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Representations of Motion and Direction

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In 6 experiments, incidental memory was tested for direction of motion in an old–new recognition paradigm. Ability to recognize previously shown directions depended greatly on motion type. Memory for translation and expansion–contraction direction was highly veridical, whereas memory for rotation direction was conspicuously absent. Similar results were obtained in conditions in which motions were illustrated with pictures. Results suggest that explicit representations of direction in long-term memory are not so much related to motion per se as to the consequences of motion, the displacements of objects. Memory for all motions following circular pathways was found to be corrupted by a generic bias to regard the clockwise direction as familiar. Assessment of memory in these cases required disentangling familiarity bias for the clockwise direction from explicit recognition of direction.

The perceptual representation of object motion has been an important issue in cognitive science dating back to the early days of Gestalt psychology. Object motion is susceptible to a range of descriptions, and here we are concerned with the appropriate level for understanding representations in memory. In particular, we were concerned with whether memorial representations respect the computational and neural complexity of the information available in optic flow, or whether these representations are more directly related to their ecological significance (Gibson, 1986). In this article, we empirically tested these two alternatives by examining the circumstances under which the simplest aspect of motion, its direction, can be remembered.

When objects move there is drift of photic energy in proximal stimulation. This drift is known as optic flow and takes different forms depending on the kind of distal motion that gives rise to it. There are three independent and distinct patterns of flow associated with small foveated objects as shown schematically in Figure 1: translation, expansion–contraction (looming), and rotation. These patterns are generated by displacement orthogonal to the line of sight, displacement along the line of sight, and rotation about the line of sight, respectively. Note that this description of motion is completely egocentric in that a distal object translation can generate either a looming or translation flow depending on the placement of the observer.

As a flow pattern, translation is a special case because of its homogeneity. Every point in a translation flow suffices to completely specify its global direction. Looming and rotating flow fields are not homogeneous and cannot be so reduced. Instead, they are organized with respect to an axis that serves as a local frame of reference. In specifying the global orientation of a rotating or looming flow field, a local motion analysis must be performed at several points coupled with a spatial analysis of the locations of these points relative to the organizing axis. For example, expansion flow toward an observer is defined by texture at the top of the field moving upward, texture at the bottom moving downward, and so forth. Similarly, clockwise rotational flow is defined by the following relations relative to the axis of rotation: top–rightward flow, bottom–leftward flow, and so on. Markers of spatial layout such as "top" and "bottom," which are required to describe looming and rotation flow, are not necessary in the analysis of translation direction. Translations are not organized with respect to local axes and so can be globally described without reference to spatial markers. It is this feature that makes translation representable in the early visual system through Reichardt-like detectors (Adelson & Bergen, 1985; Watson & Ahumada, 1985). In terms of how motion proximally appears as optic flow, translation is distinguished from rotation and looming by its simplicity.

What is known about the neural processing of motion is consistent with and extends the optic flow description of motion complexity. Directionally sensitive neurons can be found in the visual cortex (V1), the medial temporal (MT) region, and the medial superior temporal (MST) region (Adelson & Movshon, 1982; Tanaka & Saito, 1989). Of these areas, the lower level V1 and MT neurons are tuned to respond to translational motions, with local analysis occurring in V1 (see Movshon, Adelson, Gizzi, & Newsome, 1985, for a review) and a more global analysis occurring in the MT region (Adelson & Movshon, 1982). It is not until later in the MST region that neurons selective for rotation and looming motions are found. Even here, the absolute number of neurons devoted to translation is much greater than for the other motion types (Graziano, Anderson, & Snowden, 1994; Saito et al., 1986; Tanaka & Saito, 1989; Tanaka, Sugita, Moriya, & Saito, 1993). Units selective for looming and rotation direction are conceived of as being

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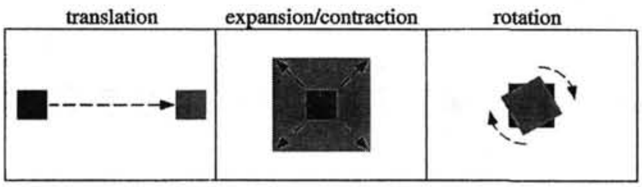

Figure 1. The three basic types of motion studied, with Time Step 1 in black and Time Step 2 in gray. In the left panel, a square is shown translating rightward across a viewing area. The same square is shown in the middle panel expanding as a looming motion. In the right panel, the square is rotating clockwise.

constructed from ensembles of more primitive units that are selective for translation direction. The physiological connection between rotation and looming may be deep. The selectivity found in MST neurons suggests that together they form a continuous two-dimensional space that includes the intermediate family of spiral motions (Graziano et al., 1994).

The physiological distinctions between translation and other flows appear to be reiterated in the psychophysics of motion perception. In terms of early visual processing, looming and rotation motions are both demanding of attentional resources and do not permit texture segmentation on the basis of direction (Braddick & Holliday, 1991; Julesz & Hesse, 1970; however, see Takeuchi, 1997), unlike translation (Nakayama & Silverman, 1986). Note that the parallel processing of translational texture is well-known because it is this competency that underlies the perception of depth from motion parallax.

A nonegocentric, object-oriented analysis of motion perception gives a much different description of the elementary flow fields and the relations among them. First, the optic flow patterns specified by translation and looming both signify essentially the same object displacement. They are distinguished only by the line of sight that happens to be available to the observer. In this sense, any difference in representation between translation and looming is more informative of observer perspective than of any feature in spatial layout. There is information present in the optic array that distinguishes generalized translations from rotations, but it is unrelated to flow complexity. Translations and looming motions accrete and delete background texture across the bounding contour of the object. This type of texture transformation, known as "dynamic occlusion," is the optical information that an object is changing its location (Gibson, 1986). Rotations about an axis internal to the object do not occlude background texture in this way precisely because a pure change of orientation is not the same thing as a change of location. In essence, a displacement is always distinguishable from a simple angular change on the basis of how background texture is occluded.

Egocentric and object-centered descriptions of motion differ in terms of what aspects of the flow are represented, and consequently they disagree on what counts toward motion similarity. In terms of egocentric proximal flow, rotations and looming motions are similar on the basis of computational and neural complexity, whereas translations are isolated by virtue of their homogeneity. In terms of what objects are doing distally, translations and looming motions are similar because both signify that something is changing its place, whereas rotations do not entail net displacement. The variation between these two frameworks on what attributes are relevant for similarity allows for an empirical investigation of the level of memorial representation. Such an investigation will be informative to the extent that at least one motion type is distinguished by significantly better or worse memory performance than the others.

The literature on motion memory has not been articulated in terms of the egocentered/object-centered distinction, but it is nevertheless relevant. There is some evidence that memory for translation direction is good. Blake, Cepeda, and Hiris (1997) found that memory for direction of translating dots was surprisingly accurate and resistant to decay over short delays. The method used in that study was not suitable for probing looming or rotational motions. Other researchers examining representational momentum have measured memory for the final position of an object but have not directly focused on memory for the type of motion or its direction (see Hubbard, 1995, for a review).

In the following six experiments, we used an incidental recognition memory paradigm to demonstrate the basic phenomena regarding memory accuracy for motion direction.[1] We first examined isolated rotations, translations, and looming motions to clarify and establish what competencies exist. We then focused on rotation in more elaborate settings in which (a) rotations and translations were combined into tumbling and rolling motions, (b) rotations led to object occlusion, (c) rotations occurred about an axis external to the object, and (d) the percept of rotation was contingent on the formation of perceptually organized groups.

