physical objects deform in a manner that is dictated by their material composition and the forces exerted on them (Love, 1944).

Summary of Results

Experiment 1 examined whether observers can represent objects moving nonrigidly. More specifically, when two structurally different views of a rotating, malleable prime object were presented under conditions of apparent motion, priming (or speeded matching judgments) was observed for target figures having the same structure as the first view of the prime object and oriented within the prime object's path of apparent rotation. A much more limited pattern of priming was found when the same stimuli were presented under static conditions. Thus, contrary to the predictions of most current models of object recognition, individuals can easily represent at least some objects after they have been significantly deformed. Furthermore, motion processes may play a central role in this generalization process (Kourtzi & Shiffrar, 1997, 1999a, 1999b). Experiments 2–6 set out to identify those factors that determine when the visual system can integrate structurally dissimilar object views. The results of Experiment 2, in which the malleable objects from Experiment 1 were modified so as to appear rigid, suggest that surface malleability may define when the visual system tolerates changes in object structure. Generalization appears to be superior when changes in an object's shape are consistent with the object's material composition. Incompatible combinations of material composition and object deformation may increase the difficulty with which individuals can represent deformed objects.

Experiments 3 and 4 addressed whether structural and orientation changes are continuously represented when objects deform as they rotate. By definition, malleable objects deform smoothly and continuously, whereas rigid objects undergo abrupt changes in their shape. Consistent with this, the results of Experiments 3 and 4 suggest that curvilinear deformations of malleable, but not rigid, objects may be continuously represented under conditions of apparent motion. Thus, although only two views of a deforming, malleable object were presented, priming patterns suggest that the visual system may have created representations of that object in its intermediate shapes and orientations. Experiment 5 indicated that kinematic cues to elasticity can also determine the way we represent objects deforming. Experiment 6 illustrated that this effect of kinematic cues did not result from the use of extended display durations.

When considered together, the results of these experiments suggest that the visual system can generalize across simultaneous changes in the shape and orientation of moving objects. Moreover, the visual analyses underlying the perception of surface malleability may play a defining role in this process. Static and kinematic cues to malleability can control whether visual objects are represented as continuous events.

One possible limitation of these studies is that, to investigate how surface properties affect the representation of moving objects, we manipulated, across experiments, properties that may have affected the perception of apparent motion. For example, the increased number of frames in Experiment 5 and the longer prime durations in Experiment 6 may have affected the perception of apparent motion. It is possible that when apparent motion is perceived, these properties affect the quality of motion perception rather than the representation of moving objects. For example, it has been shown that when presented with a sequence of two dissimilar and nontransformable figures in apparent motion, observers rate the smoothness of apparent motion highly (Berbaum et al., 1981); they also frequently report the perception of two separable objects instead of one object in motion (Warren, 1977).

Similarly, one could suggest that the perceptual similarity between the two prime views was higher for malleable objects with "wavy" contours, because they were high in curvature, than for rigid objects having straight contours. This higher perceptual similarity between the two prime frames for malleable objects may have enhanced motion perception and resulted in the continuous representation of deforming malleable objects. However, the only physical difference between the malleable and the rigid objects is a difference in their texture maps that makes the malleable object contours appear wavy. That is, both types of objects undergo the same structural changes, and the structural similarity between the two prime views is therefore similar for malleable and rigid objects. Instead, it is more likely that wavy contours facilitate locally elastic correspondences (Basri, Costa, Geiger, & Jacobs, 1998), which in turn facilitate the continuous representation of malleable objects deforming nonrigidly.

Importantly, in all of the current studies, all observers reported that they perceived apparent motion in the apparent motion conditions. Moreover, a pilot study empirically tested the perception of apparent motion across experiments. Eight observers were asked to rate the "goodness" of apparent motion on a scale ranging from 1 to 3 (1 = *no motion*, 2 = *good apparent motion*, 3 = *very good apparent motion*). Observers were presented with malleable and rigid objects rotating at all of the durations used in Experiments 1–6. Overall, apparent motion for malleable objects (average rating of 2.5) was found to be nearly identical to apparent motion for the rigid objects (average rating of 2.4). Malleable (average of 2.5) and rigid (average of 2.5) objects were given identical average "goodness" ratings when they were presented under the conditions used in the first four experiments. Interestingly, rigid objects (average of 2.4) were rated significantly higher than malleable objects (average of 2.2) when they were presented at the longer durations used in Experiment 6. This effect is consistent with previous studies suggesting top-down influences in the perception of apparent motion for longer stimulus presentations (Shiffrar & Freyd, 1990, 1993). This slight advantage in the perception of apparent motion for rigid objects could account for the increased priming observed for the second prime frame in Experiment 6 when presented at long durations. Nevertheless, these explicit ratings of apparent motion "goodness" do not predict when moving objects are represented continuously (i.e., when objects were primed at the novel target orientations).

Taken together, the preceding observations suggest that changes in surface properties (i.e., malleability and kinematic elasticity)—and, to a much lesser extent, temporal duration—strongly influ-

ence the way moving objects are represented rather than the perception of apparent motion. Thus, the results of the current experiments suggest an important role for surface properties in the representation of moving objects. This conclusion provides additional support for the hypothesis that visual representations are surface based (e.g., Nakayama et al., 1995).

Alternative Perspectives on Object Representation

Previous researchers have outlined a static generalization process that may enable observers to recognize deformed object views that are presented statically and linked only by temporal sequence (Sklar et al., 1993; Ullman & Basri, 1991). The current results are consistent with the use of such a static generalization mechanism in the representation of previously seen views of an object as long as variations in the object's orientation remain small. However, this mechanism cannot account for priming of rotating objects across large orientation changes or for the differences between malleable and rigid objects.

