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An Objective Criterion for Apparent Motion Based on Phase Discrimination

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Studies of visual apparent motion have relied on observers' subjective self-reports of experienced motion, for which there is no objective criterion of right or wrong. A new method of phase discrimination is reported that may offer an objective indicator of apparent motion. Ss discriminated the direction of an objective 75-ms phase shift, away from strict temporal alternation of 2 stimulus dots. Accuracy increased from 50% to 100% correct as rate of alternation and distance between the dots was decreased, in conformity with Korte's third law of apparent motion. This and additional evidence suggests that phase discrimination may be mediated by asymmetries between the experienced strengths of leftward and rightward motion. Phase discrimination may also be adaptable to the study of apparent motion and related phenomena in other sensory modalities and other animal species.

When presented with static stimuli that are successively displayed in different spatial positions, one may experience *apparent motion* of a single enduring object undergoing a continuous motion between those positions (Exner, 1875; Wertheimer, 1912/1961). Because there is no motion of the physically presented stimuli, apparent motion is a subjective phenomenon. Accordingly, experimenters have traditionally relied on subjects' subjective ratings of the occurrence or quality of experienced motion under various conditions of presentation. In the absence of an objective criterion for classifying a subject's report of apparent motion as correct or incorrect, the empirical laws that have emerged concerning the spatiotemporal conditions yielding good apparent motion have had an essentially subjective basis.

Perhaps the most fundamental of these laws is the time–distance relation, proposed in its initial form by Korte (1915) and known since Koffka (1931) as *Korte's third law of apparent motion*. In its most widely confirmed modern formulation, this law states that the minimum time between the onsets of two alternately presented stimuli yielding good apparent motion–the critical *stimulus onset asynchrony* (SOA)–is an increasing (and typically quite linear) function of the extent (or path length) of the motion needed to carry the object from the one position to the other in space (e.g., see Corbin, 1942; Kolers, 1972; Neuhaus, 1930; Shepard, 1984; Shepard & Judd, 1976; Shepard & Zare, 1983).

The work we report here was motivated by a desire to establish laws governing mental experience such as Korte's third law on a firmer scientific footing by finding more objective ways to investigate and to quantify the subjective. Our approach is thus in the spirit of earlier work in which subjective imagery was investigated by timing objective responses to objective visual probes (for an overview, see Shepard & Cooper, 1982). The essential step (as noted in a review of this approach by Kubovy, 1983) was to devise experimental tasks that admit an objective criterion for whether each response made by a subject is correct or incorrect. Subjects were not asked to rate the subjective quality of a mental image–a rating that could never be classified as correct or incorrect. Instead, subjects were required to make one of two responses, as quickly as possible, depending on whether a physically presented probe stimulus matched in some specified way the object or pattern that would result from a specified operation. In the absence of a physically manipulable object or its parts, the specified operation could only be carried out mentally, for example, by imagining a pictured object rotated into a different, specified orientation (Cooper & Shepard, 1973; Shepard & Metzler, 1971) or by imagining specified parts assembled into a whole in accordance with verbal instructions (Glushko & Cooper, 1978; Podgorny & Shepard, 1978). Although the operations were carried out only mentally, a subject's overt response to the ensuing physical test probe could be objectively classified as correct or incorrect based on whether the probe stimulus would match an object that had physically been rotated or assembled in the specified way.

To render the subjective phenomenon of apparent motion susceptible to objective study, we have explored a method of *phase discrimination* in which subject's responses could similarly be classified as objectively correct or incorrect. Instead of requiring subjects to perform a mental operation and to match the mental result to a visually presented target, as in the study of mental imagery, we required subjects to discriminate the direction in which we broke the temporal symmetry of what have traditionally been temporally symmetric apparent motion displays. We hoped that the objective discriminatory performance would provide evidence about the form of the basic laws underlying apparent motion, such as Korte's third law, without having to rely on the unverifiable self-reports of subjects.

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A paper describing this experiment was first presented (by Roger N. Shepard) at the 24th Annual Meeting of the Psychonomic Society (Miller & Shepard, 1988).

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In perhaps the simplest form of visual apparent motion, initially investigated by Helmoltz's student Exner (1875), two elementary stimuli, such as pointlike flashes of light, are alternately presented in two nearby spatial locations. Under suitable conditions of time and distance, such a display gives rise to the visual illusion of a single stimulus moving back and forth over a straight path between the two locations. The critical conditions of time and distance, established by now extensive research, are the following. First, the interstimulus interval (ISI) between the offset of each stimulus and the onset of the other must not be too long. Second, the path over which the stimulus would have to move between the two locations (in this case, the connecting straight path) must not be too long relative to the time (i.e., the SOA) available for determining and representing such a motion (see Shepard, 1984; Shepard & Cooper, 1982; Shepard & Zare, 1983).

The phenomenon of apparent motion itself and the requirement of a sufficiently short ISI are readily understandable in terms of a very general perceptual principle that is, in essence, Helmholtz's principle of "unconscious inference." The principle has two parts: First, perceptual experience, which is generally of an object or event in the external world, must be consistent with the information available at the sensory surface (in this case the spatiotemporal pattern of light falling on the retina). Second, because there are always many possible distal objects or events that could give rise to the same proximal stimulus, the one that is perceptually experienced is selected on the basis of its probability of having actually occurred in the external world. In short, what is perceptually experienced is determined both by current sensory input and by prior knowledge, whether in the form of innate perceptual dispositions shaped by the evolutionary history of the species, long-term fine tuning through learning in an individual, or short-term priming through the immediately preceding context.

The proximal stimulus in visual apparent motion may be equally consistent with either of two alternatives: two objects alternately materializing and dematerializing in different spatial locations or a single, enduring object moving back and forth between those locations. Provided that the ISI is not too long, the latter alternative is perceptually favored because that alternative is more probable in our world, in which material objects are conserved.