Experiment 1: Translation and Rotation

The starting point of our investigation was to evaluate memory for the direction of objects either translating or rotating about an internal axis. In this experiment, participants viewed objects at study that were either translating right or left across the screen or rotating clockwise or counterclockwise about their centers. At testing, participants were shown the objects from the study phase either moving identically to their study motion or moving in a new way, either in the opposite direction or with a different motion altogether. Noting that both direction (Halpern & Kelly, 1993; however, see also Hubbard, 1990; Hubbard & Bharucha, 1988) and speed (Freyd & Finke, 1985) have been implicated in memory shifts for object position, we investigated memory for direction across varying speeds of motion:

[1] Our work focused on the explicit, long-term representations of motion in memory. It should be recognized that there are distinctions between implicit and explicit representations, and our results may depend on the nature of the memory test used. Similarly, motion representations within visual working memory (Baddeley, 1986) would surely differ from those within long-term memory.

subjectively fast, subjectively slow, and objectively still (a nonanimated depiction).

Method

Participants. Forty-eight students from introductory psychology classes at the University of Texas at Austin served as participants for this experiment. The students participated to fulfill part of a research requirement for the course and were naive about the purpose of the study. Participants were assigned to one of three motion speed conditions, with 16 participants in each condition.

Materials. The stimuli consisted of simple object animations presented as Quicktime movies, which yielded the percept of continuous motion. Eight objects were constructed so that their motions would be suprathreshold; bold interior stripes or asymmetrical features were used so that the direction of motion was readily apparent. The objects ranged in size from 2.5 × 3.5 cm to 4.5 × 7 cm and included various colors and textures. A sample of objects in these experiments is shown in Figure 2. Stimuli were presented via a Macintosh Quadra 800 on a 16-in. (40.64-cm) color monitor with a white background at a viewing distance of approximately 45 cm.

Design. This experiment was run as a 2 × 2 × 3 mixed factorial design. The within-subjects variables were motion type (translation or rotation) and motion direction at study (a nested variable within motion type: translation right or left, or rotation clockwise or counterclockwise). The between-subjects variable was motion speed, with the participants assigned to either the fast, slow, or static motion speed condition.

In the fast condition, each object was viewed in motion for approximately 3 s, either translating at about 11.4 cm/s or rotating at about 1.0 rev/s. For the slow condition, each object was shown for approximately 11 s, either translating at about 3.8 cm/s or rotating at about 0.2 rev/s. In both the fast and slow conditions, the animation was shown and repeated once. Note that this choice of parameters was designed to equate the animations in the slow and fast conditions in terms of net contour displacement rather than on event duration. Our results may not generalize to equation on event duration.

For the fast and slow conditions, translations and rotations looked like those depicted in Figure 1. All rightward translations began on the left side of the screen, centered vertically, and then moved smoothly across to the right side of the screen. The vertical component of the motion did not change. Leftward translations were created by reversing the sequence. Rotations occurred with the object's center aligned with the center of the screen. A complete rotation through 360° was shown.

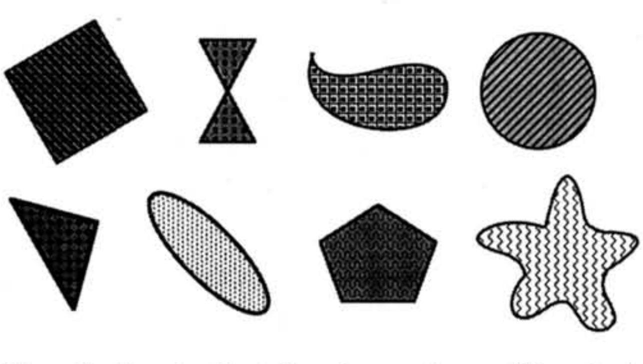

Figure 2. Sample objects from the experiments. Objects in the actual experiments were of various colors and fills.

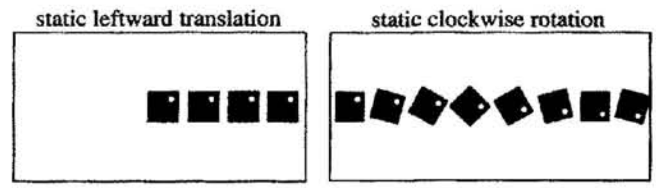

Figure 3. In the static motion condition of Experiment 1, leftward translation was represented as four still pictures originating at the right side of the screen and continuing leftward across to the center, shown in the left panel. Rightward translation, not shown, was depicted as four still pictures originating at the left side of the screen and continuing rightward across to the center. Clockwise rotation, shown in the right panel, was represented as eight still frames of motion across the entire screen with each frame rotated clockwise with respect to the frame before it. Counterclockwise rotation, not shown, was also depicted as eight still frames across the screen; each frame was rotated counterclockwise with respect to the frame before it.

In the static condition the objects did not move; rather, the still frames from an animation were presented side by side for approximately 3 s, as shown in Figure 3. All frames appeared at the same time and remained visible until the end of the trial. For the static rotation presentations, eight frames were shown across the entire screen, with each successive frame rotated farther clockwise or counterclockwise depending on the direction condition. For the static translation displays, four frames were shown originating on one side of the screen and staggered across to the center of the screen. "Rightward" translation was represented as four frames originating from the left side of the screen, and "leftward" translation was represented as four frames originating from the right side of the screen. We assigned direction labels to the static condition as a matter of convenience; these could be interchanged depending on which side the "motion" was thought to originate.

Procedure. The experiment consisted of a study phase and a recognition memory test phase. At study, participants were instructed to pay close attention to what they saw on the screen; however, they were not told that their memory would be tested. A series of animation events was then presented. An animation event consisted of one object in one motion condition; for example, a baseball would be shown translating to the right. After each animation event ended, the participant pressed a key to begin the next event (e.g., a square rotating clockwise). This procedure continued until all study events had been presented. All participants viewed the same eight basic objects at study, and the type of motion and direction assigned to a particular object was counterbalanced across subjects. Of the eight objects shown at study, two translated right, two translated left, two rotated clockwise, and two rotated counterclockwise. The order of stimulus presentation was randomized for each participant. The study phase was followed by a filler task in which participants completed an unrelated questionnaire for approximately 5 min.

In the recognition test phase, another series of animation events was presented. Participants were told to press the *Y* key if they had seen the test animation during the study phase (i.e., if the item was old) and the *N* key if they had not seen the test animation during the study phase (i.e., if the item was new). The experimenter emphasized that the test animation had to be identical to the study item in every way in order to warrant an "old" response (including both the pictorial aspects of the object and the way in which the object moved). After viewing each animation event, the participant had as much time as needed to enter a response. The next event would then begin. In this manner, participants saw objects either moving identically to their study motion or moving in a new way, either with the opposite direction or with a different motion type (i.e., translating rather than rotating). During the test phase, all 32 possible animation events (eight objects in four motions) were shown. That is, each object was shown in four separate animations: one in which the object translated right, one in which it translated left, one in which it rotated clockwise, and one in which it rotated counterclockwise. One of those animations would be identical to the study animation; the other three would be new animations. The order of all 32 test animation events was randomized for each participant. Responses across test animations were independent; the participant had a choice of "old" or "new" for each test item regardless of his or her pattern of earlier test responses.

