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# Effects of motion on perceived pointing of ambiguous triangles

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Two experiments investigated the effects of the direction of straight-line motion on the perceived pointing of moving ambiguous (equilateral) triangles. Experiment 1 used a "preference" paradigm in which observers reported the direction in which they first saw a moving triangle point, and Experiment 2 used a performance-oriented "interference" paradigm based on a discrimination task. Results from both tasks showed systematic biases due to the relation between the direction of motion and the structure of the triangle: Motion along an axis of symmetry (parallel to a possible direction of pointing) facilitated perceived pointing along that axis. However, motion along a side of the triangle (perpendicular to a possible direction of pointing) produced no such facilitative effect, in contrast to analogous perpendicular effects in previous studies using static patterns (Palmer, 1980; Palmer & Bucher, 1981, 1982). These results are interpreted as evidence that event symmetry is an important stimulus characteristic underlying directional biases due to motion. Response compatibility was also found to affect performance on both tasks.

Equilateral triangles are perceptually ambiguous figures in that they can be seen to point in any one of three directions (see Figure 1A), but in only one of them at any given moment (Attneave, 1968). The direction in which such triangles are perceived to point can be systematically biased by contexts such as linear configurations composed of several equilateral triangles (Attneave, 1968; Palmer, 1980; Palmer & Bucher, 1981) and textural stripes inside a single triangle (Palmer & Bucher, 1982). When the orientation of the configural line or texture is aligned with one of the triangle's three axes of symmetry, observers tend to see the triangle point in a direction that coincides with that axis (see the "axis-alignment" conditions shown in Figures 1B and 1D). When the orientation is parallel to one of the triangle's three sides, observers tend to see it point perpendicularly to that side (see the "base-alignment" conditions shown in Figures 1C and 1E).

It has frequently been suggested that these contextual effects arise because of the influence of a *perceptual reference frame* that is sensitive to the directional properties of the biasing context (e.g., Attneave, 1968; Palmer, 1980, 1983). In the present paper, we explore the question of whether *movement* of an ambiguous triangle along a straight path also produces bias effects due to the directional properties of the motion. There are several reasons to think that this might occur and that it would be interesting if it did.

One well-known phenomenon in which movement is associated with a perceptual reference frame is "induced motion" (Duncker, 1929/1950). When a stationary dot is surrounded by a slowly moving rectangular frame—or is located in close proximity to any larger, slowly moving, figure—most observers see the moving figure as stationary and the stationary dot as moving in the direction opposite to the motion of the surrounding figure. The

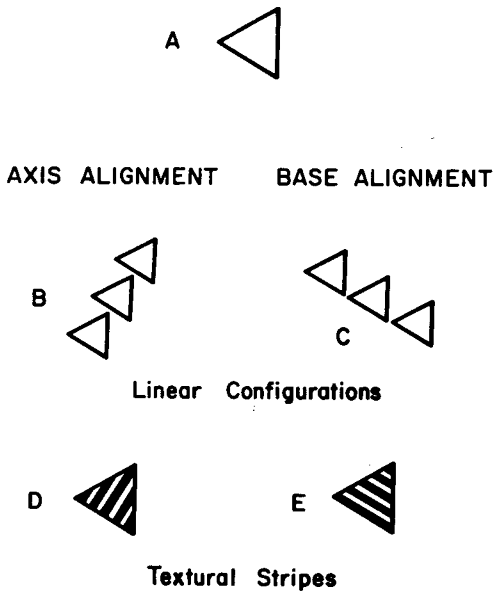


**Figure 1. Ambiguous triangles alone and with axis- and base-aligned biases due to linear configurations and textural stripes.**

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larger, surrounding, perceptually dominant figure seems to serve as a frame of reference relative to which the position of the dot is perceived. Johansson (1950) greatly extended this kind of phenomenon by showing that the direction in which several component dots are perceived to move is determined by a reference frame established by the "common motion" of the entire display. For instance, if two vertically separated dots move together in horizontal harmonic motion while a third dot moves in phase diagonally between them, the third dot is perceived to move vertically between the two outer dots while the whole unit moves horizontally. The common motion of all three dots defines the perceptual reference frame, and the motion of the third dot is seen within this frame as vertical rather than diagonal.

While these results suggest that reference frames are sometimes related to perceived motion, they do not show that motion affects the perceived properties of the moving figures. The present hypothesis suggests that the direction in which an ambiguous triangle moves will influence how people perceive it to point, a property readily perceived in unmoving triangles. Such effects of motion on the perceived orientation and/or shape of a figure have rarely been reported. The clearest case with which we are familiar is Tinbergen's (1951) demonstration that an ambiguous goose/hawk figure is seen as a long-necked goose when moving in one direction and as a short-necked hawk when moving in the other. This example, however, seems to rely heavily on prior knowledge of the shapes of different types of birds and the direction in which they invariably fly. Effects of motion in perceived pointing of equilateral triangles would be far less explicable in terms of prior knowledge and would suggest that some more primitive perceptual mechanisms might be at work.

Another motivation for studying the possible influence of motion on perceived pointing of ambiguous triangles is to test two alternative theories about why bias effects arise in the kinds of stimuli we have been studying. One hypothesis is that the critical feature is the elongation of linear configurations and textural stripes (Palmer, 1980; Palmer & Bucher, 1981, 1982; see, also, Humphreys, 1983, and Wiser, 1981). This "elongation hypothesis" accounts quite nicely for the axis-aligned effects. However, accounting for the equally large base-aligned effects requires an additional assumption: There must be a second biasing orientation perpendicular to the axis of elongation that biases the perception of the base-aligned triangles. This additional assumption, although plausible, seems somewhat ad hoc, especially because the bias perpendicular to the stimulus orientation would have to be just as strong as the one parallel to it. An alternative account of both axis- and base-aligned effects can be given in terms of the symmetry of linear configurations and textural stripes (Palmer & Bucher, 1982). If an axis of bilateral symmetry produces the bias, no additional perpendicular orientation is needed to explain the base-aligned effects, because a symmetry axis coincides with the perceived direction of pointing for both axis- and base-aligned patterns (see Figure 1). In the present experiments, we present a test between the elongation and symmetry hypotheses by extending them to events in space-time, where they predict different effects due to motion.

