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Explorations of Representational Momentum

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Figures that have undergone a rotation or translation are remembered as being slightly beyond their final position. This phenomenon has been termed "representational momentum" because of the possibility that it reflects the internalization in the visual system of the principles of physical momentum. This paper explored the questions of what gets transformed in representational momentum, and what types of transformations induce such representational distortions. The experiments in Part 1 indicated that representational momentum is associated with the representation of a particular object rather than an abstract spatial position. Figures of radically different shapes shown in spatial positions that implied a rotation did not produce momentum effects. On the other hand, figures that could be construed as identical objects moving to different locations led to momentum effects. The experiments in Part 2 revealed that transformations not related to actual physical momentum, such as changes in the pitches of tones, can produce representational momentum. These findings suggest that representational momentum is abstractly related to physical momentum. The final discussion explores the implications of representational momentum for the analog/propositional debate. © 1987 Academic Press, Inc.

Human evolution has occurred in a three-dimensional, locally Euclidean environment that is furnished with rigid to semirigid objects whose movements are constrained by invariant physical laws. Shepard (1981, 1984) has speculated that these most enduring characteristics of the environment have been internalized in perceptual systems during the course of evolution. As a consequence of this internalization, perceptual processes would be expected to resemble corresponding physical processes. For example, in rotating between two orientations, an object will traverse completely the intervening space. The processes people use to imagine such rotations also appear to represent intervening points along the path of motion. In addition, an object moving at a constant speed will require more time to complete a large angular rotation than a small one, and the time needed to perform a mental rotation is linearly related to the size of the angle traversed in the rotation (Shepard & Cooper, 1982).

Given the pervasiveness of motion as opposed to stasis in the environment, one would expect the perceptual systems to have internalized laws of physical motion, which would be revealed in appropriate perceptual tasks. Freyd and Finke (1984) have explored the potential internalization of one principle of physical motion: momentum. As Newton (1687/1962) states in his *Mathematical Principles of Natural Philosophy*, due to inertia "Projectiles continue in their motions [along a straight line], so far as they are not retarded by the resistance of the air, or impelled downwards by the force of gravity" (Vol. 1, p. 13). As one knows from driving, resistance imposed by braking does not lead to an instantaneous stop. Rather, because of momentum, the car travels beyond the point at which breaking began. Given the pervasive tendency for moving objects to continue along an established direction, the visual system may simulate momentum in its operations. On detecting a moving object, the visual system might automatically calculate future positions of the object based on a perceived trajectory. This ability might play an important role in a number of activities, such as anticipatory reaching and avoidance of projectiles.

If perceivers do extrapolate beyond the present position of a moving object, one might expect their perceptual and/or memory representations for that position to be distorted forward. Freyd and Finke (1984) tested this hypothesis by presenting viewers with a sequence of static displays implying a rotation of an object. Subjects saw a series of three rectangles at different orientations. After watching the series, a fourth rectangle was displayed whose orientation was the same as the third rectangle, slightly further than the third, and so continuing in the same direction as that established by the series, or slightly backward against the established direction. The subjects judged whether the orientation of the fourth rectangle was the same as that of the third. Subjects were more likely to err in judging the fourth rectangle as being in the same orientation as the third when it was displaced slightly forward from the third than when it was displaced slightly backward by an identical amount. In addition, when correctly rejecting the fourth figures as different, the subjects took more time for those rectangles whose displacement was consistent with the direction of rotation. The results indicate that the representation of the third orientation had been distorted in the direction of rotation, as would be predicted from a mental analog of physical momentum. This mental analog has been termed "representational momentum."

These representational distortions do not appear to be caused by elementary sensory processes related to motion. Afterimages, iconic memo-

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ries, or motion aftereffects should tend to reduce the effect or actually produce effects opposite to that predicted by representational momentum. Though physical momentum of the eye during rotation could explain the results, further studies controlled eye movements by having subjects fixate on a central point while surrounding dots moved in separate directions, but momentum effects were still obtained (Finke & Freyd, 1985 and Experiment 8 below; see Posner, Nissen, & Ogden, 1978, for evidence that human beings are quite good at maintaining fixations). In addition, the effects do not depend on the presence of actual or apparent motion, since they can be found when the interval between stimulus presentations reaches 2 s (Finke & Freyd, 1985), which is well beyond the intervals at which apparent motion is experienced. Finally, the distortions occur very rapidly (under 20 ms; Freyd & Johnson, 1987) and are quite resistant to practice, error feedback, or both (Finke & Freyd, 1985).

Subsequent investigations have explored the extent to which physical models of momentum can predict aspects of representational momentum. The greater the correspondence between these two processes, the more likely that the visual system has internalized knowledge of physical momentum. Since physical momentum is proportional to velocity, one would predict that greater representational shifts would occur with increased velocity of a moving object. Freyd and Finke (1985) manipulated velocity by varying across trials the interstimulus intervals (ISI) between the first, second, and third rectangles. Short ISIs would imply greater velocity than longer ISIs. Freyd and Finke found that the representational distortions increased linearly with velocity. Additional studies (Finke, Freyd, & Shyi, 1986) manipulated the acceleration of the rectangles by varying the ISI within a trial. Moving from a long ISI between the first and second display to a short ISI between the third and fourth represented an acceleration, whereas the opposite pattern represented a deceleration. As would be predicted from principles of physical momentum, representational distortions were dependent on the implied final velocity rather than the average velocity within a trial. Finally, when a braking car comes to a halt, all the positions between its final location and its initial location will have been traversed. By varying the retention interval between the third and test rectangle, Freyd and Johnson (1987) determined whether representational distortions due to representational momentum also traversed intervening values. At short retention intervals, a linear relation was found between representational shift and retention interval. This finding resembles the analog nature of mental rotation. The imagined rotation of an object also appears to traverse the points between the origin and destination (Shepard & Cooper, 1982). Further highlighting the resemblance between physical and representational momentum is the finding that the rate of change in representational momentum is approximately equal to the rate of change in observed physical motion for a wide range of velocities (Freyd & Johnson, 1987).

In contrast to these quantitative investigations of representational momentum, the present studies focus on qualitative aspects of the effect. In particular, we address the questions of what exactly gets transformed in representational momentum and what types of transformations elicit such distortions. Part 1 investigates whether the representation of a particular object becomes distorted as a consequence of momentum or whether the representation of an abstract spatial position becomes transformed. These alternatives can be tested by presenting different objects in each display rather than four rectangles. If representational momentum operates at the level of object representations, the effects should be reduced or eliminated by disrupting object identity across presentations. On the other hand, if the momentum effect involves a rotation of an abstract frame of reference, such as the major axis of a series of differently shaped objects, then altering the identity of the objects in each display should be irrelevant to the effect.

Part 2 explores the types of transformations that can produce representational momentum. In particular, previous studies have examined only simple types of transformations such as rotations and translations in the picture plane. In Part 2 we examine more complex types of proximal changes that are more indirectly related to actual motion. For example, Experiment 6 examines whether changes in the shape of an object produce representational distortions consistent with the direction of the implied change.

PART 1: OBJECT IDENTITY AND REPRESENTATIONAL MOMENTUM

In a standard mental rotation study, the time required to identify two objects as the same is proportional to the angular disparity of the objects. Performance of this task apparently entails a mental rotation of one object into congruence with the other, with longer paths of rotation requiring more time to complete. However, if subjects are given advance information of the object they are to imagine rotating as well as the orientation of the comparison object, the relation between angular disparity and identification time disappears (Shepard & Cooper, 1982). The subjects can apparently perform the mental rotation during the preparation period, leaving only a comparison process when the second object is presented. This beneficial effect of advance information does not occur if the subject is provided only with orientation information. The subject must also be presented with the particular object to be imagined as rotating. Rotation of an abstract frame of reference or coordinate system appears to be difficult if not impossible. The mental rotation must involve a particular concrete object.

If representational momentum also involves a specific object rather than an abstract coordinate system, then changing the identities of the objects in successive displays should reduce or eliminate the phenomenon. The first four experiments explored this possibility. In each experiment, viewers were shown three objects in succession. The objects differed in orientation in a manner that implied a clockwise or counterclockwise shift in spatial position. A fourth object was then presented whose orientation was the same as the third object, or was rotated slightly forward or backward relative to the third object. The subject's task was to indicate whether the fourth object was in the same orientation as the third or in a different orientation.

The objects used in each experiment were either the same (Experiment 1) or differed in shape (Experiments 2 and 3) or internal markings (Experiment 4). These variations were selected to determine, first, whether an object constancy assumption was required for representational momentum to occur and, second, whether some parameters more nearly satisfy that requirement than others. In Experiments 1, 3, and 4, the patterns were selected so that their contours could be mapped onto one another through projective transformations of a rigid object. In Experiment 2, on the other hand, the patterns were selected so that they could not represent different projections of the same rigid object. In order to perceive these patterns as the same object, they would have to be interpreted as undergoing nonrigid changes in shape. Given the visual system's preference for rigid transformations (Shepard, 1984), such an interpretation might not be favored. Instead, the rigidity preference might be preserved by perceiving the patterns as different objects in different locations. Since a single object is not being transformed in this situation, momentum effects might be eliminated. Of the remaining studies, the patterns in Experiment 3 varied slightly in shape, whereas those in the Experiments 1 and 2 had the same dimensions. If momentum can be induced only through patterns whose proximal dimensions remain constant, such effects should be absent in Experiment 3. Finally, though the contours of the patterns in Experiment 4 were the same, their internal markings varied. The markings were varied in such a way that they could not represent different projections of the same pattern. If internal markings are as critical for object identity as contour, momentum effects should be absent in Experiment 4.