Results and Discussion

The test animations fell into three categories: (a) An object moved with the same motion and in the same direction as at study, (b) an object moved with the same motion but in a direction different from study, and (c) an object moved with a different motion type from that at study (e.g., translating rather than rotating). To assess the unique effect of direction, we first focused attention on those objects at testing that had the same motion type as seen at study: the first two categories above. Memory competency was measured by computing d' for each condition defined by motion type and direction. A limitation of our methodology is that within any condition individual participants had only two opportunities for hits or false alarms. Clearly, stable values of d' cannot be computed from such data, so we pooled hits and false alarms across participants. Figure 4 shows the computed values of d' in each condition. Error bars were calculated by explicitly constructing the sampling distribution of d' for these data. As depicted, these error bars represent the standard deviation of the sampling distribution.

As shown in the figure, the d' values for translation were all greater than zero ($p < .02$ for every point), indicating sensitivity to translation direction. Within the translation condition, d' values across direction were all highly similar, so we could not evaluate our choice of "left" and "right" labels for the static condition. We could determine only that both directions were remembered well regardless of speed. The rotation d' values were much lower and, except for a single point, were not significantly different from zero ($p > 0.1$ for each measure). This point corresponded to the static clockwise condition in which d' was marginally greater than zero ($p = .05$). However, in this condition we also observed a negative d' for objects studied in a counterclockwise rotation. Negative d' values are not typical and are generally interpreted as a mistake, such as when a participant reverses response keys. This possibility does not explain the data here, in which the negative d' was restricted to only those objects moving counterclockwise at study. The d' sign reversal with studied direction was generally encountered in our rotation data, and its interpretation centers on biases in background familiarity.

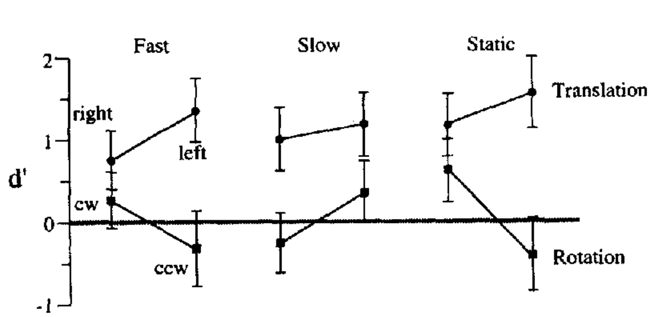

Figure 4. Experiment 1 d' values are plotted for translation and rotation separated by study direction and speed of motion. Error bars depict the standard deviation of the sampling distribution of d'. cw = clockwise; ccw = counterclockwise.

In the Appendix we show that all of our data on circular motions can be interpreted in terms of explicit recognition processes that are supplemented by a generic sense of familiarity for the clockwise direction. The theory we present is fairly straightforward and essentially consists of the proposal that clockwise test items receive additional "old" responses because of some basal familiarity that looking at clockwise objects generates. These responses augment those that are generated by explicit recognition. Sign reversal occurs when the "true" d', that associated with explicit recognition, is small, "true" $d' < 0.5$. In general, the theory predicts that $d'(\text{cw}) > d'(\text{ccw})$. Here and elsewhere, cw and ccw refer to the motion directions observed at acquisition, such that cw = clockwise and ccw = counterclockwise.

Animated motion sequences and still frames generated equivalent data; the displacement itself appeared to be sufficient for direction memory regardless of how that displacement was represented in the stimulus. This finding is of interest because Nakayama and Tyler (1981) found that motion sensitivity is based on motion per se as opposed to representation of positional changes. The findings in the present experiment suggest that the cognitive representations of motion and position may be more entwined than lower level sensitivity functions would suggest.

Responses for test items not used in the previous analyses allowed us to evaluate memory for the type of motion observed at study. We examined the overall false-alarm rate across speed conditions for motions not viewed at study (e.g., errors in which a particular object that rotated at study was "recognized" when translating at testing). There were few motion-type errors, and the false-alarm rate for translations ($M = 0.11$) was roughly equivalent to that of rotations ($M = 0.12$); that is, participants were able to remember which objects at study were translating and which were rotating.

Experiment 2: Expansion–Contraction (Looming)

Looming flow provides the critical case for determining whether motion direction is encoded using egocentric or object-centered representations. If flow complexity is decisive and egocentric descriptions of motion are encoded, then looming and rotation should generate comparable levels of recognition performance. However, if object-centered descriptions are used to specify motion in terms of displacement, then people should be as accurate with looming motions as they have been found to be with translational motions. Therefore, either

$$d'(\text{rotation}) = d'(\text{looming}) < d'(\text{translation}),$$

if memory representation is based on flow complexity, or

$$d'(\text{rotation}) < d'(\text{looming}) = d'(\text{translation}),$$

if it is distal displacement that is decisive. In the following experiment we evaluated these two inequalities by assessing whether the direction of looming flow would be remembered.

Method

The method used here and in the following experiments was basically identical to that used in Experiment 1. Only changes in the method across experiments are noted.

Participants. Sixteen undergraduates from the University of Texas at Austin volunteered to participate in this experiment and were paid \$3 each.

Design and materials. This experiment was run as a one-factor design, with the direction of looming as the single variable. Participants viewed objects either expanding or contracting, as depicted in the center panel of Figure 1. Sixteen basic objects were used in both motion directions, resulting in a total of 32 events. Each object's largest size was about 6 × 6 cm. Each object was viewed in motion for approximately 6.7 s, growing or shrinking from its initial state twice during that time. After the initial growing or shrinking phase, the object immediately returned to its initial state (without undergoing the opposite motion direction) and began growing or shrinking again.

Procedure. During the study phase of this experiment, participants were shown eight distinct events, with each involving a separate object. In half of these events an object was shown contracting, and in the other half an object was shown expanding. The assignment of motion direction to objects was counterbalanced across participants, as was assignment of objects to the study phase and order of presentation. All 32 possible events, each object contracting and expanding, were shown at test in random order.

Results and Discussion

The test animations fell into three categories: (a) an object moved in the same direction as at study, (b) an object moved in the opposite direction from study, and (c) an object that was not shown at study was presented either expanding or contracting. Our initial analysis was concerned only with objects shown at study, the first two categories above. In this data set each observer had only four opportunities to make a hit or false alarm for each direction, so we again pooled hits and false alarms across participants within each condition. Figure 5 shows d' for each study direction, with error bars depicting the standard deviation of the sampling distribution of d'. The d' values were significantly greater than zero ($p < .001$) for both contracting and expanding motions.

The differences in recognition accuracy that we found between rotation and looming motions in the first two studies may underestimate the true disparity that exists in encoding strength. In both studies participants were shown eight animations at acquisition. However, in the first study half the animations were of translating objects and half were of rotation objects, so participants had to encode only the rotation directions of four objects. In the second experiment all objects executed looming motions, so there were fully eight directions to be encoded—clearly a potentially more confusing set of events, in that people rarely mistake rotations for translations. The evidence that translations and looming directions are both more recognizable than rotation direction supports the notion that what is important are distal translations: People remember the direction of a transformation when that transformation signifies a change of place.