As the ISI is made longer, however, the conservation interpretation becomes either less consistent with the proximal pattern of stimulation or less probable in the external world for the following reasons. If the object's motion were represented over some probable (e.g., straight) connecting path, the motion during the long ISI would have been slow enough to stimulate corresponding retinal receptors along that path. The absence of activity in retinal receptors corresponding to a connecting path is therefore inconsistent with the hypothesis of a single moving object. Alternatively, if the motion were so fast that it failed to stimulate any receptors along the path, then given the long ISI, the path would have to be very long, curved, and accordingly improbable in the world. Moreover, because there is always an infinite variety of possible long, curved paths, there would be no basis for selecting any particular one to represent the motion of the conserved object. To summarize, in the absence of retinal activity over a connecting path and with the difficulty and implausibility of hypothesizing any particular long connecting path, a long ISI provides little support for representing the motion of a conserved object over a definite path.

The second condition for the experience of apparent motion–that the SOA not be too short relative to the length of the path of motion–may arise because apparent motion must be represented within a physical system (the brain) in which activity (in this case, neural activity) necessarily has a limited rate of causal propagation (Shepard, 1989; see also the related earlier proposals by Caelli, Hoffman, & Lindman, 1978; Jones, 1976; Shepard, 1981, 1984). By analogy with the theory of relativity, according to which two events that are too widely separated in physical space relative to their separation in time cannot be causally connected, given the limiting velocity of light, two visual events that are too widely separated in representational space relative to their separation in time cannot be connected in the brain, given the limiting velocity of neural signals. (For long-range apparent motion, anyway, the critical separation may be an internal representation of distance in the external, three-dimensional world, and not simply distance on the retina; see Corbin, 1942; Shepard, 1984; Shepard & Zare, 1983; similarly, Burt & Sperling, 1981, reported that the pattern of apparent motion induced by their displays did not depend on the distance of the viewer from the screen, a phenomenon they called *scale invariance*, but that might be more accurately termed *viewing distance invariance*.)

In short, two visual events separated by too great a distance and too short a time are necessarily perceived as independent, not as unified into the apparent motion of a conserved distal object over a connecting path. Indeed, when apparent motion has thus broken down, observers find it difficult to discern any temporal connection between the two spatially separated streams of events (Robins & Shepard, 1977). For example, they experience two flashing dots, one on the left and the other on the right, but may be unable to say whether the flashes on the right precede, follow, coincide with, or alternate with the flashes on the left. This is the observation that led us to investigate judgments of the objective phase relation between two such spatially separated streams of events for an objective measure of apparent motion. If the events on the left are suitably phase shifted relative to the ones on the right, the SOAs in one direction could be above the critical SOA for apparent motion whereas those in the other direction could be below that threshold. The resulting asymmetry in apparent motion could then mediate discrimination of the objective direction of the phase shift.

To justify the application of a proposed objective measure to a previously only subjectively rated mental phenomenon, we need to establish that the proposed objective measure is suitably correlated with the subjective ratings and, hence, that it supports the same lawful relations, such as Korte's third law of apparent motion. This is the main objective of the experiment we report. (If our objective measure instead yielded results different from subjective ratings but more consistent with other psychological and neurophysiological data, we would have reason to question previously accepted interpretations of the subjective ratings themselves.) In addition, the justification for the proposed application will be strengthened to the extent that we can offer theoretical reasons for why the objective measure may tap into the same underlying process that has been expressed through subjective ratings. We argue that it is the perceptual experience of apparent motion, which depends on the occurrence of certain temporally constrained neural interactions, that mediates the judgment of objective phase relation when the rate of presentation becomes too great for a confident, categorical analysis of the exact sequence of visual events.

Method

The Phase Discrimination Task

The basic nature of the phase discrimination task is schematically indicated in Figure 1. Here, time goes from left to right, and the spatial separation of the two dots is represented vertically (for each illustrated case: A, B, or C). For comparison, the symmetric alternation that has typically been used in apparent motion research is that shown in Part A, in which the onset of each dot coincides with the offset of the other dot. Instead, we used asymmetric alternations in which the dots were of the same duration, but in which the onset of the left dot either preceded the offset of the right dot, the *left-leading condition* (Part B), or followed the offset of the right dot, the *right-leading condition* (Part C). For all recorded trials in either direction of this phase shift, the absolute temporal magnitude of the phase shift was always 75 ms.

The subject's task was to indicate the direction of this phase shift, that is, whether the left dot came on earlier (as in Case B) or later (as in Case C) than it would have in a strictly symmetrical alternation (as in Case A). We sought to determine how the objective accuracy of this phase discrimination varied as a function of the principal independent variables of Korte's third law, namely, the distance between the dots and the temporal rate of their alternation. To determine when the subjective experience of apparent motion broke down and to facilitate comparison with the more usual, self-report methods of investigating apparent motion, we also obtained ratings of the subjective strength of the apparent motion; in this case, in each of the two directions of the possibly asymmetric motion.

Our expectation was that subjects who were given feedback concerning accuracy could learn to infer that stronger leftward apparent motion indicates Case B, whereas stronger rightward motion indicates Case C. Essentially, we trained subjects to exploit the limitations of their own motion perception systems (e.g., their inability to perceive apparent motion given short SOAs) in the phase discrimination task. Then, by analyzing subjects' performance on that task, we could make inferences concerning their motion perception systems (e.g., we could determine the critical SOA at which apparent motion breaks down). Although stimulus position, onset, and offset logically determine the experience of apparent motion, subjects may have better access to motion percepts than they do to the stimulus cues on which these percepts are based.

Subjects

Data were collected from 13 subjects with normal or corrected-to-normal vision, including 11 students and staff of Stanford University who were recruited by poster and paid for their participation, and the 2 authors. Subjects served individually in two experimental sessions, usually scheduled on 2 consecutive days and usually lasting about 75 min each.