Experiment 1: Identical Objects

Experiment 1 was a replication of a standard representational momentum study. Subjects viewed successively three rectangles of identical dimensions that were oriented 17° apart. The shift in orientation suggested a clockwise or counterclockwise rotation of a single rectangle. After the third figure was removed, a fourth rectangle was shown that was in the same orientation as the third or slightly forward or backward relative to the implied rotation. Subjects judged whether the fourth rectangle was in the same orientation as the third rectangle or in a different orientation. As in previous studies, subjects should commit more false positives for forward distractors than for backward distractors, indicating that their representation for the position of the third rectangle had been distorted forward. In addition, subjects should take longer to reject correctly forward distractors compared with backward distractors since the representation of the third position should be more similar to the perceived positions of forward distractors. Because the figures displayed in this experiment have the same dimensions, the visual system has sufficient information to assume that they represent the same object at different spatial locations. Any momentum effects found in this study, then, can be used as a standard of comparison for the remaining studies, in which the assumption of object identity may be less warranted.

Method

Subjects. Sixteen members of the Cornell community were paid for their participation. Eight observed an implied clockwise rotation and 8 observed an implied counterclockwise rotation.

Apparatus and stimuli. Stimuli were presented on a Hewlett–Packard (HP) 1340A vector plotting graphics display screen, which was controlled by an HP-1351A graphics generator and an HP-9133A computer. The stimulus figure was a 3.7 × 1.9-cm rectangle presented about 40 cm away from the subjects. On each trial this figure was presented in three "inducing" orientations that implied a clockwise or counterclockwise rotation. These three orientations were the same across trials. The figure was first presented with its major axis oriented toward 12 o'clock. The figure was then shown twice more at successive 17° rotations from the first orientation. After the third display was removed, the rectangle appeared again at one of nine "probe" orientations: −8, −6, −4, −2, 0, 2, 4, 6, or 8° of rotation from the orientation of the third rectangle.

The first three displays of the rectangle lasted for 250 ms whereas the fourth display remained until the subject responded (see Fig. 1). The interstimulus intervals (ISI) between displays varied from 100 to 900 ms in 100-ms steps. The ISIs were constant within a trial.

Procedure. The participants received random sequences of 50 practice and 243 experimental trials. The experimental trials were obtained by combining the nine different probe orientations with nine different ISIs and having three replications of each of the 81 trial types. The 50 practice trials were randomly selected from the 243 possible trials. The subjects were tested in a well-lit room and sat approximately 40 cm away from the display screen.

Each trial began with the presentation of a fixation cross. After focusing upon this cross, the subject pressed a foot pedal, after which the rectangle appeared successively in the three inducing orientations and the single probe orientation. For eight of the subjects, the inducing orientations implied a clockwise rotation of the rectangle, whereas for the remaining eight the inducing orientations implied a counterclockwise rotation. After the

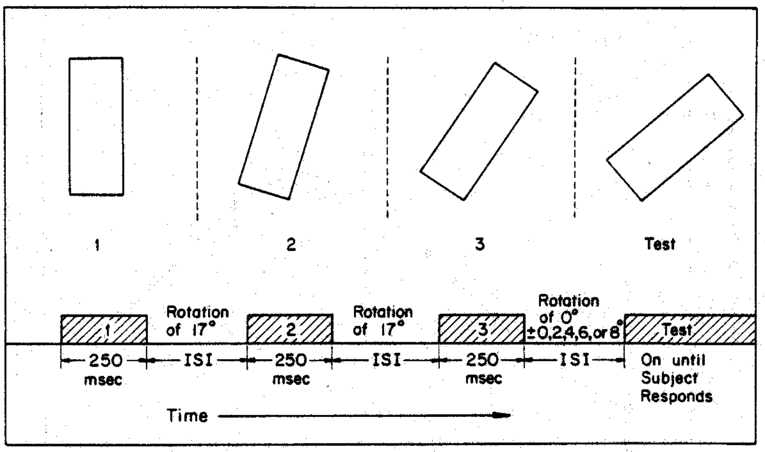

FIG. 1. Schematic diagram of a clockwise trial in Experiment 1. The test orientation displayed is for an 8° forward rotation. Identical rotations and ISIs were used in Experiments 2–4.

fourth presentation of the rectangle, the subject judged whether it was in the same orientation as the third presentation or in a different orientation. If the former, the subject pressed a "same" button which was held in the dominant hand; if the latter, the subject pressed a "different" bottom which was held in the nondominant hand. After the subject responded, the rectangle was replaced by a fixation cross signaling the start of the next trial.

Subjects were instructed to respond as rapidly as possible while maintaining a high degree of accuracy. Since the probe orientation was identical to the third inducing orientation on only one-ninth of the trials, the participants were told not to expect an equal number of "same" and "different" trials, though they were not told the direction of the asymmetry. They were informed, however, that an equal number of probe orientations would be rotated forward and backward relative to the third inducing orientation.

Results and Discussion

The subjects' error rates were in accord with representational momentum predictions. Subjects committed more false positives (63–32%) when the orientation of the fourth rectangle continued along the progression established by the preceding three than when it reversed that progression ($t(15) = 6.08$, $p < .001$). The results were quite robust, as 15 of the 16 subjects produced error patterns in accord with momentum predictions. In addition, as Fig. 2 shows, each of the forward probe orientations revealed more errors than its corresponding backward probe orientation. (No differences between the clockwise and counterclockwise conditions were found in this and subsequent experiments.)

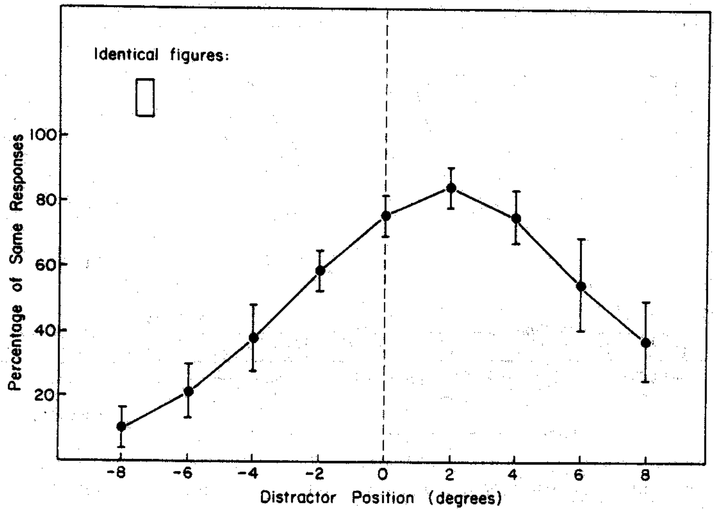

FIG. 2. Percentage of responses in Experiment 1 that judged the third and fourth figures to have the same orientation, as a function of the actual orientation of the fourth figure relative to the third. A schematic drawing of the figure shown in each display is presented in the upper left corner. In this and other figures, error bars represent the standard errors. Note that using these errors to compare means would be to perform a between-subjects analysis. However, actual comparisons used within-subject tests, which take into account differences across subjects in the tendency to commit false alarms.

In all experiments, reaction times greater than 2000 ms were removed before analyzing these data. These accounted for less than 1% of the times across the experiments. In Experiment 1, no significant patterns emerged in the reaction time data. The mean time needed to reject forward distractors was 762 ms, whereas the mean time needed to reject backward distractors was 784 ms ($t(15) = -0.72$, $p > .40$). The reaction times do not, therefore, replicate previous momentum studies that indicate greater confusion between forward distractors and the third orientation than between backward distractors and the third orientation. At the same time, however, the lack of significant patterns in response times rules out a speed–accuracy trade-off explanation for the highly significant error effect.

Overall, then, the results of Experiment 1 indicate that an implied rotation of a rectangle leads to a forward distortion in one's representation for its final position. However, the question remains whether what is distorted is the orientation of a particular object or simply an abstract spatial position. The following experiments determine whether the strength or existence of this effect relies on the assumption that each of the static displays represents a single object in different spatial positions.

Experiment 2: Radical Shape Changes

In this experiment, subjects were no longer presented with four figures of the same shape and dimensions, but four figures having radically different contours: A rectangle, an hourglass, a diamond, and a triangle.

Because of the large differences among the figures, they could not represent perspective transformations of a single object. Hence the visual system had no information to warrant the conclusion that the four displays represented a single object moving through different spatial positions. The objects instead should be viewed as four independent and stationary objects at different locations. Under these circumstances, no momentum effects should appear, since no motion of a single object is present. However, if what is being distorted by representational momentum is an abstract frame of reference, then strong distortions for the orientation of a final figure in an implied rotation should be found.