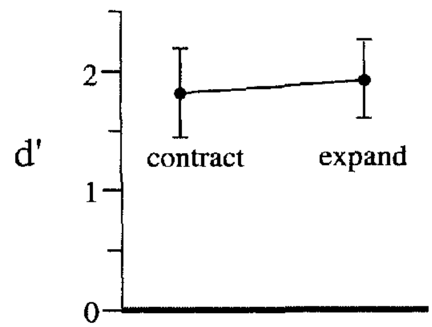

Figure 5. Experiment 2 d' values for looming motions separated by study direction. Error bars depict the standard deviation of the sampling distribution of d'.

Finally, the false-alarm rate for looming novel objects, errors in which novel objects were "recognized," was negligible ($M = 0.02$), indicating good memory for the objects as well as for their direction of motion.

The finding that memory for looming direction was highly accurate strongly supports an object-centered representation of motion. We suggest that motion representations in explicit memory are informed not by neural or computational complexity but by the elementary token of displacement; if the flow displaces, then there is memory for direction. In this sense, representations in memory are attuned to translations along any line of sight. Where things are is consequential for behavior.

Experiment 3: Combined Motion

The motions of everyday objects are often combinations of translations and rotations. Dropped or thrown objects tumble and wheels do not just rotate—they roll. So although the results from our first experiments are clear and systematic, they do not address typical combined motion events. In this experiment, rotations and translations were integrated into tumbling and rolling motions.

As in the previous experiments, we were interested in the frequency and types of errors that are made in memory for direction. However, when rotations and translations are combined, the data are considerably more complex because there are three ways that errors can be made. Denoting by T_e an error made on translation direction, by R_e an error made on rotation direction, and by T_c and R_c correct evaluations of those directions, the three types of error that can be made on a combined event are as follows: (T_c & R_e), (T_e & R_c), and (T_e & R_e). The relative frequencies with which these errors arise will depend on how people encode combined motion events.

There are four specific patterns of hypothetical data that illustrate the range of what might be encountered for combined encodings:

1. Veridical direction memory for translation may generalize to the rotational component. In this case errors should be relatively rare, and if they are independent of the motion class, one should observe

$$p(T_e \,\&\, R_c) = p(T_c \,\&\, R_e) \gg p(T_e \,\&\, R_e),$$

where p refers to the probability of this type of error being encountered.

2. Poor memory for rotation may generalize to translation in a combined motion. If all direction information is lost, then

$$p(T_e \,\&\, R_c) = p(T_c \,\&\, R_e) = p(T_e \,\&\, R_e).$$

3. The event may be encoded categorically in terms of whether it is rolling or not rolling. A rolling event must have the linkage (rightward translation–clockwise rotation) or (leftward translation–counterclockwise rotation). If the category membership is encoded, but not the overall sign, then these frequencies would be obtained,

$$p(T_e \,\&\, R_c) = p(T_c \,\&\, R_e) \ll p(T_e \,\&\, R_e),$$

because an error on only one component takes it out of the category.

4. The two motions may be memorially separable even though the distal event is combined. In this case we expect the results from the first experiment to be replicated,

$$p(T_c \,\&\, R_e) \gg p(T_e \,\&\, R_c) = p(T_e \,\&\, R_e),$$

if people are roughly at chance at remembering the rotational direction and have a pretty good idea of the object's translation direction. The present experiment provided the necessary data to distinguish among these possibilities.

Method

Participants. Sixteen students from introductory psychology classes were participants in this experiment.

Design and procedure. The experiment was run as a 2 × 2 within-subjects design. The variables were direction of translation (left or right) and direction of rotation (clockwise or counterclockwise).

The same basic objects from Experiment 1 were used in each of the four motion combinations, yielding a total of 32 distinct events. The objects ranged in size from 2.5 × 3.5 cm to 4.5 × 7 cm and were of various colors and fills. Objects were viewed in motion for approximately 3.5 s, translating at about 11.5 cm/s while rotating at about 0.6 rev/s. Each object was shown translating across the screen while making a full rotation about its central axis. The animation was then repeated.

During the study phase of this experiment, participants were shown eight distinct animation events. Two animations were chosen from each of the four possible translation and rotation direction combinations. Thus, there were four rolling events and four nonrolling events. The assignment of motion combinations to objects was counterbalanced across participants, and order of presentation was randomized. All objects in all four motion combinations (32 events) were shown at testing in random order.

Results and Discussion

Because each motion contained both a translating and rotating component, false-alarm rates were not independent and it was inappropriate to compute d' values in the context of this experiment. Instead, we examined the overall pattern of errors to determine how these combined motions were represented.

The overall hit rate (corresponding to T_c & R_c) was .62. The number of errors made on rotation but not on translation (T_c & R_e), errors made on translation but not on rotation (T_e & R_c), and errors made on both components (T_e & R_e) are shown in Figure 6. It is evident from the pattern of data obtained that $p(T_c \,\&\, R_e) \gg p(T_e \,\&\, R_c) = p(T_e \,\&\, R_e)$, implying that the combined event is memorially separable and people's memory for translation direction is much better than their memory for rotation direction, even when the two motions are coupled. These results essentially replicate the findings of Experiment 1 for isolated rotations and translations.

When errors were made on rotation and not translation (T_c & R_e), the number of false alarms to clockwise motion ($n = 31$) was slightly lower than the number of false alarms to counterclockwise motion ($n = 37$). Therefore, in the combined displays we see no evidence of a direction-contingent familiarity bias. It appears that when rotation and translation occur together, the rotational information is not available for explicit recognition.

Finding robust memory for translation direction and poor memory for rotation direction when those motions are

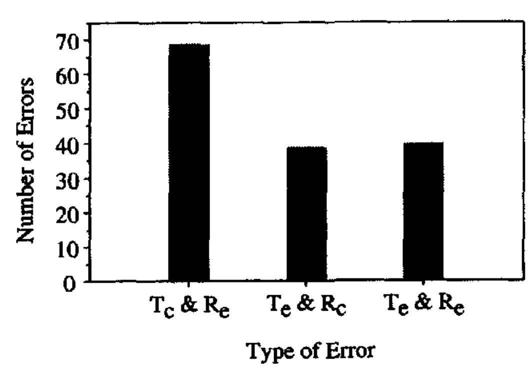

Figure 6. The frequency of false alarms from Experiment 3 separated by dimension of error: rotation, translation, or both rotation and translation. T_c = correct evaluation of translation direction; R_e = error made on rotation direction; T_e = error made on translation direction; R_c = correct evaluation of rotation direction.

combined is reminiscent of earlier work by Hecht (1993), who was interested in the information people use in making naturalness judgments of a wheel rolling down an inclined plane. Participants in Hecht's study attended primarily to the translational component and disregarded what was occurring in the rotational kinematics. If the analogy to our memory studies were to be complete, we would expect people to be highly sensitive to the naturalness of translational motions and correspondingly insensitive to the naturalness of rotational motions when presented in isolation. Such is indeed the case (Kaiser, Proffitt, Whelan, & Hecht, 1992). It may be that people cannot judge what they cannot or do not encode.