The position of a single equilateral triangle can be changed over time so that its direction of motion is either aligned with one of its symmetry axes (analogous to the static axis-aligned conditions studied previously) or aligned with one of its sides (analogous to the static base-aligned conditions). The symmetry hypothesis predicts that only axis-aligned motions will produce biases, whereas the elongation hypothesis predicts that both axis- and base-aligned biases will exist. To see why, consider Figure 2, which depicts the space-time structure of a moving equilateral triangle by vectors representing the direction and velocity of motion at representative points. If the motion is a pure translation and if its direction is aligned with one of the triangle's axes of symmetry, then global symmetry along that axis is preserved in the space-time event, because the motion vectors are symmetric about an axis of the triangle (see top of Figure 2). However, if the direction of motion is aligned with one of the triangle's sides, the resulting event is not symmetric in space-time, because the motion vectors are asymmetric about any axis of the triangle (see bottom of Figure 2). Thus, there is global event symmetry in axis-aligned motion, but not in base-aligned motion. If symmetry is the critical feature that establishes contextual bias in the processing of moving figures, axis-aligned motions should produce bias effects toward seeing the triangle point along its symmetry axis, whereas base-aligned motions should not. This is a bold prediction, because we have *always* found both axis- and base-aligned effects to be present—and equal in magnitude—in all of our previous experiments. The elongation hypothesis, however, predicts no

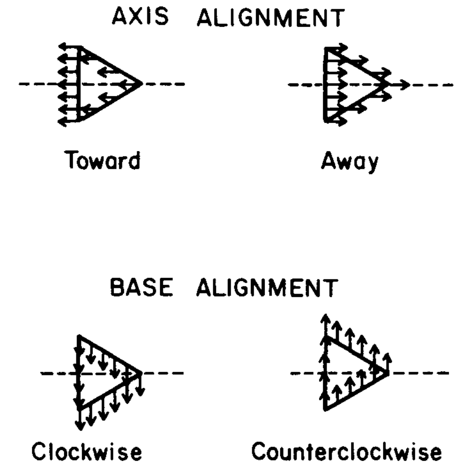


**Figure 2. Moving ambiguous triangles in which motion is depicted by the vector displacement of representative points. Notice that one of the triangle's axes of symmetry is preserved by the axis-aligned motions, whereas none of them are preserved by the base-aligned motions.**

such differences, because both types of motion are equally "elongated" in their space-time structures.

The effects of motion in biasing perceived pointing of ambiguous triangles were explored in the first experiment, using a free-choice task (see Palmer, 1980). Subjects were asked to indicate the direction in which they first saw each triangle point while it moved in each of 12 directions. We hoped to find out which ones, if any, induced systematic biases in perceived pointing. The second experiment employed a more rigorous, performance-oriented "interference" paradigm (Palmer & Bucher, 1981, 1982) to provide converging evidence about the same issues.

## EXPERIMENT 1
## Motion Effects on Perceived Pointing

In this experiment, subjects were asked to indicate the direction in which they first saw a moving triangle point. Four kinds of potential motion bias were studied: two axis-aligned motions and two base-aligned motions (see Figure 3). These are defined by the relation between the direction of motion and the nominally biased direction of pointing. In the "axis-toward" condition the triangle moved along one of the triangle's three axes of symmetry directly toward the nominally biased direction of pointing. In the "axis-away" condition it moved along an axis of symmetry directly away from the biased direction. In the "base clockwise" condition, the triangle moved parallel to one of the triangles's three sides in a direction 90° clockwise from the nominally biased direction of pointing, and in the "base-counterclockwise" condition it moved parallel to a side in a direction 90° counterclockwise from the biased direction. If the symmetry hypothesis is correct, the triangles in both axis-aligned conditions should tend to be seen pointing along the axis of symmetry aligned with the direction of motion, but no corresponding bias should be present in the two base-aligned conditions when the triangle moves along one of its sides. If the elongation hypothesis is correct, however, both sorts of motion effects should be present and be equally strong.

### Method

**Subjects.** Sixteen undergraduates at the University of California, Berkeley, were subjects in the experiment. They received partial course credit for their participation. All subjects had approximately normal or corrected-to-normal vision and were naive about the experimental hypotheses.

**Design.** The experiment consisted of the orthogonal combination of four factors: biased direction of pointing (−180°, −150°, ..., −30°, 0°, 30°, ..., 150° clockwise from upward), relative direction of motion (axis toward, axis away, base clockwise, and base counterclockwise), replications (two blocks), and subjects (1-16). A stationary control condition was included for each of the four orientations of triangles and combined orthogonally with the factors of replications and subjects.

**Stimuli.** The stimulus set was defined by the first two factors, as shown in Figure 3. The triangles were generated and displayed on a Hewlett Packard 1345A graphics system controlled by a PDP-11/10 computer. Each triangle subtended about 0.5° of visual angle at the 1.2-m viewing distance. The maximum excursion of the motion subtended about 2.1° of visual angle over an interval of 1 sec. The motion consisted of a single unidirectional sweep of the triangle, starting at the fixation point and ending 2.1° radially outward. Successive frames of the triangle in motion were displayed at 10-msec intervals, producing the perception of smooth, continuous motion. Due to the relatively slow decay of the P31 phosphor, there was a slightly luminous trail behind the moving lines. Room illumination was kept high enough for the luminous trail to be scarcely perceptible under these viewing conditions. The CRT screen was surrounded and partly covered by a large black sheet of cardboard with a circular hole cut in it—roughly 5° in diameter—through which the figures were visible, but the sides of the CRT were not.