Method

Twenty-four members of the Cornell community were paid to participate. None of the subjects participated in Experiment 1. Twelve were included in a clockwise rotation condition and 12 were included in a counterclockwise rotation condition. The equipment used to generate the stimuli and control the experiment was the same as that used in Experiment 1.

As in Experiment 1, subjects were presented with three figures at different "inducing" orientations followed by a final figure at one of nine probe orientations. The angular disparities separating the figures were the same as those used in the first experiment. However, instead of viewing a single figure at different orientations, subjects saw four different figures at varying orientations: a rectangle, hourglass, triangle, and diamond (see Fig. 3). Across subjects, these figures were presented in different orders according to a Latin square. As in Experiment 1, for half the subjects, the orientation changes for the three inducing figures implied a consistent clockwise shift whereas for the remaining half the changes implied a counterclockwise shift. The procedure was identical to that used in Experiment 1, except for the changes in the stimulus figures. Thus, the subjects were instructed to compare the orientation of the fourth figure with their memories for the orientation of the third.

Results and Discussion

Figure 3 shows the percentage of responses that classified the third and fourth figures as being at the same orientation as a function of the actual angular disparity between those figures. As can be observed, there was no evidence for a systematic tendency to commit more false positives on forward distractors than on backward distractors. The subjects accepted a mean of 51% of the forward distractors as being identical in orientation to the third figure compared with an acceptance rate of 48% for backward distractors, a difference that was not significant ($t(23) = 0.53$, $p > .50$). The reaction time data also revealed no momentum effects. In correctly rejecting probe orientations as different from the third inducing orientation, subjects required a mean of 802 ms for forward probes compared with 795 ms for backward probes ($t(23) = 0.21$, $p > .80$).

Thus, with figures of quite different shapes, no distortions for spatial position appeared that were reminiscent of momentum effects. Compared with the strong distortions observed in Experiment 1, these results suggest that one's representation of the position of a particular moving object is distorted, and not an abstract spatial position per se. The visual system apparently requires the assumption that the same object be presented at each display before it calculates an expected future position. Still, however, what classifies as being the "same" object may vary depending on the level of information processing being investigated. For example, when an uppercase and lowercase *T* are presented simultaneously, subjects take longer to classify them as identical than when they are both of the same case. However, when they are presented sequentially with a suitable lag, this difference disappears (Posner, 1978). The initial stages of information processing, then, appeared more concerned with physical than functional similarities in treating objects as the same. In the representational momentum case, the features considered most relevant to object identity remain unclear. The figures presented in Experiment 2 were quite different in contour. Perhaps less radical differences in the figures would produce momentum effects, indicating that satisfying an object identity assumption at the level of representational momentum does not demand objects of exactly the same dimensions. The next two studies investigate this possibility.

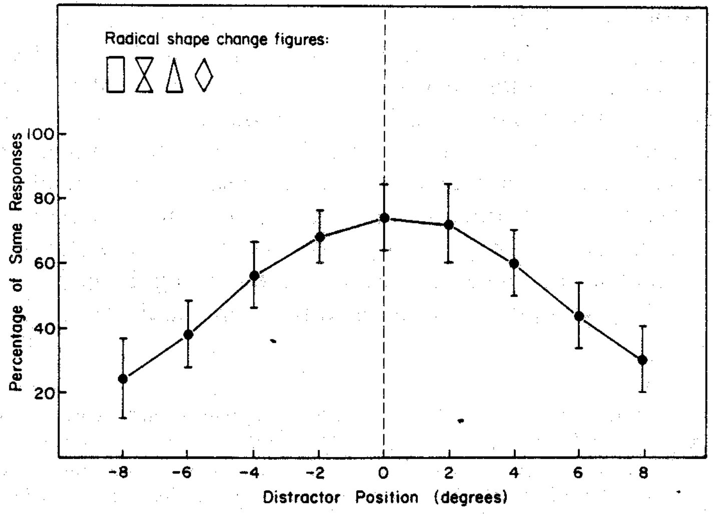

FIG. 3. Percentage of responses in Experiment 2 that judged the third and fourth figures to have the same orientation, as a function of the actual orientation of the fourth figure relative to the third. Schematic drawings of the figures are shown in the upper left corner.

Experiment 3: Rectanges of Different Dimensions

This experiment once again asked subjects to compare the orientation of a visible figure with their memories of the orientation of a final figure in a series that implied a predictable change in spatial position. The figures used in this study were rectangles of equal lengths but varying widths. Thus, the general shapes of the figures were identical in that they could all be classified as rectangles. However, if the visual system requires exact dimensional correspondence for momentum to occur, no distortions should be observed in this study.

Method

Twenty-four members of the Cornell community were paid to participate. None participated in previous experiments. Twelve individuals were included in a clockwise rotation condition and 12 were included in a counterclockwise rotation condition. The equipment used to generate stimuli and control their presentation was the same as that used in the previous studies.

The procedure was identical to that used in the first two experiments except for the nature of the stimulus figures (see Fig. 4). The four figures used were rectangles identical in length (4.5 cm) but varying in width (2.5, 2.0, 1.5, 1.0 cm). The order in which these figures were presented was counterbalanced across subjects. The first three figures were presented at orientations that indicated a clockwise or counterclockwise shift in spatial position. Half the subjects received the clockwise and half the counterclockwise presentation. After the first three figures were presented, the fourth figure was shown at one of nine probe orientations. The angular disparities of the figures were the same as those used in the previous studies. The subjects were instructed to compare the orientation of the fourth figure with their memories for the orientation of the third.

Results and Discussion

Representational distortions consistent with momentum predictions were obtained for both error rates and reaction time. Figure 4 shows the percentage of "same" responses at each of the nine probe positions. Subjects were more likely to accept a probe figure as being in the same orientation as the third when it followed the direction of change implied by the inducing orientations than when it reversed that direction. The mean percentage of false positives committed for forward distractors was 54% compared with 41% for the backward distractors ($t(23) = 2.07$, $p < .05$). Within reaction times, subjects took significantly longer to correctly reject forward distractors (mean reaction time, 798 ms) than backward distractors (mean reaction time, 731 ms), $t(23) = 2.26$, $p < .05$.

Changing the dimensions of a figure of the same overall shape does not eliminate representational momentum. The displays are similar enough for the visual system to conclude that they represent the same object at different spatial positions. Of course, one would not expect the visual system to require that two presentations of a figure be exactly identical for object identity to be inferred. Objects undergo perspective transformations continually as they move, and so the visual system must conclude distal object identity in the face of proximal variation. It should be noted, however, that the difference between the error rates for forward and backward conditions when the rectangles had exactly the same dimensions (Experiment 1) was over twice as large as the error rate effect obtained when the rectangles had slightly different dimensions. This finding suggests that object identity is not a discrete category even at levels of visual processing that are not accessible to direct conscious influence. Rather, certain displays might satisfy the object identity assumption to different degrees, which is then reflected in the strength of the momentum effects.

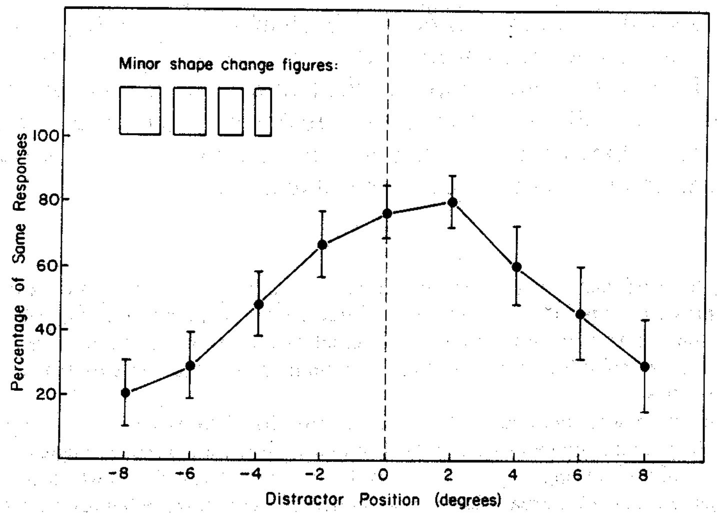

FIG. 4. Percentage of responses in Experiment 3 that judged the third and fourth figures to have the same orientation, as a function of the actual orientation of the fourth figure relative to the third. Schematic drawings of the figures are shown in the upper left corner.

Experiment 4: Internal Marking Changes

In the previous experiments, the figures varied in terms of external contour while leaving identical (blank) internal markings. In Experiment 4, the contour of the figures was held constant while internal markings or texture was varied. With this manipulation, we can determine whether the visual system at the level of representational momentum takes into account internal markings as well as external contour in inferring object identity.

Method

Twenty-four members of the Cornell community were paid for their participation. None participated in previous experiments. Twelve subjects participated in a clockwise rotation condition and 12 participated in a counterclockwise condition. The equipment used to generate and present stimuli was the same as that used in the previous studies.