Equipment

The apparent motion stimuli were displayed on the screen of a Silicon Graphics IRIS 2400 computer graphics workstation, which controlled the randomization and timing of the stimuli as well as the recording of responses. This 19-in. (38 × 28 cm) color display screen presented 768 noninterlacing lines with a resolution of 1,024 pixels per line and a raster scan rate of 60 Hz. This scan rate limited accuracy of timing the visual presentations to ±16 ms.

During the experimental trials, a subject viewed the display through an enclosed hood mounted on the monitor and fitted with a headrest. The hood and headrest eliminated extraneous illumination and reflections and ensured a constant viewing distance of 68 cm. At this distance, the screen, which generated 28 pixels per cm, provided a horizontal visual resolution of 33.5 pixels per degree of visual angle. A mouse-controlled cursor enabled subjects to use response scales on the screen without having to move away from the hood to look at a keyboard.

Stimulus Display

The apparent motion stimuli consisted of two solid white circular dots, equally displaced to the left and right of the center of a darker rectangular field that spanned the top half of the display screen. Each dot (24 pixels in diameter) subtended a visual angle of 0.72°. The rectangular background field against which the dots were displayed was a desaturated green that pilot subjects favored for easier viewing and phase discrimination.

Before each trial, the graphics computer internally readied four complete display fields (screen buffers): one containing the left dot only, one containing the right dot only, one containing neither dot, and one containing both dots (refer to Figure 1). Following the presentation of a "ready" signal, the computer then created the phase-shifted apparent motion display for that trial by cyclically presenting the appropriate sequence of these four fields, with each field maintained for its assigned duration (as determined by an internal clock with 1-ms resolution). The actual time for a particular frame buffer to appear on the 60-Hz display screen could lag as far as 16 ms behind this specified display time. Thus, all half-cycle and phase-shift times specified hereafter should be construed only as average, not numerically exact for every stimulus presentation.

The visual display on each trial was characterized by three independent variables: interdot distance, half-cycle duration, and (left-leading vs. right-leading) direction of phase shift. During the experiment itself, the distance between the centers of the dots was 40, 120, 200, or 280 pixels, yielding visual angles of 1.2°, 3.6°, 6.0°, or 8.4°. (These distances put our displays in the category of long-range apparent motion, as defined by Braddick, 1974.) The half-cycle duration was 100, 150, 200, or 250 ms. (For each trial, half-cycle also equaled the duration of each dot and the ISI between successive dots on the same side.) The phase shift was always 75 ms in magnitude, but equally often in the left-leading and in the right-leading directions (indicated in Figures 1B and 1C, respectively). The experiment thus included 4 × 4 × 2 combinations of distance, half-cycle, and direction of phase shift, for a total of 32 conditions.

Structure of Experimental Sessions

In the first session, the experimenter introduced the basic features of apparent motion and the phase discrimination task. Before

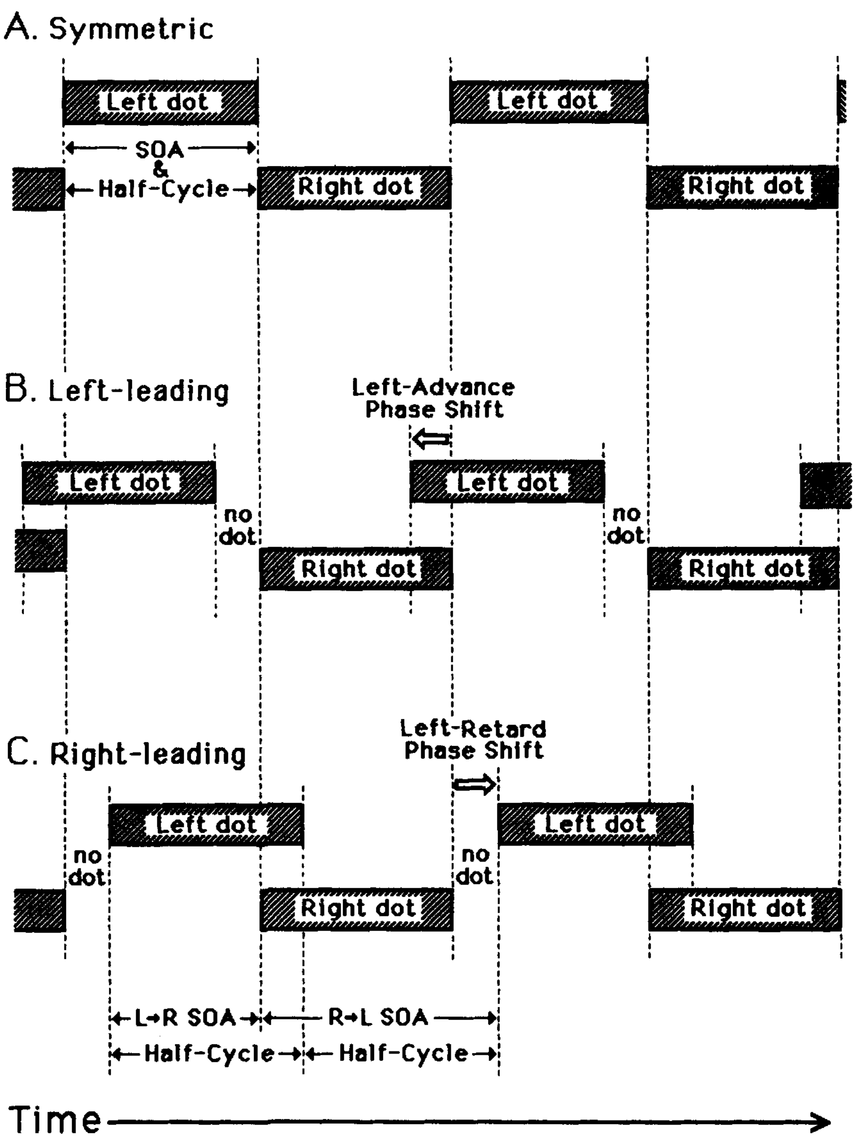


Figure 1. Timing relations between a left dot and a right dot in standard apparent motion (Part A) and in phase-shifted apparent motion that is either left-leading (Part B) or right-leading (Part C). (L denotes left, R denotes right, and SOA denotes stimulus onset asynchrony.)

affixing the viewing hood to the monitor, the experimenter presented a short sequence of demonstration trials to illustrate the two asymmetric phase relations. To make the asymmetries relatively visible, these demonstration trials used long half-cycle times (400 and 600 ms), short interdot distances (1.2°, 3.6°, and 6.0° of visual angle), and large phase deviations (all 200 ms). When subjects indicated that they could perceive these relatively obvious phase deviations, they tried a sequence of 24 practice trials with more challenging half-cycle times (150, 200, 250, and 300 ms) and phase deviations (100 ms), but with the same interdot distances used in the preceding demonstration trials.