Experiment 4: Dynamic Occlusion and Object Permanence

An important difference between rotations about internal axes and translations is that translations produce dynamic occlusion but rotations do not. This type of occlusion has the remarkable property that it is perceived to be reversible (Gibson, 1986). That is, background texture that is deleted does not go out of existence. Rather, it is progressively covered up and available for reappearance. In this sense, deleted texture is perceived, although it may not have current support in the optic array. A similar thing occurs when an object's motion takes it behind a stationary occluder. Here the occluding edge is stationary and it is object texture that is deleted. In this case the transformation is also perceived to be reversible; the entire object continues to be perceived as long as its progressive deletion is specified in the optic array. It is of some interest to examine what kind of memory accuracy exists when the moving object rather than the background is dynamically occluded. Partially occluding a rotating object produces just this type of dynamic occlusion (see Figure 7). In particular, occlusion of object texture during object rotation may create enduring representations of motion direction because of the progressive (hence dynamic) nature of the occlusion. If it is possible to improve memory accuracy for rotations by simply changing the occlusion relationships (the rotating object becomes dynamically occluded by a stationary mask rather than by the rotation occluding a background), the notion that displacement is necessary for direction memory would have to be abandoned.

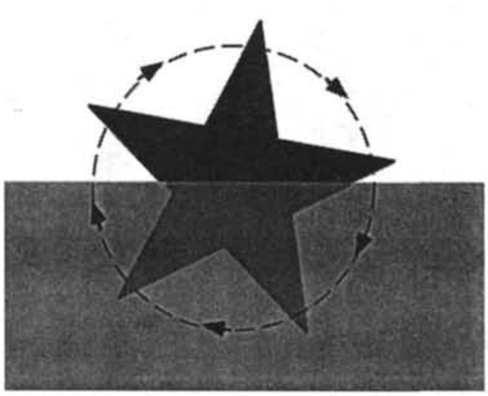

Figure 7. An object rotates clockwise behind a stationary occluder in Experiment 4. The occluder shown here is transparent to facilitate the percept of the object; in the actual experiment the occluders were opaque.

Method

Participants. Sixteen students from introductory psychology classes served as participants for this experiment.

Design and procedure. This experiment was run as a 2 × 2 within-subjects design. The variables were direction of rotation (clockwise or counterclockwise) and position of occluder (top or bottom). Participants viewed each object rotating about its center while either the top or bottom half of the object was occluded. Figure 7 illustrates the typical stimulus format used. Eight basic objects were used in each of four direction–occluder combinations: rotating clockwise or counterclockwise while being occluded either on the top or the bottom. There were 32 events total. Objects varied in size from 3 × 9 cm to 8 × 8.5 cm and were of various colors and fills, with a black 20 × 8 cm rectangle masking half the object. Animation sequences lasted approximately 6 s. Each object was shown making two full rotations.

At study, participants were shown eight distinct events. Each object was shown in one of the direction–occluder combinations, so that at the end of the study phase each participant had seen each combination a total of two times (each time associated with a different object). The assignment of direction–occluder combinations to objects was counterbalanced across participants, and study animations were presented in random order. All 32 possible events were shown at test in random order.

Results and Discussion

The test animations fell into four categories: (a) an object moved in the same direction and had the same occluder placement as study, (b) an object moved in a different direction and had the same occluder placement as study, (c) an object moved in the same direction and had a different occluder placement as study, and (d) an object moved in a different direction and had a different occluder placement as study.

Memory for the position of the occluder was good. The false-alarm rate for "recognizing" the wrong occluder position ($M = 0.14$) was much lower than the hit rate ($M = 0.70$). Again, observers were generally highly accurate in their memories for the pictorial aspects of the animation. In the following analysis we examined only the cases for which the occluder was in the same position for a given object at study and at testing (Categories a & b). Figure 8 shows the d' values for both clockwise and counterclockwise study directions using aggregate hits and false alarms from the entire participant pool. The derived values of d'(cw) and d'(ccw) were shifted positively with respect to the values found earlier for rotation; they were no longer roughly symmetrical about $d' = 0$. This lack of symmetry is symptomatic of explicit recognition. The theory presented in the Appendix implies a small but measurable level of memory fidelity, "true" $d' = 0.22$. Still, relative to translation and looming motions, direction recognition was marginal. Whether occluded or not, memory for rotation appeared to be limited to the object information and to the fact that a rotation occurred.

Experiment 5: Revolution

In the previous experiments we obtained evidence that memory for rotation direction is generally poor when rotation is observed in isolation (independent of speed), when it is coupled with a translation, and when depth assignments are created by occlusion at a stationary edge. Our interpretation of this deficiency is centered around the notion that memory fidelity reflects the presence or absence of information specifying a displacement. There is an intermediate class of motions that have an ambiguous status in this theory: rotations about an axis external to the body. We refer to such motions as "revolutions." Revolution is a hybrid motion. It is a rotation because the object suffers repetitive displacement—it never gets anywhere. Unlike rotations, however, the paths of revolving objects are locally translation-like. This leads to an interesting distinction in object representation on the basis of short- and long-run behavior. In the short run a revolving object behaves as if it is translating, but in the long run its motion is essentially rotational.

Our theoretical framework does not predict how people will deal with information from two time scales, so we pose it as an empirical problem without conjecture. There are two extreme possibilities: Revolution could be encoded as a series of piecewise translations, in which case

$$d'(\text{revolution}) \approx d'(\text{translation}) \gg 0.$$

Rather, if revolutions are treated as rotations by virtue of the circularity of their global motion, then

$$d'(\text{revolution}) \approx d'(\text{rotation}) = 0.$$

Between these two limits, there is the compromise outcome that revolutions will generate weak memories, in which case one should find the residue of direction-contingent familiarity bias and the general ordering

$$d'(\text{translation}) > d'(\text{revolution}) > d'(\text{rotation}).$$

Method

Participants. Forty students from introductory psychology classes served as participants for this experiment. Sixteen participants were assigned to the constant orientation condition and 24 to the changing orientation condition.

Design and procedure. This experiment was run as a 2×2 mixed factorial design. The between-subjects variable was orientation. In the constant orientation condition, objects remained in the same orientation while revolving, much like a Ferris wheel, as shown in the left panel of Figure 9. In the changing orientation condition, depicted in the right panel of Figure 9, objects revolved so that the base of the object was always closest to the axis of rotation, as though the object were rigidly attached to a rotating wand. The within-subjects variable was direction of revolution (clockwise or counterclockwise).

Participants viewed objects revolving about the center of the screen in either a clockwise or counterclockwise direction. The objects revolved at distances of about 2–4 cm from the center of the screen. Sixteen objects were created for use in this experiment, ranging in size from 2×2.5 cm to 4.5×7 cm, and were of various colors and fills. A small back dot (approximately 0.5 cm in diameter) was shown in the center of the screen as a reference point during each animation. Animations lasted about 4 s each, with each object making two 360° revolutions.

During the study phase of this experiment, participants were shown 8 of the 16 objects, 4 revolving clockwise and 4 revolving counterclockwise, in random order. The assignment of motion directions to objects at study was counterbalanced across participants, as was assignment of objects to the study phase. All objects in all motion directions were shown in random order at testing, resulting in a total of 32 test items.