Subjects were once again presented with three figures at inducing orientations followed by a single figure at one of nine probe orientations. The angular disparities separating the figures were the same as those used in the previous studies. For half the subjects, the inducing orientations implied a clockwise shift in spatial position whereas for the remaining half a counterclockwise shift was indicated. The four figures were rectangles of identical dimensions (3.7 × 1.9 cm) that varied in textural markings (see Fig. 5). Across subjects, the order in which these figures were presented was counterbalanced according to a Latin square. The procedure was the same as that used in Experiments 1–3, with subjects comparing the orientation of the fourth figure with the remembered orientation of the third.

Results and Discussion

Figure 5 shows the percentage of responses that judged the fourth figure as being in the same orientation as the third as a function of the actual angular disparity separating those orientations. Subjects judged a mean of 56% of the forward distractors to be identical in orientation to the third figure compared with 48% of the backward distractors. Though in the predicted direction, this difference was not significant ($t(23) = 1.65$, $.10 < p < .12$). The reaction time data, however, revealed a significant momentum effect. Subjects required a mean of 910 ms to reject correctly forward distractors compared with a mean of 807 ms to reject correctly backward distractors ($t(23) = 3.25$, $p < .005$).

Internal marking changes thus appear to be insufficient evidence to overrule the assumption that the four rectangles are the same object shown at different spatial positions. It is, however, difficult to compare the extent of these internal marking changes with the extent of the contour changes in Experiments 1 and 2. To determine whether external contour is indeed more relevant to object identity inferences than internal markings, one would have to equate the extent of change in each situation. Still, however, the results indicate that completely identical displays are once again unnecessary to produce a momentum effect.

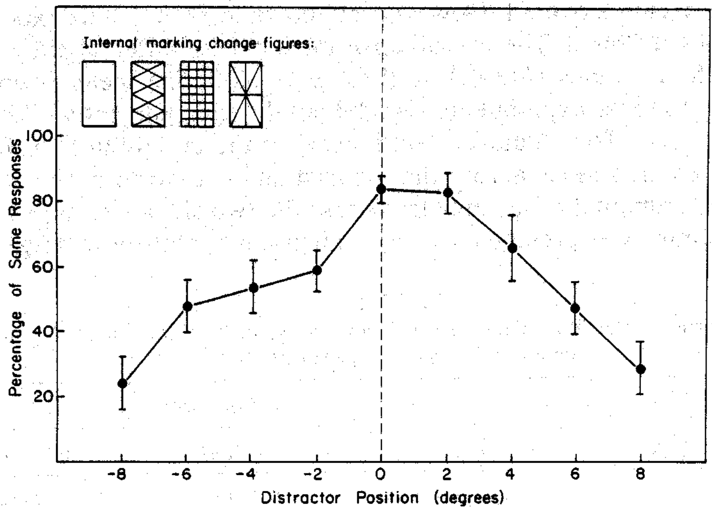

FIG. 5. Percentage of responses in Experiment 4 that judged the third and fourth figures to have the same orientation, as a function of the actual orientation of the fourth figure relative to the third. Schematic drawings of the figures are shown in the upper left corner.

Discussion of Part 1

Representational momentum appears to require some type of object identity assumption. The lack of any hint of a momentum in Experiment 2 when figures of very different shapes were shown at different orientations indicates that for momentum-induced distortions to occur the visual system must be able to assume that the same object is being shown at different positions. When this assumption is not met, the visual system takes the displays as representing four independent objects at different, stationary positions. Since in such a case no motion or momentum would be implied by the displays, no representational momentum occurs.

It is important to rule out an alternative explanation for the null effects in Experiment 2. Perhaps the radical nature of the shape changes resulted in a more difficult task for the subjects, and hence momentum effects were washed out. If the task were generally more difficult in Experiment 2 than in the other studies, one would expect this increased difficulty to produce more errors overall. However, as shown in Table 1, this expectation was not confirmed. The overall error rates did not differ significantly across the four studies ($F(3,84) = 0.85$, $p > .40$). The mean reaction times across the four experiments also did not differ significantly ($F(3,84) = 1.30$, $p > .25$). The studies differed solely in the distribution of these errors and reaction times across the forward and backward probe situations. In Experiment 2 no asymmetry across the two situations appeared, whereas asymmetries predicted by the momentum hypothesis emerged in

TABLE 1

Mean Proportion Error Rates (and Standard Deviations) for Forward, Backward, and Combined Probes in Experiments 1–4

Experiment	Type of probe		
	Forward	Backward	Combined
Same pattern	0.63 (0.17)	0.32 (0.10)	0.48 (0.10)
Large shape change	0.51 (0.21)	0.48 (0.19)	0.49 (0.12)
Small shape change	0.54 (0.19)	0.41 (0.18)	0.48 (0.09)
Internal marking change	0.56 (0.17)	0.48 (0.16)	0.52 (0.12)

other studies. Hence the null results of Experiment 2 cannot be explained by attributions of greater difficulty to this study.

It is important to point out as a remaining caveat that we have no direct evidence that the stimuli in Experiments 1, 3, and 4 were perceived as the same object in different positions whereas the stimuli in Experiment 2 were perceived as different objects in different positions. Our evidence for this assumption is more indirect. Given the nature of the stimuli, the patterns in Experiments 1, 3, and 4 could correspond to different projections of the same rigid object. The patterns in Experiment 2, on the other hand, could not represent different projections of a rigid object. These patterns could therefore be perceived as the same object only if they were construed as undergoing nonrigid deformations in shape. However, as apparent motion (Kolers, 1972; Shepard, 1984) and shadow-casting (Wallach & O'Connell, 1953) studies have consistently revealed, the visual system favors transformations of an object that preserve rigidity. Thus, although an infinite number of possible functions could map one object onto another in apparent motion, the visual system selects solutions that preserve the rigidity of objects (Shepard, 1984). This rigidity preference suggests that permitting nonrigid perceptions in order to construe object identity would be relatively unnatural. As a result, one might expect the visual system to interpret the patterns in Experiment 2 as different objects in different positions, thereby not violating the rigidity preference. As we have said, this argument rests on indirect assumptions regarding how the patterns in the different experiments were perceived, and so more complete interpretations of Experiments 1–4 depend on further investigation of the visual system's criteria for object identity.

In sum, the results of Experiments 1–4 suggest that object identity, as determined through shape correspondence, is more critical to representational momentum than pure shifts in the location of visual stimulation. One potential objection to these results could claim that they contradict the fact that in some situations pure spatial position dominates shape information. For example, when people check the positions of the hands on their watch, they cannot even a moment later remember the actual shape of the numerals on the watch (Morton, 1967). As Fodor (1983) states, in this situation "one recalls, as it were, pure position with no shape in the position occupied" (p. 57). Such evidence that shape, and hence object identity information, is lost to conscious recall in some cases should not lead to the inference that earlier levels in perceptual processing have similar priorities. If a good deal of mental life is modular, as Fodor proposes, then the information requirements in one module might be quite different from the information requirements in another. Thus, whereas the ability to consciously conceive of pure spatial positions in the absence of particular objects might be highly useful in, say, algebraic geometry, we must not assume that other aspects of perception are "space" rather than "object" centered.

PART 2: TYPES OF TRANSFORMATIONS THAT INDUCE MOMENTUM

Whereas Part 1 was concerned with what gets transformed in representational momentum, Part 2 explores the types of transformations that can induce representation distortions consistent with momentum predictions. Previous studies, including those in Part 1, have examined representational momentum in simple types of transformations, such as rotations and translations in the picture plane. We consider these transformations relatively "simple," because both the proximal display in the picture plane and the distal, three-dimensional event that it represents specify a change in position. However, other types of transformations exist that, first, do not represent motion in the two-dimensional display but could specify actual motion in a three-dimensional environment and second, might not represent motion either directly or indirectly. As an example of the first type of transformation, consider motion in the third dimension. Proximally, this transformation is specified by a change in the projected size of an object. However, distally this transformation represents an approach or recession of an object. Such approaches and recessions follow physical laws of motion identical to those that operate in translations and rotations in the picture plane. Thus, one might expect momentum effects in this type of situation if the visual system responds to the size changes as indicating motion in depth. As an example of a transformation that is neither directly or indirectly related to motion, consider changes in the pitch of a tone. Such changes typically do not specify changes in the position of a sounding object, and so might not be expected to induce momentum. However, if momentum is only abstractly related to physical motion, momentum effects might still be caused by such auditory changes since they represent a continuous, predictable change. The following studies explore these possibilities.

In each experiment, the participants were presented with a series of three stimuli selected from a continuous physical dimension, such as size. The three stimuli formed a progression along the relevant continuum, e.g., increasing or decreasing in size. A fourth stimulus was then presented which was identical to the third, or differed from it by being slightly further along in the same direction of change implied by the previous three stimuli or else slightly backward along the same dimension of change. The subjects' task was to decide whether the fourth stimulus was identical to or different from the third. As in the studies reported in Part 1, each stimulus in a series was presented for 250 ms, with the interstimulus interval (ISI) varying from 100 to 900 ms in 100-ms steps. In each experiment, the first three stimuli were identical across trials. The fourth stimulus was selected from a set of nine patterns. One of the patterns was identical to the third, four were slightly further along in the direction of change implied by the initial series, and four were slightly backward. The eight "different" test patterns varied in the extent to which they deviated from the third pattern.