**Procedure.** A subject was told that he or she was to indicate the direction in which he or she first saw the triangle point on each

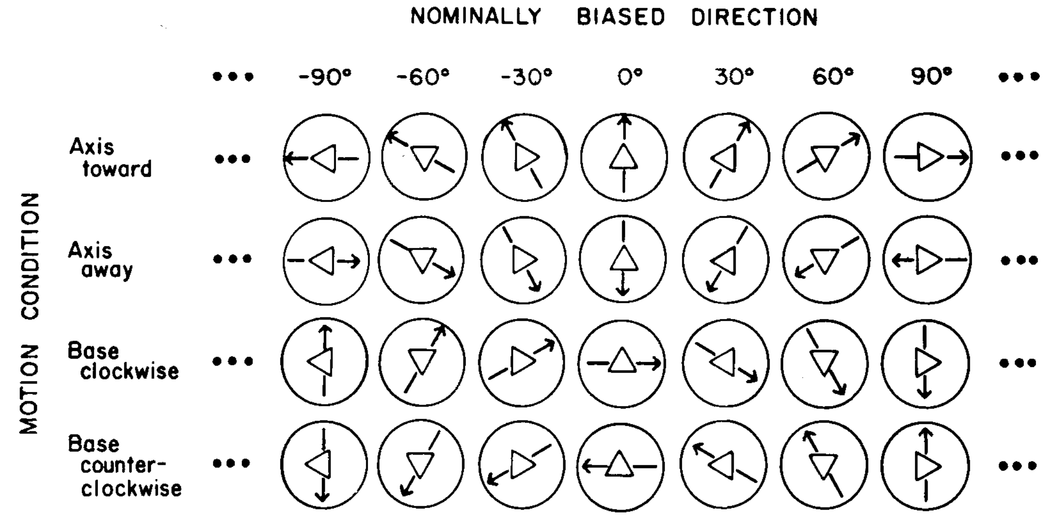


**Figure 3.** The stimulus set for Experiment 1. Ambiguous triangles were nominally biased in each of 12 directions for each of four conditions of motion relative to a possible direction of pointing: along an axis and toward it, along an axis and away from it, along a base and clockwise from it, and along a base and counterclockwise from it.

trial. The 12 possible directions of pointing corresponded to 30° divisions of a circle, and were marked by lines on a joystick response box. The sequence of events for each trial was as follows: first, a 500-msec fixation point was presented in the center of the screen to serve as a "ready" signal. The triangle was presented 500 msec after the fixation point disappeared and, whether moving or stationary, remained on the screen for 1 sec. If the triangle was moving, it appeared at fixation and swept once across the screen in one of the 12 directions; if it was stationary, it appeared unmoving at fixation for the 1-sec presentation time. The subject moved the joystick in the direction corresponding to his or her first impression of the triangle's direction of pointing. After he or she responded, a small radial line appeared on the screen for 1 sec to indicate the recorded direction of the response. Two seconds later, the next trial began.

The instructions to subjects emphasized that they were to respond to the direction in which the triangle appeared to *point*, not that in which it appeared to *move*. The subjects were then shown a series of example trials with the experimenter present so that any questions about the procedure could be answered before the actual experimental trials began. After these example trials, there were 20 practice trials followed by two blocks of experimental trials. The experimental blocks were separated by a short break. Three more practice trials followed the break to prevent transient start-up effects from affecting the data. All subjects were tested individually in a single session lasting about 25 min.

## Results and Discussion

On each trial, the subject's directional response was assigned to one of four response categories. Three categories corresponded to the three possible directions of pointing for that particular triangle and included responses with 45° on either side of each possible direction of pointing (see Figure 4, categories 1, 2, and 3). This wide margin of error was used to allow for imprecision in subjects' joystick responses. The fourth category included anomalous responses which fell between the other three response categories and were not in close proximity to any possible direction of pointing for that triangle (see Figure 4, category 4). Response probabilities were calculated for each of these four response categories averaged over trials.

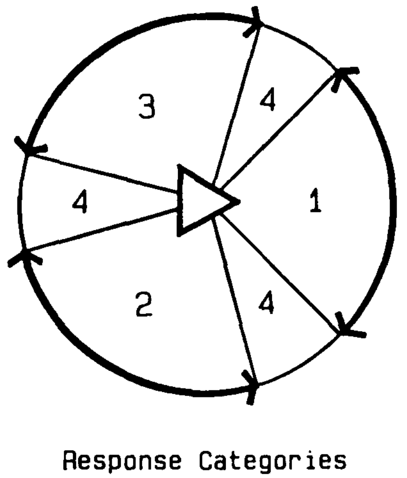


**Figure 4. The categorization scheme for responses in Experiment 1. Each response was classified as one of the three possible directions of pointing (1, 2, or 3) within a 45° tolerance of the precise direction, plus a fourth "anomalous" category (4) for responses that did not fall into any of the other three.**

Mean response probabilities are plotted in Figure 5 for both moving and stationary conditions as a function of the nominally biased direction of pointing.[1] (The "nominally biased directions" for some representative motion conditions are shown in Figure 3.) These data were analyzed by analysis of variance for the appropriate repeated measures design, excluding the stationary control conditions. The results showed main effects of direction of pointing [$F(11,165) = 15.19$, $p < .001$] and type of motion alignment [$F(3,45) = 18.01$, $p < .001$]. The interaction between the two did not quite reach significance [F(33,495 = 1.67, $p < .10$]. The base-clockwise and base-counterclockwise conditions have been averaged into the single "base-aligned" curve in Figure 5 because specific comparisons revealed no significant differences between them or significant interactions with the directional factor ($F < 1$ in both cases).