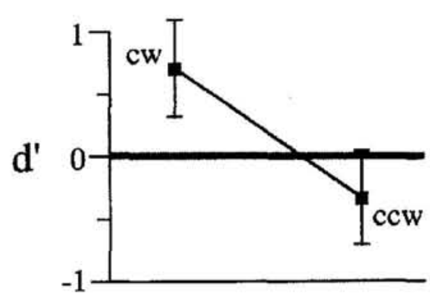

Figure 8. Experiment 4 d' values for occluded rotations separated by study direction. cw = clockwise; ccw = counterclockwise. Error bars depict the standard deviation of the sampling distribution of d'.

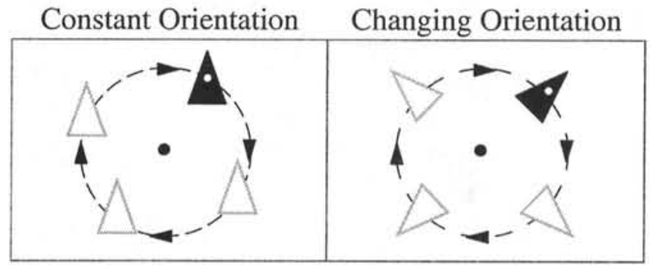

Figure 9. The two orientation conditions of Experiment 5. In the constant orientation condition, the triangle remained upright as it revolved about the center of the screen. In the changing orientation condition, the triangle revolved so that its base was always pointed toward the axis of rotation. Additional time steps are shown as gray outlines.

Results and Discussion

Figure 10 shows the mean d' values for both clockwise and counterclockwise study directions across orientation condition. As before, we pooled hits and false alarms across observers to calculate d'; participants in this study had only four opportunities for hits or false alarms. In both the constant and changing orientation conditions, d' values for the clockwise direction were significantly greater than zero ($p < .001$ in each case). However, the d' values for the counterclockwise direction did not significantly differ from zero in either the constant orientation ($p = .18$) or the changing orientation ($p = .32$) condition.

The pattern of data observed for revolutions had essentially the same structure as observed in the previous experiment: an asymmetrical displacement of the clockwise

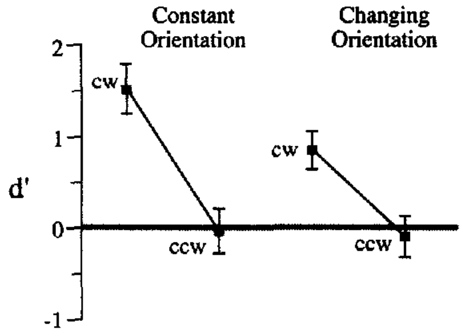

Figure 10. Experiment 5 d' values for revolutions separated by study direction and orientation condition. cw = clockwise; ccw = counterclockwise. Error bars depict the standard deviation of the sampling distribution of d'.

and counterclockwise d' values about zero accompanied by few false alarms to novel objects ($M = 0.05$). The new feature in these data was the better overall memory performance; both d'(cw) and d'(ccw) were respectively larger than those found in rotation driven occlusion (Experiment 4). Studies involving the ability to perceive or imagine rotations have shown a similar distinction between revolution and rotation. Revolutions appear to be an exception to the typical difficulty people exhibit in those tasks (Pani, 1993; Pani & Dupree, 1994; Pani, William, & Shippey, 1995; Shiffrar & Shepard, 1991).

In the Appendix we calculate the true level of direction memory for revolutions and find that it is not insubstantial; true $d' = 0.45$ in the changing orientation condition but true $d' = 0.95$ in the constant orientation condition. This last result is especially interesting because it clearly suggests that one of the reasons that memory for rotation direction is so weak is that the object keeps changing its orientation. If so, these data support the multiple-views model of object representation; that is, representations of objects are attached to learned orientations (Tarr, 1995). A d' value of near unity is respectable in the context of the exact methods (number of objects at acquisition and testing) used in our studies. However, it is also clear that constancy of orientation is not the most important factor distinguishing rotation from looming and translation motions. Both sets of revolution data show strong and consistent direction-contingent familiarity bias. In contrast, translation and looming motions manage to generate veridical direction memory without an attendant direction-contingent bias. The mere presence of circular structure has a profound and disabling effect on memory performance.

The finding of a significant level of direction memory in these studies implies that both the short-run translational behavior and the long-run rotational behavior are active in the creation of a memory trace. Analysis of motion in terms of time-localized properties such as dynamic occlusion at a moving edge does not suffice to explain memory. Memory representations are apparently also sensitive to long-term event structure and therefore to the time-integrated attributes of motion that create persisting change in spatial layout.

Experiment 6: Perceptual Completion

The finding that revolving objects generate nontrivial levels of recognition accuracy for direction is not only important for understanding how representation is sensitive to time scale, but it also creates a useful tool. We can now manipulate memory for circular motions, and this allows for a novel investigation into the level of object analysis that informs memory representation. Here we consider objects in which the parts revolve but the whole is a pure rotation. The kind of memory that is observed for such objects places immediate constraints on where in the part–whole hierarchy representations are formed.

Objects that have revolving parts but globally rotate may be created using an extension of the gestalt law of common fate. Consider an object that is revolving about an axis some distance from its center, as though it were attached to a rotating wand. If a second object is placed opposite to the first so that they rotate at the same angular speed, the percept is dominated by the impression of a bipartite rotating object.[2] The sense that one receives from such an object is that the parts are not revolving independently but are being carried as part of a general rotation. If memory representations are sensitive to part motions, then one should recover the data patterns appropriate to revolution, $d'(\text{cw}) > 0$, $d'(\text{ccw}) = 0$. However, if the event is encoded as a rotating object, then at no time is displacement indicated, and one should recover the symmetry associated with pure clockwise direction-contingent response bias, $d'(\text{cw}) \approx -d'(\text{ccw})$. In this experiment, revolutions and perceptually completed rotations were directly compared to determine the order of the inequalities.

Method

Participants. Forty students from introductory psychology classes served as participants in this experiment.

Design and procedure. Two spatial configurations were used in this experiment, as shown in Figure 11. In the isolated condition, objects were shown revolving about a point just external to the bounding contour. This condition replicated that used in the previous revolution experiment. In the rotational common fate condition, the same objects were paired with partners having similar shape and color. The partner moved with the same angular velocity but was located 180° from the object with which it was paired. The two objects moved as though they were attached across the axis of rotation, although this attachment was not specified in the stimulus. A small black dot was shown in the center of the screen during each animation as a reference point. This experiment was run as a 2 × 2 within-subjects design. The variables were type of display (isolated or rotational common fate) and direction of rotation (clockwise or counterclockwise).

Eight basic objects were created and used in each of four different conditions, such that all possible combinations were represented: isolated or rotational common fate and rotating

[2] This form of grouping by motion is strong. If the two objects are given a common translational component of motion, it is impossible to see the two separate cycloidal motions that each object generates (Proffitt, Cutting, & Stier, 1979). Rather, one sees a wheel-like motion where the objects rotate about a common translating center.

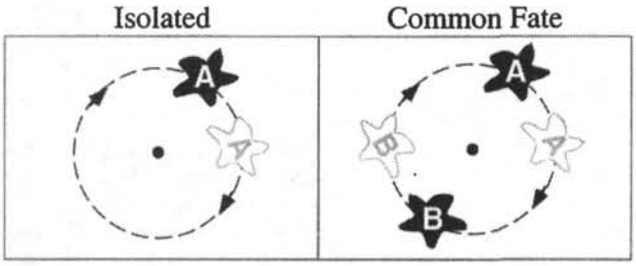

Figure 11. The two object-display conditions of Experiment 6 are illustrated. In the isolated condition, an object A revolves about an external axis at constant orientation. In the rotational common fate condition, a pair of objects (A is now paired with B) rotates at constant orientation about an axis internal to the pair. A future position is shown in gray outline.

clockwise or counterclockwise, resulting in a total of 32 events. Objects ranged in size from 6.5 × 4 cm to 11 × 5 cm and were of various colors and fills. Each animation lasted approximately 6.7 s, in which each object (or group of objects) was shown making a 360° rotation two times.