During the first few of these 24 practice trials, the experimenter also suggested some attentional strategies that pilot subjects had reported as helpful in making the phase judgments when the presentation rates became too rapid to permit easy analysis of the sequence of individual events. Principally, these strategies included (a) attending to which dot seemed immediately to precede the blank period containing no dot, (b) attending to the relative strength, intensity, and robustness of apparent motion in the rightward versus the leftward direction, and (c) attending to the relative smoothness, uniformity, or fluidity of apparent motion in the rightward versus the leftward direction. At the same time, however, subjects were encouraged to use any other strategy that they found to improve the accuracy of their judgments. The first strategy was suggested mainly to help subjects understand the relations among the objectively presented phase shifts, the response scale for making the phase discrimination, and the subjectively experienced motion asymmetries. Very few subjects reported being able to perceive directly the blank intervals or the objective discrete sequence of stimulus events during the experimental trials with shorter half-cycles. Most subjects reported switching quickly to a combination of the second and third strategies.

Next, subjects were shown how to indicate their choices on the response scales displayed in the lower portion of the screen. The viewing hood was then affixed to the monitor, the current subject completed the practice trials, and the experimenter answered any remaining questions concerning the task and offered encouragement when necessary. After completion of the practice trials, the subject began the main sequence of 160 experimental trials, with the final, more challenging interdot distances of 1.2°, 3.6°, 6.0°, and 8.4°, half-cycle times of 100, 150, 200, and 250 ms, and phase deviations of 75 ms (in either direction). Subjects were told that they could take a break after recording their phase relation judgment on any trial. To reduce fatigue and eye strain, subjects were required to take at least a 5-min break halfway through the session. At the end of this first session, the second session was scheduled, usually for the next day.

The second session began with another series of 24 practice and warmup trials. The subject then completed a second series of 160 experimental trials. All subjects were interviewed at the end of their second sessions regarding their experience of apparent motion in this task, the judgment strategies they used, and their assessment of their performance.

Structure of Experimental Trials

At the beginning of each trial, a small cross-shaped ready cue appeared for 2 s in the middle of the apparent motion display field. Eye movements were neither constrained nor recorded, however, and subjects were told that they could direct their gaze to whatever part of the apparent motion display most helped them in making the phase discriminations. Immediately following the offset of the ready cue, the stimulus cycle began at a randomly chosen point in the display cycle (between 0 and 2 half-cycles). Thus each dot was equally likely to appear first. The dots continued to appear in phase-shifted alternation until the subject completed the last of three responses for the trial. Subjects could thus view the apparent motion display as long as they wished before making each judgment.

Subjects used a mouse-controlled cursor to record three judgments in fixed order during each trial: an objective phase relation judgment, a subjective rightward strength-of-motion judgment, and a subjective leftward strength-of-motion judgment. The objective phase relation judgment was a two-alternative forced-choice discrimination with an objectively correct answer. Subjects positioned the cursor to the left of a displayed scale to indicate a phase relation described as "left–blank–right," meaning the left dot preceded the blank interval for each cycle in the ongoing stimulus sequence, or to the right of the scale to indicate a "right–blank–left" phase relation, meaning the right dot preceded the blank interval for each cycle. We hoped to take advantage of natural stimulus–response compatibility effects (see Michaels, 1988) by allowing subjects to make a rightward response to stronger rightward apparent motion and a leftward response to stronger leftward motion. Subjects also indicated a (subjective) degree of confidence in this discrimination by positioning the cursor within one of four equal intervals on the chosen side (left or right) of the scale, with intervals farther from center indicating higher confidence. Latency to make this phase relation discrimination, defined as the time interval from onset of the first stimulus dot in the trial to the subject's mouse click indicating the discrimination judgment, was also recorded. The scales on which subjects indicated subjective strengths of rightward and leftward motion were divided into four equal intervals, with the first marked "None," indicating no apparent motion, and the fourth marked "Strong," indicating strong apparent motion.

At the end of each trial, a salient "right" or "wrong" appeared in the lower right corner of the response window to indicate the objective accuracy of that phase relation judgment. This feedback enabled subjects to monitor their performance and perhaps to refine their strategies of phase discrimination. Subjects were told that this feedback pertained only to their objective phase relation judgments, not to their subjective strength of motion judgments. Following the 2-s interval during which the accuracy feedback was displayed, the ready cue again appeared, signaling the beginning of the next trial.

Results

Establishment of an Accuracy Criterion for the Task

Over the two experimental sessions, each subject completed 320 recorded trials. Because these trials included 32 combinations of distance, half-cycle, and direction of phase shift, there were 10 trials of recorded data for each such combination for each of the 13 subjects. Accuracy data for the objective phase discrimination task were collapsed over the two directions of phase shift, yielding 20 trials per subject for each of the 16 combinations of distance and half-cycle. Averaged over these 16 conditions, performance on the phase discrimination task was 76% correct—well above 50% chance level—for 11 of the 13 subjects. (Even the least accurate of these 11 subjects maintained 63% correct overall.) In contrast, the performance of the 2 remaining subjects, only 52% and 53% correct, did not differ significantly from chance. In the postexperimental interviews, these 2 subjects said that they were unable to find a successful strategy for determining the direction of phase shift for the rapid rates of alternation used in the experimental trials. Accordingly, the data for these 2 subjects were omitted from all of the following analyses.