**Directional effects.** The main effect of direction of pointing is due to the higher probabilities associated with environmentally salient directions of directly up, down, left, and right (0°, 90°, 180°, and 270° clockwise from upright) relative to the oblique directions (30°, 60°, 120°, 150°, 210°, 240°, 300°, 330° clockwise) [$F(1,15) = 10.20$, $p < .01$]. Within this environmental frame, vertical directions (0° and 180°) were reported more often than horizontal directions (90° and 270°) [$F(1,15) = 12.75$, $p < .01$]. Upward and near-upward directions (330°, 0°, and 30°) were reported more often than the downward and near-downward ones (150°, 180°, and 210°) [$F(1,15) = 21.40$, $p < .001$], and the rightward and near-rightward directions (60°, 90°, and 120°) were reported more often than the leftward and near-leftward ones (240°, 270°, and 300°) [$F(1,15) = 6.71$, $p < .05$]. This pattern of results replicates the essential features of the directional effects we have found using stationary triangles in this type of paradigm (see Palmer, 1980, Experiment 1).

**Effects of motion.** The influence of the biases induced by motion in different directions is reflected in Figure 5 by the separation between the curves. Because a preliminary test indicated no difference between the base-clockwise and base-counterclockwise conditions ($F < 1$), they have been combined in all of the following analyses. Axis-toward motions produced significantly higher choice probabilities than did axis-away motions [$F(1,15) = 6.22$, $p < .025$], base-aligned motions [$F(1,15) = 26.75$, $p < .001$], or the stationary control condition [$F(1,15) = 33.85$, $p < .001$]. Axis-away motions also produced higher choice probabilities than either base-aligned motions [$F(1,15) = 10.30$, $p < .01$] or the stationary control conditions [$F(1,15) = 10.59$, $p < .01$]. Base-aligned motions produced slightly lower choice probabilities than the stationary control condition, but not significantly so [$F(1,15) = 2.88$, $p > .10$].

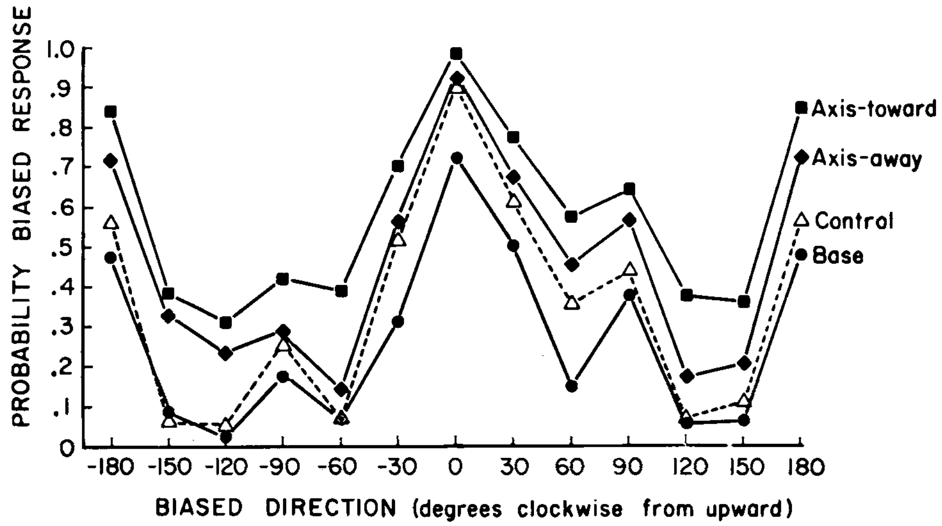


**Figure 5. Mean probabilities of responding for each of the nominally biased directions of pointing in each of the motion conditions plus the stationary control condition.**

These results show that motion can, indeed, bias the direction in which an ambiguous triangle is seen to point. In particular, axis-aligned motions *toward* a direction of pointing bias perceived pointing in that direction. The fact that axis-aligned motions moving directly *away* from the point resulted in a slightly smaller bias effect may have been due to interference between the direction of motion and the direction of the pointing response. Both were along the same axis, but oppositely directed, so that the two may have conflicted at some stage in perceptual and/or response processing. One might try to push this explanation further by suggesting that *all* of the bias effects are due to compatibility between direction of motion and direction of response. However, if this were the case, the axis-away condition should result in *lower* response probabilities than the base-aligned conditions, since the axis-away motion is directly opposite the direction of pointing. In fact, however, axis-away motions resulted in significantly *higher* choice probabilities than did base-aligned motions. Thus, the bias induced by motion is caused by more than just directional compatibility with motor responses.

The bias we have found due to axis-aligned motion is consistent with previous findings for stationary axis-aligned configurations (Palmer, 1980). What is not consistent, however, is the complete absence of *any* corresponding base-aligned bias: Motion parallel to one of a triangle's sides—that is, base-aligned motion—simply does not produce any bias toward seeing the triangle-point perpendicularly to the line of motion. In fact, base-aligned motion seems, if anything, to interfere with perception of the perpendicular direction relative to the unbiased stationary control, due to a slight bias toward seeing the triangle point in the direction closest to its direction of motion. This difference between axis- and base-aligned effects in moving versus unmoving stimuli is consistent with the current hypothesis that symmetry is a potent factor in the reference frame effects found here, and perhaps in previous research as well (e.g., Palmer, 1980; Palmer & Bucher, 1981, 1982). The difference between the axis-toward and axis-away conditions implies that some sort of perceptual or response compatibility factor is operating as well.