Each experiment consisted of two conditions that differed in the direction of change implied by the first three patterns. If we let numbers represent sampled locations on a continuous dimension, then in one condition subjects would be presented with "10," "20," "30," whereas in the second condition subjects would receive "50," "40," "30," a direction of change opposite to that of the former condition. Note that the final stimulus is identical in both conditions. In addition, the set of nine test patterns are the same in both conditions. One pattern, "30," is identical to the third stimulus, whereas two sets, {31, 32, 33, 34} and {26, 27, 28, 29}, contain patterns that differ from the third. However, in the first condition described above, subjects are predicted to commit more errors and to respond more slowly when correct for the items in {31, 32, 33, 34}. On the other hand, in the second condition subjects should be more likely to confuse the third pattern in the series with the items in {26, 27, 28, 29}, since these are further along the implied direction of change. The use of these two conditions eliminates the possibility that results in the predicted direction can be attributed to the inherent confusability of certain items with the third in the series.

Experiment 5: Changes in Size

In Experiment 5, subjects viewed a series of three squares that varied in size. In one condition, each square was larger than the previous one, whereas in a second condition the squares became successively smaller. We will call these the "grow" and "shrink" conditions, respectively. The grow condition represents a two-dimensional projection of a square approaching an observer along the line of sight, whereas the shrink condition represents a projection of a square receding along the line of sight.

After observing a series of squares in either the grow or shrink condition, subjects were presented with a fourth square that was to be judged the same or different in size as the third. If representational momentum operates with this type of transformation, the remembered size of the third object in a series should be distorted in the direction implied by the series. In the grow condition, the square should be remembered as larger than it actually was, whereas in the shrink condition, the square should be remembered as smaller. As a result, subjects in the grow condition should be more likely to commit false positives when the fourth square is slightly larger than the third. In contrast, subjects in the shrink condition

should commit more false positives when the fourth square is slightly smaller than the third. In addition, when subjects correctly identify the fourth square as different from the third, they should be more uncertain when the size of the former is consistent with the previous direction of change. Hence their reaction times should be slower in such situations.

Method

Subjects. Sixteen members of the Cornell community were paid for their participation. None took part in any of the experiments in Part 1. Eight took part in the grow condition and 8 took part in the shrink condition.

Apparatus and stimuli. The equipment used to generate and present stimuli was the same as that used in the studies reported in Part 1. The stimuli were squares of different sizes (see Fig. 6). These may be divided into "inducing" squares, which were shown on every trial, and "probe" squares, of which only one was shown on a given trial. The grow and shrink conditions each consisted of three inducing squares. In the grow condition, the sides of the squares were 0.5, 1.0, and 2.0 cm long. In the shrink condition, the sides were 8.0, 4.0, and 2.0 cm long. The squares were always presented in these orders, and the size of the third square was the same in the two conditions. There were nine probe squares, which were identical in the two conditions. One of the probes was the same size as the third inducing square. Four squares were slightly smaller than this inducing square. Their respective sides were 1.6, 1.7, 1.8, and 1.9 cm long. Four probe squares were slightly larger than the inducing square. Their respective sides were 2.4, 2.3, 2.2, and 2.1 cm long.

Procedure. The basic procedure was identical to that used in Experiments 1–4. However, in this study the subjects were instructed to compare the size of the fourth square with their remembered size of the third square, and to respond "same" if the sizes matched and to respond "different" if they did not by pressing the appropriate button.

Results

The results for both error rates and reaction times indicated distortions in representations for the size of the third inducing square in the direction predicted by representational momentum. Collapsing across the grow and shrink conditions, subjects committed more errors (62% versus 22%) when the size of the probe square continued along the progression established by the previous three squares than when it reversed that pattern ($t(15) = 6.68$, $p < .001$). Figure 6 shows the proportion of responses that classified the third and fourth squares as the same in size, as a function of the relative size of the probe square. The results were in the predicted direction for each pair of probe squares whose sides differed in length from the third square by the same absolute amount.[1] The results were not dependent on the grow or shrink condition alone. In the grow condition, more false positives were made when the probe square was larger than the third than when it was smaller ($t(7) = 3.75$, $p < .005$). In the shrink

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[1] Of course, the probe squares were not symmetrical in area around the standard square. However, the effects cannot be attributable to the inherent confusability of one set of probes with the standard square for the reasons discussed in the text.

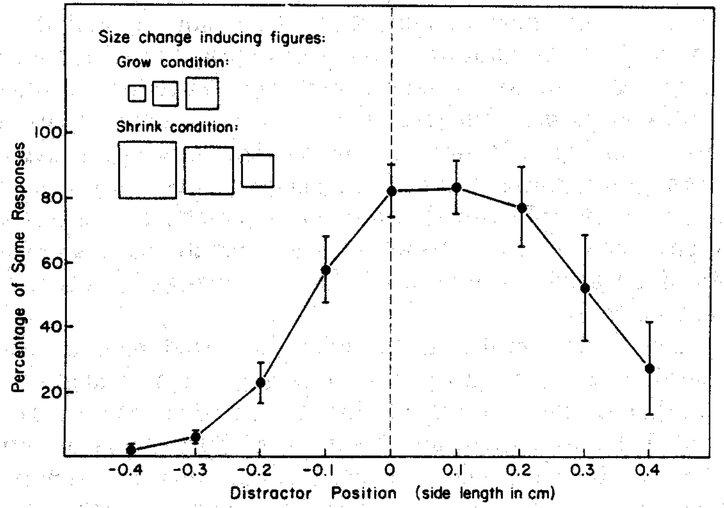

FIG. 6. Percentage of responses in Experiment 5 that judged the third and fourth squares to be the same in size, as a function of the actual size of the fourth square relative to the third. Schematic drawings of the inducing figures are shown in the upper left corner.

condition exactly the reverse occurred as more false positives were made when the fourth square was smaller than the third than when it was larger ($t(7) = 5.84, p < .001$).

As with the studies of Part 1, all reaction times greater than 2000 ms were removed in Studies 5–8 before analyzing these data. These deletions accounted for less than 1% of all responses. Overall, significantly more time was needed (a mean of 123 ms) to correctly reject a fourth square when its change in size was consistent with the preceding series ($t(15) = 3.83, p < .005$). These results were in the predicted direction for both the grow and shrink conditions, though significance was obtained only in the grow condition (grow: $t(7) = 3.77, p < .005$; shrink: $t(7) = 1.81, p > .10$).

Discussion

The results strongly indicate that successive displays of an object changing in size produce distortions in one's representation for the final display in the direction implied by the change. However, it is unclear whether the representational momentum effects observed in this study were due to changes in size per se or to perceived changes in the spatial location of an object of constant size. The displays did represent a perspective transformation of an object approaching toward or receding from the observer in depth. If the visual system at the level at which momentum occurs construed the display in this manner, then the results

can be interpreted straightforwardly as sensitivity to physical laws of motion. The laws of physical momentum do not change as one shifts from motion in the picture plane to motion in depth. Since human beings evolved to perceive motion in three-dimensional space, one would expect representational momentum effects to hold for optical situations that specify motion in depth. However, if the momentum was produced solely by transformations in size, a concrete analogy between physical and representational momentum would not apply. Since changes in size are not typically governed by laws of motion, representational momentum observed for size transformations would only be abstractly related to laws of physical momentum.

It is perhaps significant that all 16 subjects reported the impression of a single object either looming or retreating from them in depth. A wide variety of other species also react to increases or decreases in the size of a projected figure as though an object were approaching or retreating (Schiff, 1965). However, though at the level of conscious report or behavior such a display may be taken to imply changes in depth, one cannot infer that other levels of visual processing make the same assumption. In particular, perhaps momentum occurs prior to the point at which optical projections are related to distal properties of the world. In order to further evaluate the hypothesis that only perceived motion of an object leads to representational momentum effects, subjects in Experiment 6 were shown a series of figures indicating a change in shape that could not be readily attributed to a perspective transformation of an object moving in depth. Hence there is a greater possibility that the object would be perceived as undergoing a transformation that is not typically observed to have physical momentum.

Experiment 6: Changes in Shape I

The goal in Experiment 6 was to create an optical transformation that could not be readily attributed to perspective changes of an object moving in depth. In order to accomplish this goal, a series of rectangles was constructed in which each succeeding rectangle was more squarelike in appearance. This series could not have been produced by a polar projection of a quadrilateral changing its orientation to the observer, since the internal angles of the figures remained constant in all displays. A parallel projection of a rotating object or a polar projection from a very distant point could produce such transformations. However, doubts have been raised about the relevance of parallel projection for human perception (Cutting, 1986, Cutting & Millard, 1984). In addition, since the transformations were presented on a screen close to the viewers, they could not be taken as a rotating rigid object even if they were projected onto the screen from a great distance. Hence under a polar projection, the transformations could only be produced by a deformation of the rectangle itself. The viewers' introspections correspond with this analysis; the transformations were always perceived as a deforming object. Since deformations showing physical momentum are not likely to be observed, one would not expect representational distortions for the shapes of the figures if representational momentum is very concretely tied to laws of physical motion. If representational momentum is related to physical momentum more abstractly, however, momentum effects should be observed for deformations.