Verification That the Subjective Ratings of Apparent Motion Support Korte's Third Law

Before examining the objective phase discrimination data, we consider the subjective ratings of strength of apparent motion to see whether these exhibited the usual conformity with the time–distance relation referred to as Korte's third law. For this purpose, we averaged for each trial and each subject the ratings of rightward strength of motion and leftward strength of motion to obtain, despite our asymmetric conditions of presentation, a mean rating of overall strength of motion for that trial. Such a mean rating might be considered analogous to the subjective ratings of goodness of apparent motion obtained for previously used symmetric conditions of presentation. Here, the lowest mean rating, 0, would result only if no motion was reported in either direction, and the highest possible mean rating, 3, would result only if strong apparent motion was reported in both directions.

For the 11 subjects who performed above chance in the phase discrimination task, Figure 2A summarizes how the mean subjective ratings of strength of apparent motion depended on the two independent variables of distance and time. Each curve shows how rated strength of motion increased as the duration of the half-cycle increased from 100 to 250 ms, $F(3, 15) = 338.0, p < .001$. Higher curves are for the conditions with smaller spatial distances between the two alternating dots, $F(3, 15) = 72.1, p < .001$. (The smooth curves are cubic splines drawn through the empirical points for later purposes of interpolation.) The upper curves (for

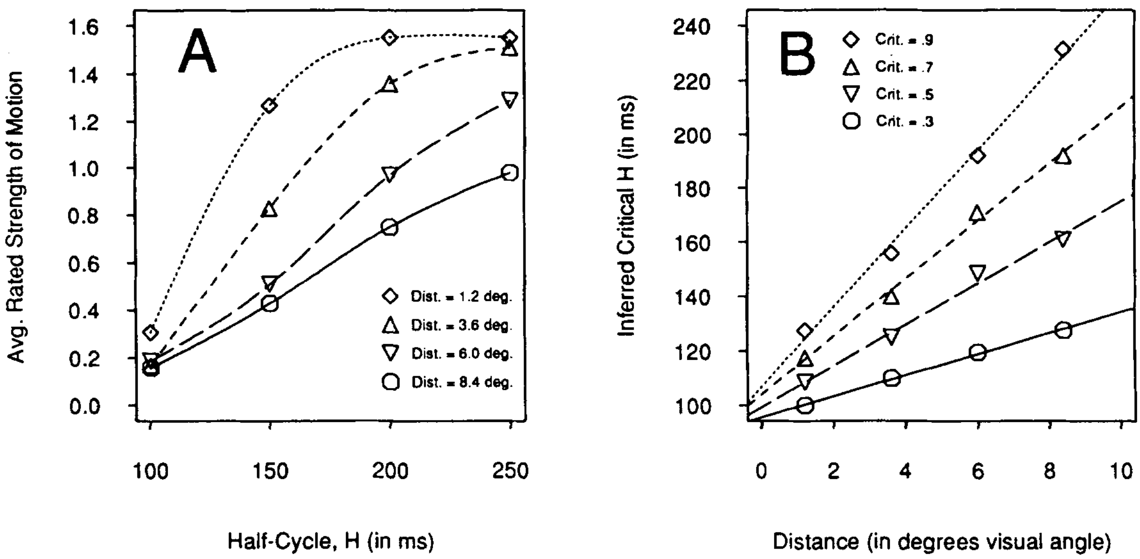


Figure 2. Panel A shows the average of rated strength of leftward and rightward apparent motion plotted as a function of half-cycle duration for each of the four interdot distances. Panel B shows the minimum half-cycle (interpolated by way of the cubic spline curves in Panel A) yielding a criterion level of average rated strength, plotted as a function of interdot distance for each of four criterion levels.

distances of less than 4° of visual angle) appear to level off near a mean rating of 1.6. Although this is little more than half of the maximum possible rating (3.0), the plotted ratings are averages of ratings that were often quite different for the two directions of motion in our asymmetrically phase-shifted displays. Subjects who had given a relatively high rating of 2 or 3 to the apparent motion in one direction may have given a lower rating of 1 or 2 even to a moderately strong motion in the other direction, if that other motion was noticeably weaker than the stronger motion. Such a contrast effect probably contributed to a relatively low ceiling on the average ratings.

Are these subjective ratings of strength of apparent motion in accordance with Korte's time–distance relation? To answer this question, we can choose a criterion level for rated strength of motion and see whether the half-cycle time needed to reach that criterion level increases in some regular way with the spatial distance between the dots. Because the resulting time–distance function might depend on the criterion level used, we constructed four such functions, one for each of four equally spaced criterion levels: 0.3, 0.5, 0.7, and 0.9. These were chosen to fall within the vertical range covered by all four curves in Figure 2A, that is, between about 0.3 (for the low point at the left of the highest curve, for distance = 1.2°) and about 1.0 (for the high point at the right of the lowest curve, for distance = 8.4°). For each of these four criterion levels, we then constructed an empirical time–distance function for each interdot distance by using the cubic spline in Figure 2A to interpolate a critical half-cycle time. From a chosen criterion level on the vertical rating scale at the left in Figure 2A, we extended a horizontal line rightward to the spline curve for a specified interdot distance and then dropped a vertical line to the horizontal half-cycle axis to obtain a corresponding critical half-cycle. For each of the four criterion levels, we plotted the resulting critical half-cycles against interdot distances and fitted a straight line to the trend by least squares regression (Figure 2B). Although the slopes systematically depend on the criterion level, the results approximate the linear form of Korte's third law (cf. Corbin, 1942; Shepard, 1984). When extrapolated back to distance = 0°, moreover, the fitted straight lines come into approximate convergence near a half-cycle intercept of 100 ms. (This positive intercept may reflect a time needed to process the onset of each dot, with or without apparent motion, as well as a regression to the mean, expected for measurements containing noise.)