In summary, the results of this experiment indicate that the direction of motion in an event can induce a bias in the interpretation of a figure, and they are consistent with the hypothesis that it is event symmetry that produces this bias. It is not clear from this study, however, whether the biases induced by motion are produced by mandatory processing mechanisms. Rather, they could have resulted from optional perceptual processes which arise in a free-choice task not constrained by time or accuracy demands. It is even possible that they reflect some sort of "demand characteristic" felt by subjects when performing this task. The second experiment was designed to rule out such interpretations.

## EXPERIMENT 2
### Motion-Induced Biases in Directional Discrimination

The primary purpose of this experiment was to establish whether motion *necessarily* induces a bias in perceived pointing of an equilateral triangle. Subjects were required to respond as quickly as possible to just one of the three possible directions of pointing for each triangle, while motion was used to bias perception toward or away from that direction. If the motion effects found in the previous experiment were due to mandatory processing mechanisms that are automatically activated by movement, then bias effects should be present as soon as the triangle's orientation is perceived. This bias is measured as follows: On "consistent" trials, in which the direction of motion should bias perception *toward* the correct percept, responses should be fast and accurate because the motion should help the subject see the triangle point as required. On "inconsistent" trials, in which the direction of motion should bias perception *away* from the correct percept, responses should be slow and/or inaccurate because the motion should interfere with perceiving the triangle point as required.

In this experiment, triangles were presented in four orientations, and subjects were required to respond to each according to whether it could be seen as pointing directly up, right, down, or left (toward 12, 3, 6, or 9 o'clock, respectively). The 12 motions included can be described by two factors relevant to the task: the consistency of the motion bias (either consistent with the task or inconsistent with it) and the alignment between the direction of motion and the required direction of pointing (axis toward, axis away, base clockwise, or base counterclockwise directions). These conditions are illustrated in Figure 6 for the left-pointing triangle.

## Method

**Subjects.** Thirteen undergraduate students at the University of California, Berkeley, participated in the experiment for partial credit in an introductory psychology course. All subjects had approximately normal or corrected-to-normal vision.

**Design.** The experiment consisted of the orthogonal combination of five factors: response direction (up, down, left, and right); consistency condition (one consistent at 0° from the required direction of pointing, and two directions of inconsistent conditions at +120° and −120° from the required direction of pointing); type of bias (axis toward, axis away, base clockwise, and base counterclockwise directions); replications (Blocks 1–6); and subjects (1–13). A stationary control condition was also included in which each of the four triangles appeared at the fixation point without moving.

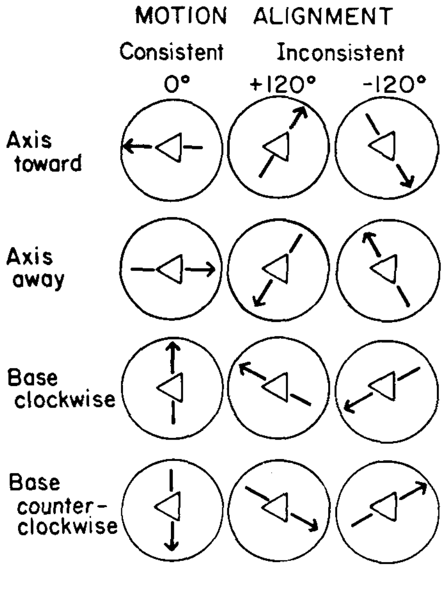


**Figure 6. Examples of the stimulus set in Experiment 2: the subset of motions for the left-pointing triangle.**

**Stimuli.** The stimulus set was defined by the first three factors, as shown in Figure 6 for the left-pointing triangle. The preparation and presentation of the stimuli was the same as in Experiment 1 except that the stimulus was turned off as soon as the subject responded. Since it took 1 sec for the triangle to reach the outer edge of the screen, where it stopped, subjects saw it stop only on trials in which their responses were more than 1 full second, and most responses were much faster than this. The control triangles appeared to be unmoving at the fixation point, as in Experiment 1.

**Procedure.** The subjects were told that they were to indicate for each triangle whether it pointed directly up, down, left, or right, while ignoring the other directions in which the triangles could be seen to point. They were instructed to respond as quickly as possible without making more than a few errors.

The sequence of events for each trial was as follows: first, a 500-msec fixation point was presented in the center of the screen. The triangle was presented 500 msec after this dot was removed and stayed on the screen until the subject responded. If the triangle was moving, it swept across the screen from the fixation point and, if the subject took more than 1 sec to respond, it stopped at the edge, 2.1° from the fixation point, and remained there until the subject responded. If the triangle was stationary, it remained in its central position until the subject responded. As soon as the subject moved the joystick through more than a criterial distance radially, the triangle disappeared and a small radial feedback line appeared for 1 sec near the edge of the screen at a position and orientation corresponding to the correct response. One second later, a new trial began.

There were six blocks of experimental trials, with a short break between the third and fourth blocks. The first block started with 20 practice trials so that the subject could learn and practice the procedure. There were three warm-up trials after the break to control for transient start-up effects. All subjects were tested individually in a single session lasting about 30 min.

## Results and Discussion

Mean reaction times (averaged across trials) are plotted in Figure 7 as a function of response direction for consistent and inconsistent motion at different alignments. An overall analysis of variance for repeated measures was performed on these data, excluding the stationary control condition. It showed significant main effects due to response direction [$F(3,36) = 12.25$, $p < .001$], consistency of motion [$F(2,24) = 10.91$, $p < .001$], and type of alignment [$F(3,36) = 2.99$, $p < .05$], plus an interaction between consistency and type of alignment [$F(6,72) = 13.85$, $p < .001$]. The base-clockwise and base-counterclockwise conditions have been combined in the graph because specific comparisons again showed no significant differences between them or interactions with response direction ($F < 1$ in both cases).