The procedure was identical to that in Experiment 5 except that the observers judged whether the fourth figure in the series was the same shape as the third. As in Experiment 5, the same probe figures were used in two conditions. This control rules out the possibility that any consistent effects found across conditions could be attributed to the inherent confusability of certain figures with the standard rather than to the progression of change within the series. In one condition (henceforth called "vertical"), the main axis of the first two rectangles in the series was oriented vertically. In the second condition ("horizontal"), the main axis was oriented horizontally. In both conditions, the longer side was progressively shortened and the shorter side lengthened so that the third figure was a square (see Fig. 7). The probe figures consisted of one square and eight rectangles oriented vertically or horizontally. If representational momentum is produced by the progressive deformations, then more false positives and longer correct reaction times should be obtained for horizontal probes in the vertical condition, and for vertical probes in the horizontal condition. These predictions follow from the fact that the next step in the series beyond the square should be a horizontally oriented rectangle in the vertical condition and a vertically oriented rectangle in the horizontal condition.

Method and Procedure

Sixteen members of the Cornell community were paid to participate. None of the subjects participated in prior studies. Eight took part in the vertical condition and eight took part in the horizontal condition. The equipment used to generate and present stimuli was the same as that used in previous studies.

As in Experiment 5, each condition included three "inducing" figures presented in a fixed order on each trial followed by one of nine randomly selected "probe" figures. In the vertical condition, the dimensions of the inducing figures (with the vertical side listed first) were 5.0 × 1.9 cm, 4.3 × 2.8 cm, and 3.5 × 3.5 cm. In the horizontal condition, the dimensions were 1.9 × 5.0 cm, 2.8 × 4.2 cm, and 3.5 × 3.5 cm. The last figure was a square of the same dimensions in both conditions. The probe figures consisted of four vertically oriented rectangles, four horizontally oriented rectangles, and one square. These probes were used in both conditions. The dimensions of the vertically oriented rectangles were 3.9 × 3.1 cm, 3.8 × 3.2 cm, 3.7 × 3.3 cm, and 3.6 × 3.4 cm. The dimensions of the horizontally oriented rectangles were 3.1 × 3.9 cm, 3.2 × 3.8 cm, 3.3 × 3.7 cm, and 3.4 × 3.6 cm. One probe square was 3.5 × 3.5 cm, the same as the final square in the two conditions. The procedure is identical to those used in previous experiments, except that the subjects were instructed to decide whether the fourth figure had the same shape as the third figure.

Results and Discussion

Figure 7 shows the proportion of responses that classified the third and fourth figures as being the same shape, as a function of each of the nine probe figures. Though the curve is skewed in the predicted direction, subjects did not commit significantly more false positives when the changes in the fourth figure continued in the direction established by the previous three ($t(15) = 1.71, p > .10$). Subjects also did not require a longer amount of time to correctly reject such figures as different from the third ($t(15) = -0.92, p > .30$).

Typical momentum effects do not seem to have been induced by continuous changes in shape. However, a number of problems with the study prevent one from concluding that representational momentum is restricted to transformations constrained by laws of motion. First, the final figure in the series was a square, which is a "stable" figure according to Gestalt laws. Perhaps the stability of such figures acts as a psychological "drag" on representational momentum. Second, since the final figure was always a square, perhaps the subjects never compared the fourth figure with a mental image of the third figure, but rather simply determined whether it also was a square. Thus, even if the mental image for

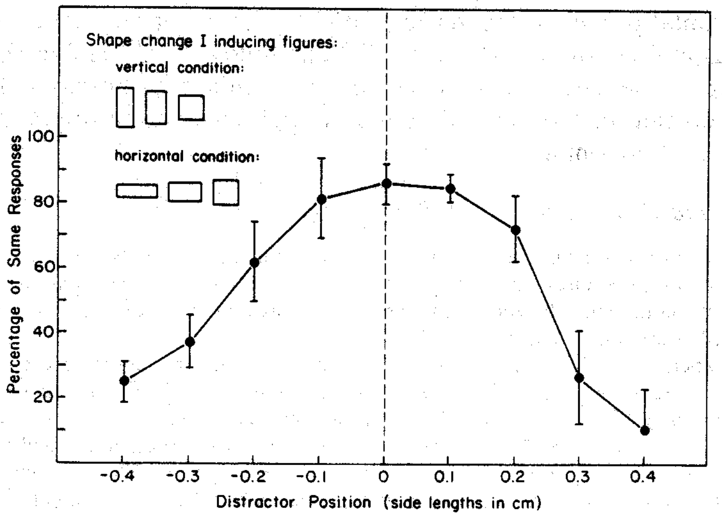

FIG. 7. Percentage of responses in Experiment 6 that judged the third and fourth figures to have the same shape, as a function of the actual dimensions of the fourth figure relative to the third. Schematic drawings of the inducing figures are shown in the upper left corner.

the third figure had been distorted by representational momentum, these effects would not have been detected, since the subjects did not use this information in their responses. Finally, for both the horizontal and the vertical conditions, the next step in the series would have resulted in a qualitative change in the stimuli. Previously vertical rectangles would have suddenly shifted to horizontal rectangles and vice versa. Perhaps such shifts are drastic enough to prevent representational momentum from occurring. Because of these problems, a second deformation study was performed to which the above criticisms do not apply.

Experiment 7: Changes in Shape II

In this experiment, subjects were presented with a series of vertically oriented rectangles that progressively became thinner or fatter, with length remaining unchanged. As in the previous two experiments, the third figures in each series were identical and the same probe figures were used. As in Experiment 6, the transformations could not correspond with a polar projection of a rectangle rotating in depth, but could only represent a shape change. Since all the figures were rectangles, a verbal encoding strategy would not be effective in comparing the shapes of the third and fourth figures. Rather, some reliance upon a mental image of the third figure seems required, and it is just this image that is believed to be distorted by representational momentum. If these shape changes do produce momentum effects, then in the "thin" condition, the third rectangle should be remembered to be thinner than it actually was whereas in the "fat" condition, the rectangle should be remembered as being wider than it actually was. Thus, subjects in the "thin" condition should commit more false positives and take longer to correctly reject fourth figures when they are thinner than the third figure. Subjects in the "fat" condition should show more confusion when the fourth figure is wider than the third.

Method

Sixteen members of Cornell University were paid for their participation. None of the subjects participated in the prior experiments. Eight took part in the "thin" condition and 8 took part in the "fat" condition. The apparatus was the same as that used in the previous studies.

Each condition included three "inducing" rectangles presented in a fixed order on each trial followed by one of nine randomly selected "probe" rectangles. In the thin condition, the inducing rectangles implied a gradual shortening of the rectangle's width, whereas in the fat condition, the inducing series implied a gradual lengthening of the width. In the thin condition, the dimensions of the inducing rectangles were 3.0, 2.4, and 1.8 cm. In the fat condition, the dimensions were 0.6, 1.2, and 1.8 cm. Once again, the last inducing figure in each condition was identical. The probe figures consisted of four rectangles that were thinner than the third inducing rectangle, four that were fatter than the third inducing rectangle, and one that was the same size as the third rectangle. The dimensions of the thinner probes were 1.4, 1.5, 1.6, and 1.7 cm. The dimensions of the fatter probes were 2.2, 2.1, 2.0, and 1.9 cm. The procedure was the same as in Experiment 7, with the subjects asked to decide whether the fourth figure was the same shape as the third.

Results and Discussion

Figure 8 presents the proportion of responses that considered the third and fourth figures to be identical in shape, and subjects committed significantly more false positives (48–34%) when the shape of the fourth figure followed in the same direction as that implied by the previous series than when it reversed that direction ($t(15) = 2.95$, $p < .01$). The results were in the predicted directions for both the "thin" and "fat" conditions, though they were not significant when considered separately. Reaction time data revealed no significant differences between forward (mean RT: 606 ms) and backward (mean RT; 598 ms) probes in categorizing the fourth figures as different from the third ($t(15) = 0.41$, $p > .60$), though the results are in the direction predicted by representational momentum.