Effects of Distance and Half-Cycle on Objective Phase Discrimination Accuracy

Having established that subjective ratings of apparent motion in our task conformed with the time–distance regularities found in previous studies, we now examine the performance of our subjects on the objective task of phase discrimination. Figure 3A plots percent correct judgments on the objective phase discrimination task against half-cycle time as four separate curves, one for each interdot distance. Again, to facilitate interpolation, cubic splines have been drawn through the empirical points. (The nonmonotonic decrease in the highest curve for long half-cycle times is attributable to a drop in the single point for 250 ms. This decrease was not reliably present in individual subjects; see Figure 4.)

As is evident on the left in Figure 3A, at the fastest rate of cycling, when half-cycle time was only 100 ms, subjects performed near chance (50%) even for the smallest interdot distances. But as half-cycle time increased, performance improved steeply, attaining an average, over the 11 subjects, of about 90% correct when half-cycles were at least 200 ms and dot separations were less than 7° or 8° of visual angle.

The main effects on objective phase discrimination accuracy were highly significant both for half-cycle time, $F(3, 15) = 184.8$, $p < .001$, and for distance, $F(3, 15) = 8.3$, $p < .001$. The interaction between these two variables was also significant, $F(9, 15) = 2.8$, $p < .005$, perhaps reflecting a tendency for the slopes and asymptotes of the curves to be higher for the smaller interdot distances (see Figure 3A).

Curves like those shown in Figure 3A (but connected by linear segments rather than cubic splines) are separately displayed for each of the 11 individual subjects in Figure 4. Despite the greater variability in the data for individual subjects, for whom each point represents percent correct across only 10 trials, similar dependencies on time and distance are manifest, both for the recruited majority of the subjects, who were naive as to the purposes of the experiment, and for the 2 authors (GM and RS) whose data (in the psychophysical tradition) are also included. Seven of the 11 subjects attained virtually 100% correct in discriminating direction of phase shift for combinations of longer half-cycles and shorter distances (see the plots for Subjects PW, EB, DB, BM, NS, RS, and GM in Figure 4).

The systematic variation in accuracy of discriminating the direction of phase shift, from chance level to 100% correct, is especially striking given that the magnitude of the phase shift itself was fixed at 75 ms throughout all 320 experimental trials. Moreover, half-cycle time affects phase discrimination accuracy in a way contrary to what might be expected from Weber's law. As the overall half-cycle time increased, the ratio of the fixed 75-ms phase shift to overall half-cycle time decreased. Yet, with this decrease in what might be interpreted as a $\Delta T/T$ ratio, accuracy, far from decreasing as Weber's law might suggest, improved markedly. More specifically, if subjects had been using the first strategy suggested during practice trials—attending to the blank intervals in which no dot appeared—then we might have expected accuracy to decrease as half-cycle increased, because the duration of blank interval compared to stimulus duration decreases as half-cycle increases. Furthermore, analysis of reaction times indicated that the pattern evident in the obtained results (Figure 3A) is not accounted for by a speed–accuracy trade-off; response latencies tended to be faster, not slower, for correct responses.

Support for Korte's Third Law From Objective Phase Discrimination Data

If the four curves plotted in Figure 3A were of the same shape and differed only by a horizontal translation (an ideal case), the extent of this translation (in milliseconds) could be plotted as a function of the interdot distance corresponding to each curve. The resulting time–distance relation might be analogous to Korte's third law but would not depend on subjective self-reports of the quality of apparent motion (as in previous studies or as in the present Figure 2B). Because the curves in Figure 3A are not strictly parallel, however, the slope of the resulting time–distance relation might depend on the criterion level selected for objective percent correct, just as slope in Figure 2B depended on the criterion level selected for subjective ratings in Figure 2A. Accordingly, we again followed the procedure of plotting different empirical time–distance curves for different criterion levels.

We chose four equally spaced criterion levels, 65%, 70%, 75%, and 80%, falling in the middle of the range between 50% and 100% performance, where the four spline curves in Figure 3A are monotonic. The 75% criterion is particularly defensible, as it matches the traditional midpoint between chance and perfect performance used in psychophysical discrimination methods, and because it lies very close to the mean level of accuracy across all 11 subjects (76%). For each of these four criterion levels, we then constructed an

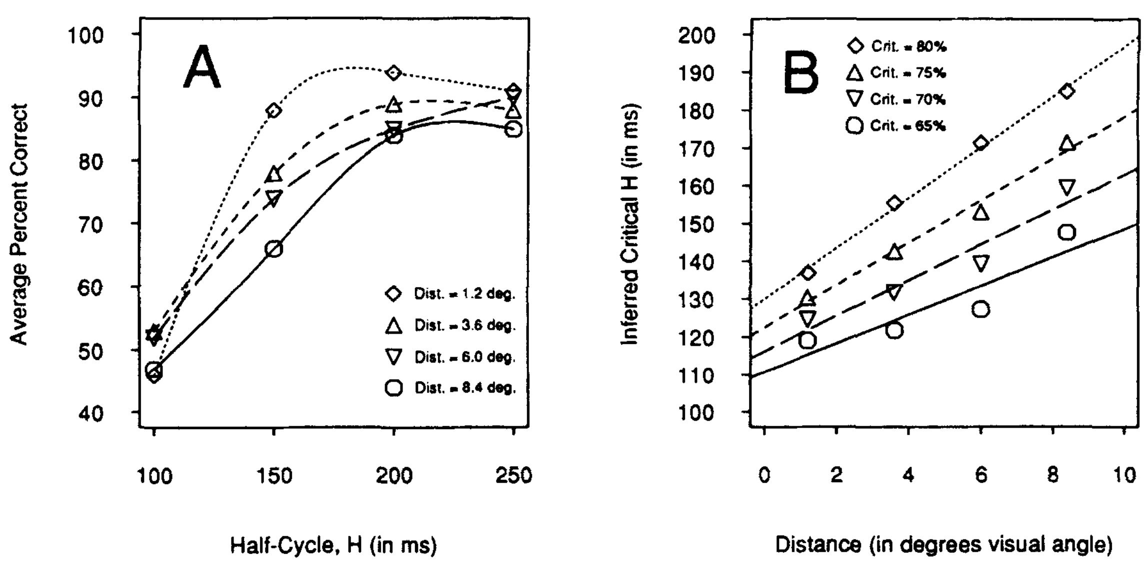


Figure 3. Panel A shows the accuracy in discriminating the direction of phase shift plotted as a function of half-cycle duration for each of the four interdot distances. Panel B shows the minimum half-cycle yielding a criterion level of accuracy (interpolated from Panel A) plotted as a function of interdot distance for each of four criterion levels.