**Response direction.** The main effect of response direction can be seen in the large variations across the abscissa in Figure 7. Responses to the vertical directions were faster than to the horizontal directions [$F(1,12) = 25.39$, $p < .001$]. Within these categories, "up" RTs were no different from "down" RTs ($F < 1$), but "right" RTs were faster than "left" RTs [$F(1,12) = 9.10$, $p < .02$]. These results are broadly consistent with previous directional effects we have found in the interference paradigm (Palmer & Bucher, 1981, 1982).

**Consistency and alignment.** The most theoretically important effect in the data is the interaction between consistency conditions and the type of alignment. As is evident by comparing the two panels of Figure 7, this

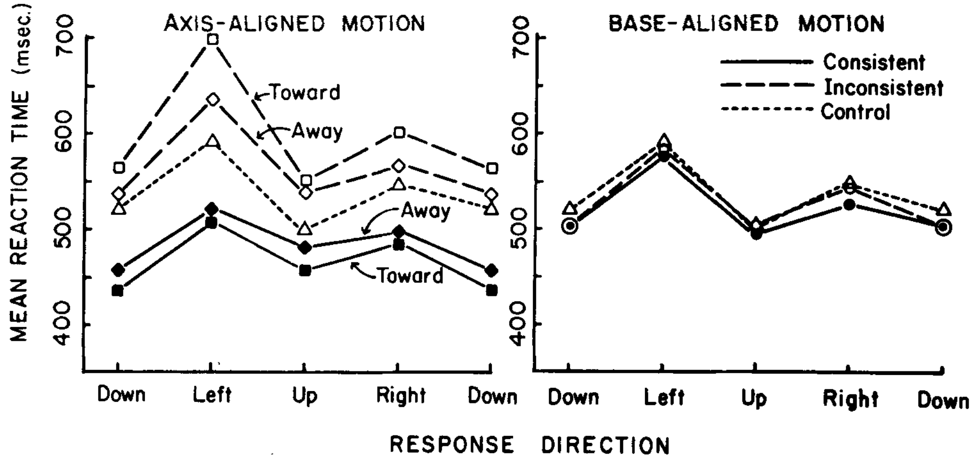


**Figure 7. Mean reaction times to discriminate direction of pointing for moving triangles in Experiment 2 plotted as a function of direction for consistent and inconsistent bias conditions. The left panel shows RTs for the two axis-aligned conditions (axis-toward and axis-away) and the right panel for both base-aligned conditions combined. The stationary control condition is shown in both panels for comparison.**

interaction is due almost entirely to the fact that there is a large and reliable difference between the consistent and inconsistent conditions in axis-aligned motion [$F(1,12) = 23.48$, $p < .001$], but virtually no difference between corresponding conditions in base-aligned motion ($F < 1$). Thus, the principle prediction of the symmetry hypothesis was strongly confirmed.

Consistent axis-aligned conditions were faster [$F(1,12) = 10.60$, $p < .01$] and inconsistent axis-aligned conditions were slower [$F(1,12) = 5.34$, $p < .05$] than stationary control conditions. The corresponding comparisons between the stationary and the base-aligned conditions revealed no reliable differences for either the consistent or inconsistent conditions ($F < 1$). Thus, axis-aligned motions produced both facilitation and interference effects relative to the stationary control condition, whereas the base-aligned conditions produced neither. The facilitation effect for the axis-aligned conditions is somewhat unusual in that we have found it only a few times before, and it has never been as pronounced as it is here. Its large size may partly be due to somewhat inflated RTs to the unmoving control; many subjects spontaneously reported that their expectation of seeing a moving triangle was so strong that the stationary stimulus "surprised" them or "threw [them] off." If there had been equally many trials of moving and stationary triangles to equalize subjective expectations, perhaps there might have been less facilitation and more interference, as measured relative to the stationary control.

Both the axis-toward and axis-away alignments produced reliable interference effects (i.e., differences between the consistent and inconsistent directions) [$F(1,12) = 24.36$ and $13.19$, respectively, $p < .01$]. However, the present results also show that there was significantly more interference in axis-toward conditions than in axis-away conditions [$F(1,12) = 6.74$, $p < .05$]. This finding is consistent with the results of Experiment 1.

It was suggested, in discussing the results of the previous experiment, that there might be a "compatibility" effect between the direction of motion and the direction of pointing or, in the case of the present experiment, the direction of response. That such an effect is indeed operating here can easily be seen by plotting the data as a function of the 12 directions of the triangle's motion relative to the direction of the required response (see lower graph in Figure 8), combined over all four response directions. The upper part of Figure 8 shows how this curve can be decomposed into the combination of two effects: (1) a "perceptual" component based on symmetry conditions, and (2) a response "compatibility" component. The perceptual component reflects whether the direction of motion facilitates (in consistent axis-aligned motions), interferes (in inconsistent axis-aligned motions), or is neutral (all base-aligned motions) with respect to perceiving the triangle as pointing in the direction required by the task. This component is responsible for the overall quadrimodal shape of the RT data with local minima at 0° and 180° and local maxima at 60°, 120°, 240°, and 300°. Note that these are not random fluctuations in the results, but systematic effects at precisely the orientations predicted by the symmetry hypothesis.