During the study phase of this experiment, participants were shown eight distinct events in random order, each associated with a different object. Each cell defined by the conjunction of object type (isolated or common fate) and direction (cw or ccw) contained one example and four filler events. The filler events were used for consistency in event number across our experiments. The assignment of direction and display type to objects at study was counterbalanced across participants. All objects in all display and direction combinations (16 events) and 16 filler events were shown in random order at testing.

Results and Discussion

The data from this experiment were treated as before in that observers each had only one opportunity for a hit or false alarm for each stimulus condition. Figure 12 shows d' values for both the isolated and rotational common fate events separated by study direction. As shown in the Appendix, the observations were consistent with an explicit recognition accuracy of true $d' = 0$ in the rotational common fate condition and true $d' = 0.5$ in the isolated

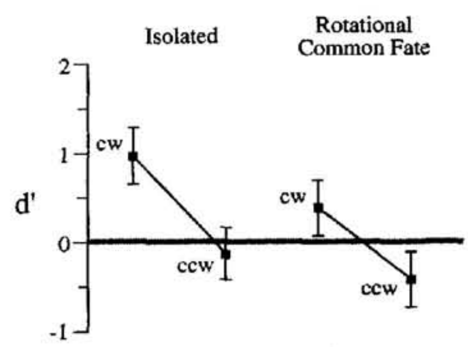

Figure 12. Experiment 6 d' values for revolution about an external axis (isolated condition) and rotation about an internal axis defined by an object pair (rotational common fate condition). cw = clockwise; ccw = counterclockwise. Error bars depict the standard deviation of the sampling distribution of d'.

condition. This is exactly what one would expect if common fate groupings based on angular velocity were encoded as rotations and isolated objects as revolutions. Although the object in our rotational common fate condition existed only as a perceptually organized entity, it defined the level of kinematic analysis. Because it did not suffer displacement, there was no memory of its direction.

General Discussion

Explicit memory for motion direction was studied across seven kinematic regimes: translation, rotation, expansion–contraction, rolling and tumbling, occlusion at a stationary edge, revolution, and common fate grouping based on angular velocity. In summary, there was accurate direction memory for translations (replicating Blake et al., 1997) and looming motions. There was no direction memory for rotations whether for single objects or objects grouped by common fate, regardless of how the rotation was presented (subjectively slow or fast, as a sequence of pictures, occluded, or coupled with translation). When rotations and translations occurred together, observers apparently decoupled the event and retained only the translation direction. Revolutions generated intermediate levels of recognition memory.

In all our studies, observers accurately remembered the pictorial aspects of objects and their motion class (i.e., whether they translated or rotated) regardless of their memory for direction. That representations of object identity were distinct in memory from representations of object position supports neuropsychological and electrophysiological work suggesting that there may be distinct visual pathways involved in object identification and location (Goodale & Milner, 1992; Mishkin, Ungerleider, & Macko, 1983; Schneider, 1969).

Understanding the peculiar patterns of data from the conditions incorporating rotating or revolving objects required a theory that could disentangle explicit recognition processes from generic familiarity bias. We found that the data for circular motions could be consistently explained in the context of receiver operating characteristics theory by the simple addition of a term corresponding to the basal probability that the clockwise direction itself occasions a feeling of familiarity. This theory was successful in that it identified a common level of clockwise bias across experimental conditions and permitted the calculation of sensible d' values. Without this theory, the data for rotations and revolutions is uninterpretable.

Our results lead to the following conclusions: First, motion is not represented in terms of the egocentric complexity of optic flow. Assessment of looming motions was critical in this regard. Rather, memory representations are based on the object's displacement. Second, memory is sensitive to this displacement over multiple time scales. Revolutions provided the critical data here because they are locally translational but globally rotational. The most robust memories ($d' \approx 1$) for direction occur when there is displacement over all time scales (translations and looming motions) and there is little or no memory if there is no displacement (rotations). Revolutions, by virtue of their hybrid status, afford intermediate ($d' \approx 0.5$) levels of direction memory. Finally, motion representations are created from whole objects, not from their parts. Even if the parts are capable of generating a motion analysis that would lead to encoding of direction, as in common fate, if the perceptually organized object is not undergoing a displacement, there is no memory.

These results are best summarized by the notion that memory for direction is mediated by the capacity that a given motion has for transporting a boundary through space. In this sense, our results provide empirical support for Glenberg's (1997) notion that memory evolved in the service of perception and action. From a practical point of view, it is a good thing that people can remember the direction of motion when the motion signifies that the object will occupy a new location. New locations require adaptive behavior; it would be disruptive if people could not remember where things went. Similarly, the direction of rotational motion does not require any adaptive behavior because any orientation can be achieved by both clockwise and counterclockwise rotation. Apparently, people do not encode this transformation in such a way that it is available in an explicit recognition test.

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Appendix

Skewing of Recognition Memory by Asymmetrical Familiarity

In all our experiments that involved some form of circular motion, memory accuracy depended strongly on the direction observed during acquisition. In eight of nine conditions, the clockwise direction appeared to be remembered with greater fidelity, $d'(\mathrm{cw}) > d'(\mathrm{ccw})$, where cw = clockwise and ccw = counterclockwise. Furthermore, in these eight conditions, $d'(\mathrm{ccw})$ was negative, which cannot meaningfully arise within the standard theory of receiver operating characteristics. These inequalities suggest that the methods we have used to assess memory are corrupted by some latent variable that influences response asymmetrically with respect to direction. The following theory identifies this latent variable and shows how the true memory accuracy may be calculated.

It is the nature of recognition that it can be elicited by any process that leads to a feeling of familiarity. These processes include but are not limited to those governing explicit awareness. Feelings of familiarity can also arise from inferential processes as well as from general expectations about the makeup and coherence of the world. We model our data from the point of view that these various sources of familiarity are not equally active across rotation direction. Specifically, we suppose that there is a tendency to experience a sense of familiarity when an object's motion is clockwise regardless of its previously seen direction. This tendency is defined by the following properties:

1. Direction-contingent familiarity bias is part of the generic content of memory and is not attached to any particular episodic traces.
2. Explicit recognition of the object itself takes precedence over familiarity bias. The misidentification of objects (responding "old" to a novel object) was both infrequent and independent of direction in all experiments.
3. The familiarity bias is independent of the motion direction seen at acquisition.

Observers then have two independent routes to the response "old" for a clockwise item at testing: They may actually recognize the object and its motion, or the motion may just seem familiar because of a latent disposition to regard it so. Similarly, observers have only a single route to the response "old" for counterclockwise items at testing: They have to recognize the object and its direction. Consequently, any object at testing is more likely to receive an "old" response if it is moving clockwise than if it is moving counterclockwise, assuming that there is no true distinction in memory that is contingent on direction. In this way, people will generate extra hits for objects that were in fact clockwise at acquisition and extra false alarms for objects that were not. Their memory accuracy will invariably appear to be skewed, and this is what we consistently found in our data. In what follows, we show how these ideas may be put into an explicit computational framework.