The results for Experiment 7 thus indicate that distortions in one's representation for the shape of an object can be induced by a previous series implying a deformation in a consistent direction of change. This suggests that representational momentum may be abstractly related to actual physical momentum rather than tied only to situations in which physical momentum can commonly be observed. However, perhaps representational momentum effects are more robust in the latter case. For example, size changes that specified an object moving in depth produced mo-

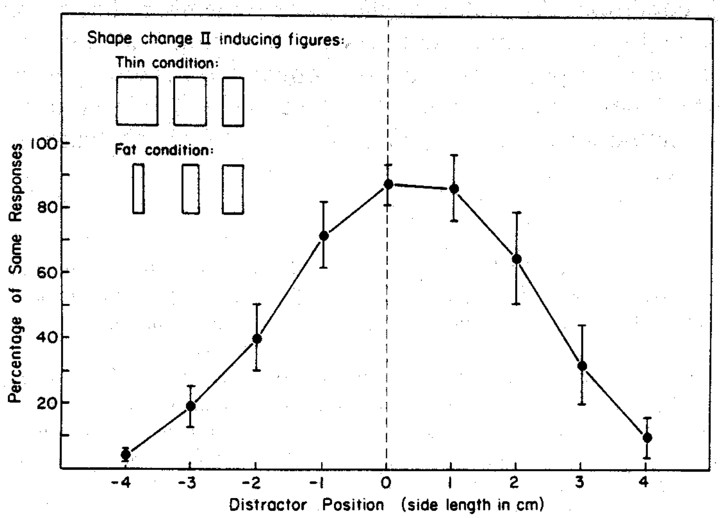

FIG. 8. Percentage of responses in Experiment 7 that judged the third and fourth figures to have the same shape, as a function of the actual width of the fourth figure relative to the third. Schematic drawings of the inducing figures are shown in the upper left corner.

mentum effects almost three times as strong as the effect observed for shape changes, as measured by error rates. In addition, the magnitude of the reaction time effect in the size study was almost 16 times larger than the effect obtained in this experiment. These differences cannot be attributed to the great difficulty subjects experienced with the deformation study, as the overall false positive rate was 42% in the size study and 43% in the shape study with the mean reaction times in the two experiments being 569 and 602 ms, respectively. Neither of these differences are significant (for error rates, $F(1,30) = 0.11$, $p > .70$; for reaction times, $F(1,30) = 0.27$, $p > .60$). Thus, although representational momentum may be induced by transformations abstractly related to physical momentum, it could be more strongly affected by transformations tied directly to physical momentum.

Experiment 8: Auditory Momentum

The results of Experiment 7 do not unambiguously demonstrate that representational momentum can occur in the absence of transformations that imply actual motion. Though the figures presented in Experiment 7 could not have been produced by a polar projection of a rotating object, they could have been generated by a parallel projection of a rotating object. Despite claims that polar projections are more relevant for human perception than parallel projections, it is still the case that the two projections are equivalent when objects are projected from sufficient distances. Although the projection screen was quite close to the subjects, at some level of visual processing the objects could have been perceived as rotating, especially given the strong bias in visual perception to maintain object rigidity (Shepard, 1984). In addition, perhaps subjects relied on local movement cues to perform tasks. Thus, as the widths of the rectangles decreased or increased, the lengths of the rectangles actually did shift spatial position. Perhaps momentum effects were induced by these local motions.

Because of these ambiguities, the final experiment asked whether representational momentum would occur with a transformation that almost surely does not correspond with actual motion, namely changes in the pitches of tones. The use of pitch is doubly interesting since it not only examines representational momentum within a physical continuum that does not typically specify motion, but also explores whether momentum is strictly a visual phenomenon.

As in the previous studies, two conditions were used in Experiment 8. One set of three tones implied a movement up the pitch scale (henceforth, the "rising" condition), whereas a second set implied a movement down the pitch scale (the "falling" condition). The final tones in each series were identical across the two conditions. The same set of probe tones were used in both conditions. Half of the probe tones were lower in pitch than the third and half were higher. If the series of pitch changes does distort one's representation for the final pitch in a manner consistent with representational momentum, then in the rising condition the probe tones slightly higher in pitch should be more confused with the standard. The reverse should take place in the falling condition: The probe tones lower in pitch should be confused with the standard.

Method

Subjects. Sixteen members of the Cornell community were paid to participate. None of the subjects participated in the prior experiments. Eight were included in the rising condition and 8 in the falling condition. Individuals with musical training were excluded because, in pilot investigations, not one of these subjects ever made an error.[2] In general, low error rates were found in this experiment because of technical limitations on the generation of stimuli (see below).

Apparatus and stimuli. The Hewlett–Packard 9133A computer used in the previous studies produced the tones and controlled the experiment. Three "inducing" tones were used in each condition. In the rising condition, the frequencies of these tones were 1220.70, 1871.74, and 2522.78 Hz. In the falling condition, the frequencies were 3824.86, 3173.82, and 2522.78 Hz. The same nine probe tones were used in the two conditions. Four of these were higher in frequency than the third standard tone (2848.30, 2766.92, 2685.54, and 2604.16 Hz), four were lower (2197.26, 2278.64, 2360.02, and 2441.40 Hz), and one was the same frequency as the third (2522.78 Hz). It would have been desirable to use finer gradations in frequency between the third tone and the probes, but the computer was limited to 81.38-Hz intervals.

Procedure. The procedure was identical to that of previous studies except that the subjects were instructed to compare the pitch of the third tone with that of the fourth. Subjects sat approximately 120 cm from the source of the tones.

Results and Discussion

Typical momentum effects were obtained for both error rates and reaction times. Figure 9 shows the percentage of responses that categorized the fourth stimulus as identical to the third as a function of each probe tone. A marked skewness in favor of more "same" responses can be observed in the area of the graph that represents forward probe tones. More false positives (15% to 5%) were obtained when the probe tone continued in the same direction as that established by the previous three than when it reversed direction ($t(15) = 3.34$, $p < .005$). These momentum effects were significant in both conditions. In the rising condition, subjects committed more false positives when the probe tone was

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[2] We believe that the lack of an effect for musically trained subjects is due to the resolution of the equipment rather than a qualitative difference in perceptual processes between these individuals and those without musical experience. The intervals between the tones were simply not confusing enough for listeners trained to perceive pitches without distortion. Of course, this is only a speculation, and future studies specifically comparing individuals with and without musical training could be interesting.

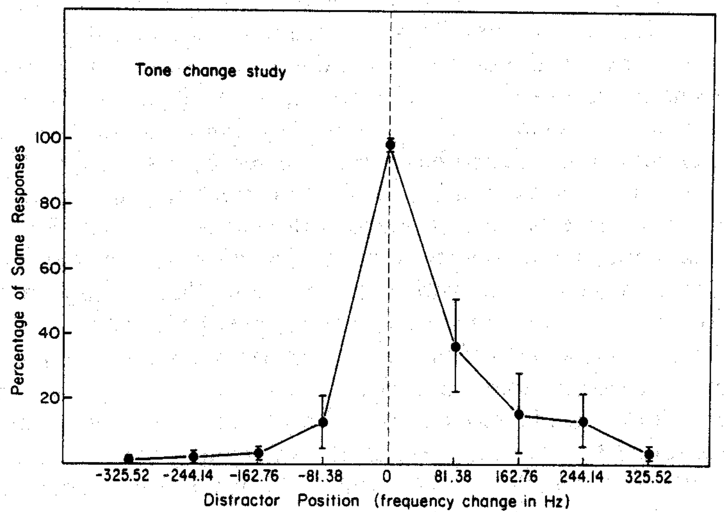

FIG. 9. Percentage of responses in Experiment 8 that judged the third and fourth tones to be the same in pitch, as a function of the actual frequency of the fourth tone relative to the third.

higher in pitch than the third ($t(7) = 2.41, p < .05$), whereas in the falling condition, subjects committed more false positives when the probe tone was lower than the third ($t(7) = 3.21, p < .025$).

Overall, more time was needed (a mean of 63 ms) to correctly reject probe tones when they were consistent with the previously established direction of change than when they were inconsistent ($t(15) = 4.71, p < .001$). Once again, these results were not restricted to a particular condition. In the rising condition, listeners took significantly longer to correctly reject probe tones that were higher in pitch than the third ($t(7) = 2.42, p < .05$), whereas listeners in the falling condition took longer to correctly reject probe tones that were lower than the third ($t(7) = 4.69, p < .001$).

The results are consistent with the hypothesis that representational momentum can be induced by changes along a continuum that is not directly related to motion or motion perception. In addition, representational momentum does not appear to be restricted to the visual modality.

Discussion of Part 2

Experiments 5 and 7 indicate that changes in size and shape can elicit representational distortions similar to those found for rotations and translations of objects in the picture plane. These findings raise the possibility that although representational momentum effects may reflect the internalization of laws of physical motion, they reflect those laws abstractly in that the effects are not tied only to transformations that follow laws of physical momentum. This interpretation is ambiguous, however, since the displays in Experiments 5 and 7 do correspond to certain projective transformations of an object moving in depth. If the visual system responded to these displays as specifying motion in depth, then the momentum effects could indeed have been caused by a sensitivity to transformations that are governed by physical momentum. However, the fact that momentum effects were obtained with changes in pitch (Experiment 8) seriously brings into question the proposition that representational momentum can only occur with transformations that specify changes in spatial location, or with transformations visually perceived.