The response compatibility component reflects how similar the direction of motion is to the required response direction. It is responsible for the slight additional upward tilt from 0° to 180° and corresponding downward tilt from 180° to 360°. There are three simple comparisons that show the compatibility factor at work in conditions that are "symmetry-wise" identical. The first is the fact that RTs at 0° are significantly faster than at 180° (this is the previously described difference between axis-toward and axis-away motions, respectively). The second effect is that the base-aligned conditions, which produced no measurable facilitation or interference, lie on a broad curve that increases monotonically with angular difference between

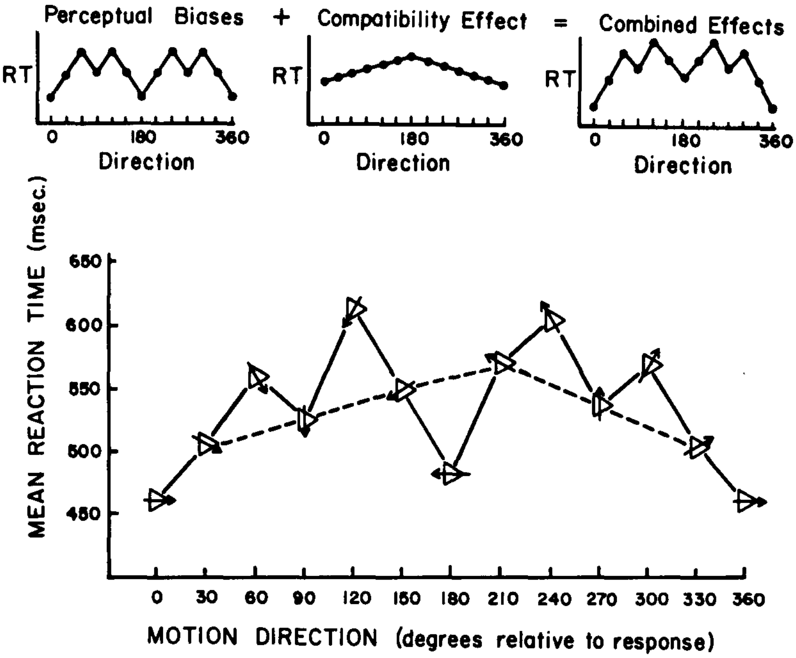


**Figure 8. Mean reaction times to discriminate direction of pointing for moving triangles in Experiment 2 plotted as a function of the direction of motion relative to the required direction of pointing. The upper three diagrams show predictions based on perceptual bias alone, directional compatibility alone, and the two combined. The experimental results are plotted in the lower graph. The triangular symbols with arrows through them iconically represent the motion conditions they depict, using right-pointing triangles as an example. The dashed line connects the base-aligned conditions which are hypothesized to reflect purely compatibility effects, uncontaminated by any additional perceptual bias.**

the directions of motion and response (see dashed curve in Figure 8). Statistical tests bear out the reliability of this increase, in that the inconsistent base-aligned conditions closer to the response direction (at 30° and 330°) are reliably faster than the ones farther from the response direction (at 150° and 210° [$F(1,12) = 13.93$, $p < .01$]. The third comparison that shows the operation of the compatibility factor is the corresponding increase with angular difference for the two inconsistent axis-aligned configurations (60° and 300° vs. 120° and 240°). This RT difference is in the same direction as that found for base-aligned conditions, but does not quite reach statistical significance [$F(1,12) = 4.36$, $.05 < p < .10$]. In fact, it is not surprising that this axis-aligned effect should be less reliable than the base-aligned one, since the angular differences for the former are only 60°, whereas those for the latter are 120°.

We conclude, then, that there are two different effects underlying the pattern of results observed in this experiment. One is a perceptual effect in which all that matters is the symmetry of the motion event: a triangle moving along one of its axes of symmetry biases an observer toward seeing it point in the direction that coincides with the axis of symmetry (axis-aligned conditions), but one moving along one of its sides produces no corresponding bias (base-aligned conditions). The other is a compatibility effect in which all that matters is how similar the direction of motion is to the required direction of perceived pointing and/or response. We do not actually know whether this compatibility effect is due to perceptual or motor interference, because the two are completely confounded in the present study.

The results of this experiment provide strong evidence that motion induces a mandatory perceptual bias effect. Furthermore, they are consistent with the hypothesis that it is symmetry in the space-time structure of the event that produces this bias. There is also a compatibility effect, but this might be due to competition at either a perceptual or a response stage.

## GENERAL DISCUSSION

The purpose of these experiments was to determine whether motion could effectively bias the perceived pointing of ambiguous (equilateral) triangles. We found that the perceived orientation of an equilateral triangle was indeed affected by the direction in which it moves. Specifically, if a triangle moves along one of its three symmetry axes, perceived pointing in that direction is enhanced. When subjects were asked to report the first direction in which they saw the triangle point, they were more likely to choose the "symmetric" direction than either of the other two (Experiment 1). Furthermore, when subjects were required to focus on just one of the three directions, motion along a symmetry axis either facilitated or interfered with their performance, depending on whether it biased the subjects' perceptions of pointing toward the correct direction or one of the two incorrect directions (Experiment 2).

Thus, axis-aligned motion has qualitatively the same effect on perception of an equilateral triangle as do axis-aligned configurations and textures (Palmer, 1980; Palmer & Bucher, 1981, 1982). However, base-aligned motion produces no bias corresponding to the large and systematic base-aligned effects found for configurations and textures. This striking difference supports the hypothesis that event symmetry is a principal factor in producing these bias effects. As discussed earlier, motion along a static symmetry axis creates a plane of symmetry in the movement event. This event symmetry seems strongly to influence the orientation of the reference frame within which the pattern is analyzed. Static linear configurations of triangles and textural stripes within single triangles also have bilateral symmetry in both axis- *and* base-aligned conditions. Base-aligned motion of a triangle, on the other hand, does not result in bilateral symmetry in the movement event. Therefore, this motion does not induce a reference frame that coincides with a direction of pointing.