We assume a standard receiver operating characteristics framework for measuring memory fidelity. Explicit memory processes are conceived as generating signal and noise distributions of familiarity and a criterion that sets the level at which an "old" response will be emitted. Let A and B be the probabilities that explicit memory processes generate a hit or false alarm, respectively. In the absence of any additional structure, we then have $d'(\mathrm{cw}) = d'(\mathrm{ccw}) = D(A,B)$, where $D(A,B)$ is the standard solution for obtaining d' from hits and false alarms. Note that $D(A,B)$ is the same for both directions in this theory. Now let F be the probability that a clockwise moving object will elicit an "old" response because of a generic familiarity for that direction. Assuming statistical independence of generic and episodically based familiarity, the hits and false alarms have the following functional forms:

$$\mathrm{hit(cw)} = A + F - A \cdot F \qquad \mathrm{fa(cw)} = B$$

$$\mathrm{hit(ccw)} = A \qquad \mathrm{fa(ccw)} = B + F - B \cdot F$$

remembering that background familiarity is operant only for those objects moving clockwise at testing. Given these hit and false-alarm probabilities, we can uniquely relate the measured values of $d'(\mathrm{cw})$ and $d'(\mathrm{ccw})$ to the true $d' = D(A,B)$ and a level of generic familiarity, F. Note that the true d' is just that part associated with explicit memory processes. In Figure A1 we present calculations for an ideal observer who places his or her criterion for an "old" response at the intersection of the signal and noise distributions; $B = 1 - A$. Such an observer is unbiased in terms of his or her propensity to say "old" or "new."

There are several features of Figure A1 to which we would like to draw attention. First, the value $d'(\mathrm{ccw}) = 0$ serves as the origin of the memory space that is parameterized by true d' and F (referred to as "generic familiarity"). Because the true d' must be

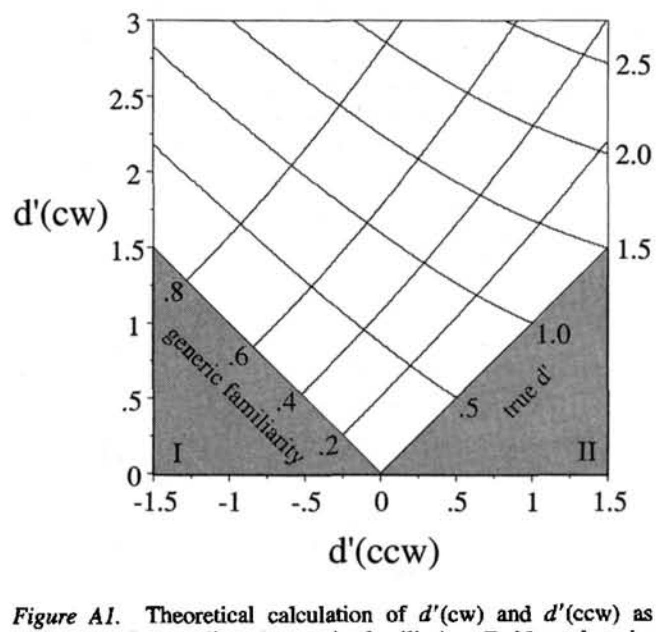

Figure A1. Theoretical calculation of $d'(\mathrm{cw})$ and $d'(\mathrm{ccw})$ as functions of true d' and generic familiarity, F. Note that the coordinate labels for true d' continue along the right-hand vertical axis. cw = clockwise; ccw = counterclockwise.

(Appendix continues)

greater than zero, there are no solutions in the gray triangle denoted by I. There are also no solutions in the gray triangle denoted by II because any point in this region has $d'(\text{ccw}) > d'(\text{cw})$, and this can only occur if it is the counterclockwise direction that is generically familiar. Any point in the white area has a coordinate description in terms of $[d'(\text{cw}), d'(\text{ccw})]$, which are measured from experimentation or in terms of (true d', generic familiarity), which are the desired theoretical constructs. Because the relation between the two coordinate descriptions is unique, the theory is well defined and can be used to make predictions.

The fact that the theory is well defined does not mean that it explains the directional asymmetry observed in our data. The relevance of the theory would be established if there was a specific level of generic familiarity, F, that pervaded our experiments. In this case the argument could be made that the psychological construct of generic clockwise familiarity is meaningful insofar as its calculated values are stable and persistent. Figure A2 shows data supporting this interpretation. In this figure the two curves depict $d'(\text{cw})$ and $d'(\text{ccw})$ as a function of true d' for a single value of generic familiarity, $F = .35$. Relative to these curves, we have replotted the measured values of d' from all experiments in which object motions at acquisition were of a single type (rotation or revolution) and the objects themselves changed orientation. This yielded four sets of points: perceptually completed rotation (Experiment 6); rotation-generated occlusion (Experiment 4); and single-object revolutions (the isolated condition in Experiment 6 and the changing orientation condition in Experiment 5). For each label, the top and bottom points refer to the clockwise and counterclockwise values of d', respectively.

Figure A2 reinforces two important points: First, the observation that all the data could be placed on the theoretical curves implies that there is a characteristic level of background clockwise familiarity that globally influences recognition. This finding is significant because it argues for the independent psychological reality of F. The experiments were in no way constrained to produce this consistency. Second, the levels of explicit memory that are entailed by the theory were meaningfully ordered. Rotations generated the least memory (true $d' \approx 0$), direction memory for occluded rotations was slightly improved ($d' \approx 0.2$), and the most accurate memories were observed for revolutions that had local displacement ($d' \approx 0.5$).

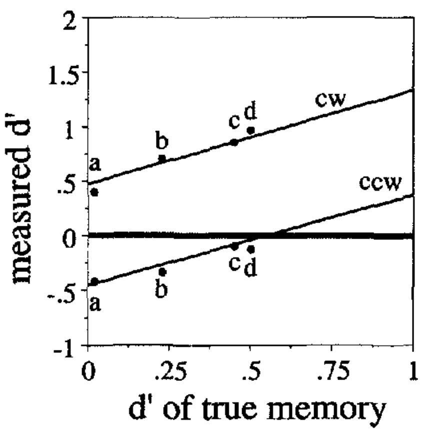

Figure A2. Interpretation of data in terms of direction-contingent familiarity. d' values from four experiments are replotted: (a) rotational common fate (Experiment 6), (b) rotation-driven occlusion (Experiment 4), (c) isolated object revolution (Experiment 6), and (d) changing orientation revolution (Experiment 5). Within each pair, the upper and lower points refer to the clockwise (cw) and counterclockwise (ccw) directions, respectively. Also shown are theoretical predictions of $d'(\text{cw})$ and $d'(\text{ccw})$ as a function of true d' for generic familiarity, $F = 0.35$.

The theory just outlined makes a compelling case for the existence of a generic sense of clockwise familiarity. It should be recognized, however, that it is incomplete; it does not address the important question of how the clockwise direction comes to be psychologically preferred, nor does it distinguish circular motions as singular in their susceptibility to direction preference. These issues are not easily resolved, and we have made little headway toward their solution.

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