Thus, the current results support the hypothesis that motion and surface processes play a fundamentally important role in the representation of objects across changes in their orientation (Kourtzi & Shiffrar, 1997, 1999a, 1999b). Specifically, motion can facilitate representations of objects deforming nonrigidly as long as the deformation is compatible with the object's apparent malleability. It appears that just as motion processes can lead to the perception of continuous motion from spatiotemporally discontinuous displays, so too can they facilitate the continuous representation of object deformation following the discontinuous presentation of two stimulus views. Importantly, motion does not facilitate continuous object representations when static cues to an object's material composition are incompatible with its structural deformation.

Taken together, the current studies suggest an alternative perspective on the visual representation of objects. Because traditional models of object recognition emphasize the maintenance of object rigidity, it is not obvious how they can account for the representation of deformed objects (Biederman, 1987; Bühlhoff & Edelman, 1992; Edelman & Weinshall, 1991; Poggio & Edelman, 1990). On the other hand, nonrigid motions can preserve intrinsic surface properties (Hilbert & Cohn-Vossen, 1952; Jansson, 1977; Koenderink & van Doorn, 1986) that the visual system may use to facilitate correspondences across different object views. Indeed, recent studies suggest that elasticity can enhance correspondences between different views of deformable shapes (Basri et al., 1998). The current results illustrate that such structural properties are best considered within the context of motion processes. That is, rotational motion is important because it defines what rigid changes in orientation are possible. Similarly, surface malleability is important because it defines what structural deformations are possible as an object moves. Thus, the current studies suggest that motion processes can speed the integration of different views of a nonrigidly deforming object. This may be the basis by which observers perceive bouncing balls and wind-blown trees as continuous events rather than as sequential snapshots of differently shaped objects. Furthermore, motion processes may function in conjunction with structural processes so that the representation of ecologically valid events is favored (Koenderink & van Doorn, 1979, 1986; R. N. Shepard, 1984, 1994).

Representation of Moving Objects

Finally, the preceding observations raise important questions about the possible mechanisms that the visual system might employ to integrate multiple object views and to construct continuous representations of moving objects. One possible mechanism is that some processes may link stored object views and facilitate generalization between them. According to this hypothesis, these linkage or generalization processes would represent static and moving objects in the same manner. This hypothesis implies the existence of long-term representations of sequences of spatiotemporally associated snapshots of moving objects. However, motion processes appear to delimit generalization within but not outside an object's motion path, whereas static generalization is observed in the space between and beyond two static object views (Kourtzi & Shiffrar, 1997, 1999b). As a result, only object views falling within motion paths would be stored as a continuum.

Another possibility is that the visual system continuously updates object representations during the analysis of object motion. This hypothesis is consistent with previous evidence suggesting that motion mechanisms operate by averaging a moving object's position over time rather than by analyzing each discrete object position independently (Morgan, 1980). Thus, this possibility suggests that representations of moving objects might be continuously remapped relative to the observer as they change their shape or orientation, or both. If so, this "dynamic remapping" of object representations may be constrained by both structural and motion processes. Intriguingly, such a fluid process might easily lend itself to the perception of continuous dynamic events unfolding over space and time.

If the visual system does construct object representations that are dynamically remapped, what purpose might these representations serve? One possibility is suggested by the assumption that priming taps implicit, but not explicit, representations. Thus, only implicit representations were assessed in the current series of experiments. Such representations, on their own, would be insufficient for many tasks such as explicit object naming. On the other hand, motor skills are generally considered to reflect implicit processes, because people can learn motor skills without conscious awareness of those skills (Squire, 1987). Thus, one possibility is that the representations of moving objects proposed here might be used to guide motor behavior rather than support object recognition. Indeed, the surface properties examined in the current experiments—namely, malleability, elasticity, and orientation—define how individuals manipulate objects (J. J. Gibson, 1979). Numerous behavioral and neurophysiological studies have indicated a tight coupling between the visual and motor systems. For example, visual cues to structural object properties, such as object size, shape, and orientation, influence manual grasping (Goodale & Milner, 1992). Furthermore, neurons have been identified in the anterior intraparietal area of the monkey that may be responsible for matching hand movements to the spatial features of viewed objects (Sakata, Taira, Kusunoki, & Tanaka, 1997). Imaging studies have also suggested the cross-modal transfer of shape and trajectory information between the visual and motor systems (Hadjikhani & Roland, 1998; Stevens, Fonlupt, Shiffrar, & Decety, 2000). When considered together, these findings support the hypothesis that the implicit object representations suggested by the

current experiments may play a role in the visual guidance of motor interactions with objects.

In summary, the current priming results suggest that visual representations of non-rigidly deforming objects may be continuously updated in a manner that is constrained by structural and motion processes (Koenderink & van Doorn, 1979, 1986; Kourtzi & Shiffrar, 1997, 1999b; Shiffrar & Freyd, 1990, 1993) as well as by ecological constraints on the movement of objects in the world (Freyd, 1987; R. N. Shepard, 1984, 1994). Such a dynamic approach is consistent with theories suggesting that motion may be better described as a change or a process that deforms the structure of space-time than as a sequence of static displacements (e.g., Capek, 1961). This twist on our understanding of object representation processes is consistent with the proposal that our perceptions and representations are "analogs" of the physical world in that they resemble or respect physical properties and processes (Morgan, 1980; R. N. Shepard, 1978). Thus, a moving object may be perceived and represented as a continuous dynamic event rather than as static frames in spatiotemporal sequence.

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