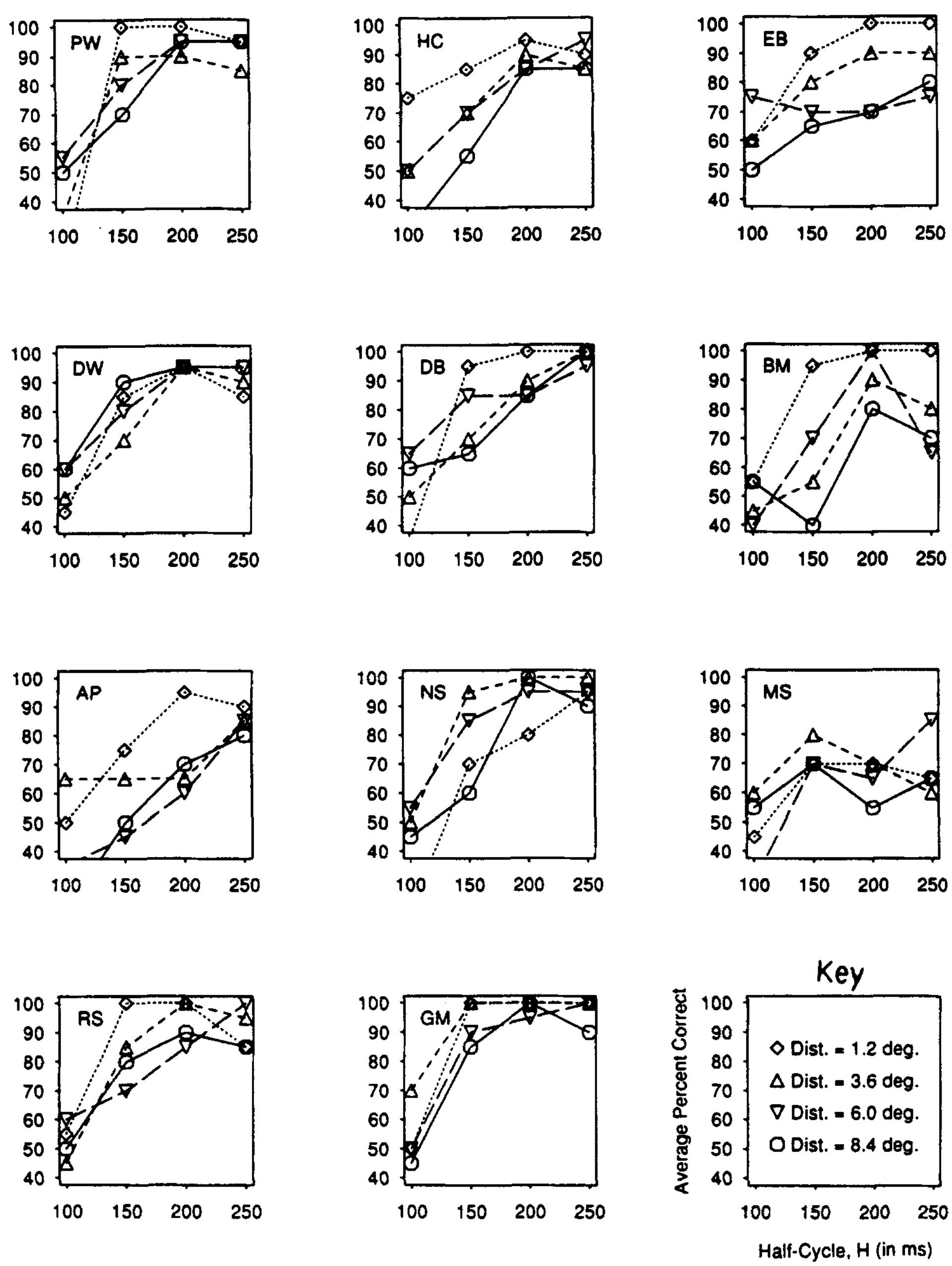


Figure 4. Accuracy in discriminating the direction of phase shift as a function of half-cycle duration and interdot distance, plotted separately for each of the 11 subjects.

empirical time–distance function by cubic spline interpolation. This interpolation graphically corresponds, as before, to extending a horizontal line from a chosen criterion level on the vertical percent correct scale at the left in Figure 3A to the spline curve for a specified interdot distance, then dropping a vertical line to the horizontal half-cycle axis to obtain a corresponding critical half-cycle. For each of the four criterion levels, we then plotted a separate set of points showing how this estimated critical half-cycle time increased with spatial distance between the dots. To each set of points, displayed in Figure 3B, we again fitted a linear function by least squares regression.

Like the curves in Figure 2B based on subjective ratings, these discrimination-based curves increase monotonically with distance, in accordance with Korte's third law of apparent motion. Also as in Figure 2B, the slopes of these functions increase with the magnitude chosen for the criterion level—here, percent correct. This moderate dependency of slope on criterion level seems, for better or worse, to arise from the intrinsic fan shape of the percent correct data in Figure 3A.