An initial response to the findings of Experiment 8 could be to propose that representational momentum is restricted to changes along physical dimensions that specify movement of an object, and hence that movement of a sounding object is correlated with changes in pitch. Due to the Doppler effect, the pitch of a train whistle varies in predictable ways depending on the direction that the train is moving relative to a listener. In addition, other associations between changes in pitch and motion could be learned. For instance, moving one's hand in a particular direction on a piano keyboard is correlated with certain changes in pitch. Thus one might expect representational momentum effects with pitch changes. There are at least two problems with this explanation, however. First, the most obvious sources of the doppler effect are moving planes, trains, and cars: very recent artifacts that move at rapid speeds. One does not notice Doppler effects for most other situations, such as approaching a talking person, and so it is doubtful that we have internalized the relation between pitch and motion through perception of the Doppler effect. If the learning of more specific associations between pitch and motion underlies auditory momentum, one might expect people who have had extensive exposure to these associations to exhibit the effects more strikingly. Although we do not have detailed knowledge of the backgrounds of our subjects, we do know from pilot studies that, with the particular tones presented, musically trained individuals did not exhibit auditory momentum. Yet, based on their knowledge of how various hand movements on an instrument lead to consistent pitch changes, these subjects would have been expected by a learning view to show auditory momentum. As with many innate versus learning issues, a more definitive solution to this conflict could be provided through developmental studies. A second problem with explaining auditory momentum through knowledge of a pitch-motion correlation is that interpreting changes in pitch as specifying spatial location can often be mistaken. Pitch often varies without a concomitant change in spatial location. Everyday, human beings hear a variety of spatially stationary events, such as speech, that traverse fairly wide ranges of the pitch continuum. This lack of a coupling between changes in pitch and changes in spatial location contrasts with the high correlation between changes in the projected size of an object and changes in spatial position. Although strongly correlated relations such as that between size and distance might have been internalized either through evolution or learning, one would not expect the same to hold for relatively ambiguous relations, such as that between pitch and distance.

These problems with a pitch-motion connection imply that representational momentum is not tied to transformations that specify actual motion, and so is related to physical momentum only abstractly. Indeed, perhaps the distortions attributed to representational "momentum" are so general that they are not at all related to knowledge of physical momentum incorporated within perceptual systems. Instead the distortions may reflect the operation of such traditional Gestalt properties as "good continuation" in the perception of events. If this explanation is correct, then the "best" position for the fourth stimulus in a series should be the next logical step in the sequence, rather than a position only slightly beyond the third. However, this "best of all possible series" does not produce momentum effects (Freyd & Finke, 1984). Even if "good continuation" plays a role in the phenomenon, it seems to be only a redescription of the effect without identifying an underlying cause. In addition, the "good continuation" account cannot provide any explanation for the specific quantitative aspects of the phenomenon, such as the fact that the representational distortions increase with the implied velocity of the display. Such effects, however, are predicted by a model of the phenomenon based on physical momentum.

At present, we favor the view that representational momentum originated as an internalization within the visual system of the principle of physical momentum which then, over the course of evolution, became extended into other areas as well, such as audition. The view is that evolution may proceed by developing task-specific systems and procedures. However, some of these procedures may have the potential to be useful in a wide variety of domains, and so task-specific systems either gain increasing access to these general purpose procedures, or else they are "copied" from the system in which they were first developed (Fodor, 1972; Rozin, 1976; Shepard, 1981). Our motivation for tentatively accepting such a model is empirically driven. As was discussed in the introduction, many of the quantitative aspects of the momentum effect correspond quite closely with expectations based on physical momentum (see Finke et al., 1986; Freyd & Finke, 1985; Freyd & Johnson, 1987). In addition, a number of theorists have speculated that the pitch continuum is a type of abstract mental "space" (Shepard & Cooper, 1982) or spatial

medium (Attneave & Olson, 1971; see also Kubovy, 1981, who suggests that the functional correlate of visual space in audition is pitch) through which tones or tonal patterns move. If this analogy is correct, one would expect processes related to visuospatial perception to reappear in audition. The analogs between visual apparent motion of objects and apparent motion of tones through the pitch "space" (Shepard & Cooper, 1982) suggest that mental transformations may occur in a spatial format.

Finally, a model of represental momentum based on physical momentum provides a richer heuristic than a good continuation explanation for further exploring the effect and the above speculations on its origin. For example, if perceptual procedures developed in one modality are copied into another, one would expect such copying to be conservative given the general conservativeness of evolutionary change (Mayr, 1963). Hence, certain aspects of the original procedure might reappear in the copying modality even though it is not needed there. Thus, one of the uses of representational momentum could be the extrapolation from a given transformation to the future course of the change, hence the motivation to copy this procedure from vision into audition. However, changes in pitch do not specify movement of an object, and so should not produce "velocity" effects. If the copying of representational momentum into audition was conservative such effects might yet appear in this modality. Future investigations of the auditory momentum effect described in this paper can therefore examine its quantitative characteristics to determine if it acts in the same manner as momentum observed for visual displays. In addition, a model based on physical momentum entails that representational momentum be sensitive to other parameters than those discussed above, such as the mass of the moving object. Extensive investigations of such parameters will not only subject the physical momentum model to a serious test, but will also provide rich information regarding the perception and memory of events in general.

CONCLUSIONS

Figures that have undergone an implied rotation are remembered as being slightly beyond their final position. This phenomenon has been termed "representational momentum" because of the possibility that it reflects the internalization in perceptual systems of the principles of physical momentum. In this paper, we have explored the questions of what gets transformed in representational momentum and what types of transformations induce such distortions. The experiments in Part 1 indicated that the transformation acts upon the representation of a particular object rather than an abstract spatial position. The experiments in Part 2 revealed that transformations not related to actual physical momentum can produce representational momentum. This finding suggests that representational momentum is not tied to transformations that specify spatial motion, but is more abstractly related to physical momentum.

Because the implications of these findings have been discussed in previous sections, we would like here to consider some potential consequences of representational momentum for the analog/propositional debate in current cognitive psychology (Anderson, 1978; Kosslyn, 1981; Pylyshyn, 1981). Representational momentum has been construed as distorting a mental image of an object along some physical dimension, such as orientation or size. Many similarities between aspects of representational momentum and visual imagery support a connection between the two phenomena. For example, representational distortions for the final position of a rotating object develop gradually across the retention interval between the final inducing figure and the probe figure (Freyd & Johnson, 1987). The shift appears to be a linear function of the retention interval, with longer retention intervals producing greater distortions. Freyd and Johnson (1987) suggest that this phenomenon is analogous to the finding that, in mentally rotating a figure, orientations between the initial and final points of the rotation are represented.

This aspect of mental rotation has perhaps been the major justification for considering imagery to be an analog process. However, Pylyshyn (1981) has argued that mental rotation (and, by implication, imagery in general) can only be considered an analog process if it is constrained by its intrinsic nature to represent intervening positions along a path of rotation. If, however, this aspect of mental rotation can be affected, perhaps even erased, by one's beliefs or task expectations, then it cannot be intrinsically an analog process. Rather, it would be best to couch such imagery phenomena in the same sorts of mentalistic language in which we represent beliefs and inferences based on beliefs: an abstract symbol system.

There can be no doubt that much of imagery is "cognitively penetratable." Indeed, the utility of imagery largely depends upon its access to our beliefs. However, certain aspects of imagery might be largely isolated from belief systems, and so could be considered analog processes. Indeed, by Pylyshyn's own criteria, representational momentum would appear to be an analog process. Representational distortions attributed to momentum seem to be impervious to practice, error feedback, or both (Finke & Freyd, 1985). In addition, it is doubtful that the phenomenon can be explained by task demands of the type that Pylyshyn levels against imagery studies. The demand characteristic is that subjects in imagery experiments often believe they are to create a mental image that duplicates laws of motion found in the environment. The subjects in such tasks are instructed to transform a mental image, and perhaps take this to mean a "natural" transformation. As a result, imagery processes appear

to mirror physical processes, but not because of any intrinsic coupling between the two. However, in momentum experiments, the subject's task is to resist transformations of the mental image. In particular, this would require a decoupling of imagery processes with physical processes. Yet subjects simply are unable to implement this decoupling. That is, representational momentum appears to be mandatory and inaccessible to beliefs, desires, and expectations. Hence its analog characteristics should, according to Pylyshyn's own criteria, be considered a reflection of its intrinsic nature. In addition, representational momentum occurs very rapidly. Representational distortions are observed within 20 ms after the third figure is removed (Freyd & Johnson, 1987). It is hard to imagine that such rapid distortions are influenced by beliefs or expectations. The distortions appear to be more reflexive than thoughtful.

It is worth noting that these two characteristics of representational momentum—speed and mandatory processing—are also characteristics of what Fodor (1983) calls modular systems. If these aspects of momentum are indicative of its modularity, then it would not only be unsurprising but expected that momentum would be "informationally encapsulated," to use Fodor's terms. Modular systems, according to Fodor, are by their nature inaccessible to beliefs and desires. If momentun is indeed part of a modular system, and if its shared aspects with imagery phenomena reflect more than a spurious correlation, then at least one aspect of mental imagery would have been shown to be of an intrinsically analog nature.

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