In addition to the large effects of symmetry, there is a clear and consistent influence of directional compatibility. It is needed to account for the differences between the axis-toward and axis-away conditions in both experiments, and for the systematic increase in RT in Experiment 2 with angular distance from the required direction of response. This compatibility effect seems to combine more or less additivity with the effects due to symmetry (see Figure 8), although we have not made a careful quantitative analysis of this conjecture.

An alternative explanation for the results we have been discussing in terms of symmetry can perhaps be given in more sensory terms. The claim is that the orientation of the perceptual reference frame is determined by the output levels of local, oriented motion detectors. This account—which we will call the "motion detector hypothesis"—is based on an application of the aperture problem (Marr & Ullman, 1981) to the present stimuli and runs roughly as follows. The speed and direction of motion in a dynamic image is often ambiguous with respect to the output of local motion filters or detectors of the sort hypothesized by sensory physiologists—cells that respond to motion of oriented edges across the small, sensory apertures defined by their own receptive fields. The reason is that the output of any such filter will be constant for all straight edges (or lines) of the same orientation that move so that their motion vectors have identical projections normal to the oriented receptive field (see Figure 9). Thus, the output of such detectors or detector systems effectively represents motion only up to the equivalence class of vector projections onto this perpendicular direction, leaving ambiguous exactly what com-

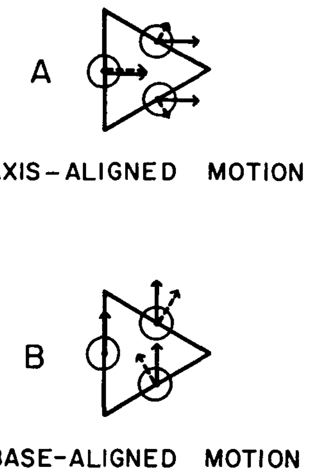


**Figure 9. The logic of the "motion detector" account of motion biases. Solid arrows represent the vectors of image motion, and dashed arrows show their projections onto directions perpendicular to the orientation of the corresponding side. The "motion detector hypothesis" suggests that the bias due to motion will be in the orientation(s) with maximal perpendicular projections (i.e., the longest dashed arrows).**

bination of speed and direction in the moving image produced it.[2]

When this computational analysis is applied to the specific case of a moving equilateral triangle, it turns out that the three sides will affect the output of such local motion detectors differentially, in ways that are suggestive of the present pattern of results. In particular, when the triangle is moved along one of its axes of symmetry (the axis-aligned case), the side perpendicular to the direction of motion will necessarily produce the greatest output, because the normal projection of its motion onto its perpendicular is, by definition, maximal and greater than that of either of the other two sides (see Figure 9A). If the orientation of the perceptual reference frame is taken to coincide with the direction at which local motion detectors have greatest output, then axis-aligned motion should produce maximal output in the direction of image motion, and this should result in the substantial axis-aligned biases observed in the previous two studies. However, when the same triangle moves parallel to one of its sides (the base-aligned case), the output associated with that same side will be just the cell's baseline rate, because its motion has zero projection onto the directions perpendicular to its orientation (see Figure 9B). The output of the local motion detectors activated by the other two sides will clearly be greater than this, and so any bias due to motion would have to be in one of these two directions.

Unfortunately, the present results do not discriminate between the symmetry and motion detector hypotheses. The symmetry hypothesis is preferable on grounds of parsimony because it is capable, without modification, of accounting for numerous previous results with stationary figures as well. The motion detector hypothesis may perhaps be preferable on grounds of physiological simplicity and plausibility, but it suffers from the drawback that it does not apply to unmoving figures. Still, further studies will be needed to discriminate between these two kinds of theories for the case of moving stimuli.

Regardless of the true nature of the mechanisms that underlie the effects we have reported, they suggest that direction of motion could be a potent factor in other "reference frame" phenomena (see Palmer, 1983)—for example, shape constancy and its failure in memory for disoriented figures (Rock, 1973; Wiser, 1981), shape discrimination between squares and diamonds (Palmer, 1985), symmetry detection in figures at different orientations (Palmer & Hemenway, 1978; Royer, 1981), and perhaps even the perceived organization of complex motion events (Johansson, 1950). These are merely conjectures at present, of course, but if the line of reasoning followed here is correct, such effects should be found for suitably constructed stimuli. We are currently exploring several of these predictions in our laboratory.

In conclusion, then, the present experiments support the hypothesis that motion induces a perceptual reference frame according to which a pattern will be analyzed. They are also consistent with the further hypothesis that bilateral symmetry in the movement event establishes this reference frame.

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## NOTES

1. It may be useful to say a few more words about the data plotted in Figure 5. First, the relevant data are *probabilities* of responses in specific directions, not measures of the directions themselves, and, so, taking means and analyzing variances is entirely appropriate. Second, each data point from moving stimuli in Figure 5 represents the probability with which subjects reported just *one* of the four response categories depicted in Figure 4—namely, the one supposedly biased by the type of motion the triangle underwent in that trial (see Figure 3). Therefore, all of these data points are logically independent and can be analyzed appropriately by analysis of variance. In other words, there are no sets of data points for the moving stimuli that logically must sum to 100%—indeed, all three of the motion curves shown in Figure 5 *could* have produced 100% biased responses. The data for the stationary control conditions, however, are not independent, since the stimuli for triples of directional conditions are physically identical (i.e., 0°, 120°, and 240°; 30°, 150°, and 270°; 60°, 180°, and 300°; and 90°, 210°, and 330°). Therefore, data from these triples must sum to 100° and cannot be properly compared with each other by simple analysis of variance techniques.

2. As stated, the aperture problem applies only to the central portions of the sides of a triangle where the local motion detectors respond to motion of a single, straight line. We will ignore what is happening at the vertices, where the situation is decidedly more complex.

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