The critical half-cycles based on objective performance (Figure 3B) are less well fit, however, by linear functions than the critical half-cycles based on subjective ratings of strength of motion (Figure 2B). Only the uppermost set of points in Figure 3B, based on the highest criterion level (80% correct), closely approximate linearity. A consequence of the method of interpolation, however, is that the four sets of points in Figure 3B are not independent. The only obviously systematic nonlinearity in this figure is the upswing in the rightmost points (corresponding to a visual angle of 8.4°) for the three lower curves. But this upswing might be attributable to the possibly anomalous lowness of a single point in Figure 3A, namely, the point on the distance = 8.4° curve at the 150-ms half-cycle time. (Indeed, the distance = 8.4° curve is the only one of the four curves in Figure 3A that lacks an upward convexity at 150 ms.) In view of such uncertainties, the results shown in Figure 3B provide only a moderately strong suggestion of the linearity of the time–distance functions obtained from objective phase discrimination. Definitive determinations may require estimates of critical half-cycle times based on more extensive data and interpolation using the least squares fitting of functions of a theoretically derived, monotonic form.

More generally, one might object that by choosing our criterion values as we did, we constrained our data analysis to reflect only the most regular and interpretable portions of the percent correct data, and thus that only a small portion of the data from Figure 3A actually determines the critical half-cycles inferred and plotted in Figure 3B. This same objection would apply, however, to any previous inference of a psychophysical threshold from an ogive performance curve. In a basic signal detection experiment with a method of constant stimuli, for example, if the stimuli span a substantial range of intensity values, detection performance will be at chance for many of the small intensity values, will seem to rise rapidly for intermediate values, and will plateau at a high level for many of the large intensity values. In such a case, only the middle few points of the detection data will influence the inference of the detection threshold. Thus, we believe that focusing our criterion levels in the midrange of performance, and inferring critical half-cycles given those criterion levels, is a defensible and efficient method in accordance with established psychophysical practice.

Weighting Discrimination Performance by Confidence Level

The possibility that the underlying time–distance relation may approximate linearity receives some support from a further analysis of the present data. Reasoning that the most noise-free judgments would be those made with greatest confidence, we reestimated critical half-cycle times by weighting the correctness of each judgment (−1 for wrong ones and 1 for correct ones) by the absolute value of its associated confidence rating (which could range from 0 to 3), yielding a measure capable of ranging from −3, for absolute inaccuracy with complete overconfidence, through 0, for chance performance, to 3, for perfect accuracy with complete confidence. (In actuality, this measure rarely went negative.) Figure 5A plots the resulting points as an approximate indication of how this confidence-weighted accuracy measure increased with half-cycle time for each of the four values of interdot distance. The cubic spline curves connecting the data appear more clearly separated in slope and asymptote than those that did not take confidence into account (cf. Figure 3A). Such a separation may reflect the weakening of the phenomenon of apparent motion that results from an increase in the separation between the alternately presented stimuli.

Figure 5B, then, shows the three time–distance functions that were obtained from the four curves in Figure 5A by again estimating critical half-cycle times through interpolation, here at three equally spaced criterion levels: 0.5, 1.0,

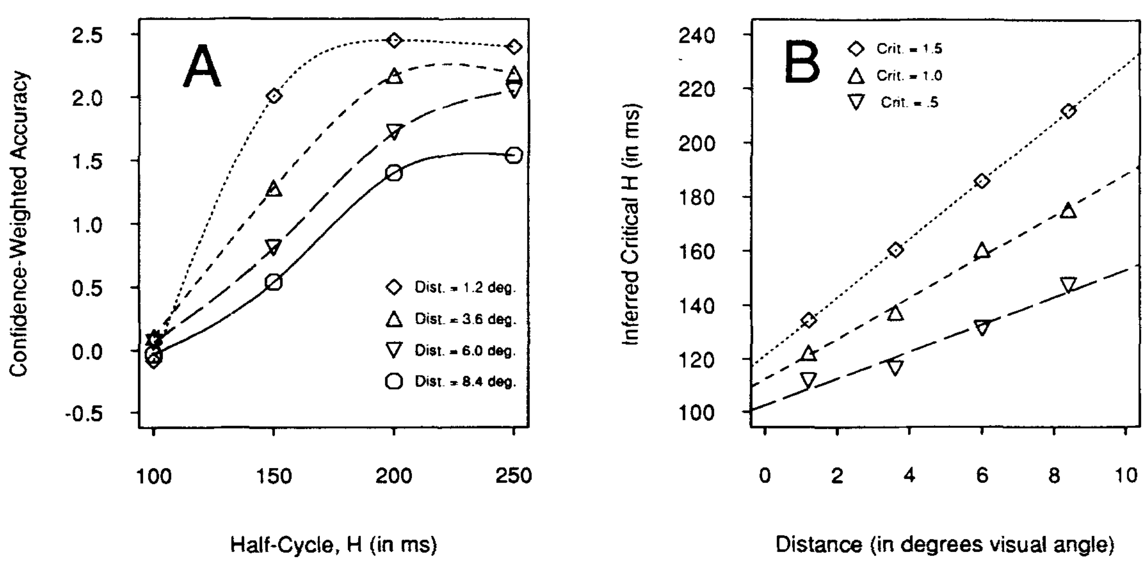
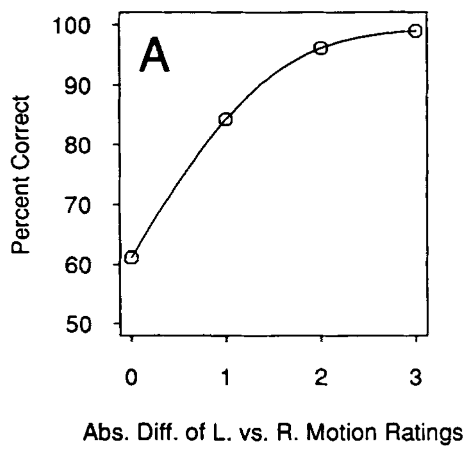


Figure 5. Panel A shows the confidence-weighted accuracy in discriminating the direction of phase shift plotted as a function of half-cycle duration and interdot distance. Panel B shows the minimum half-cycle yielding a criterion level of confidence-weighted accuracy (interpolated from Panel A plotted as a function of interdot distance for each of three criterion levels.



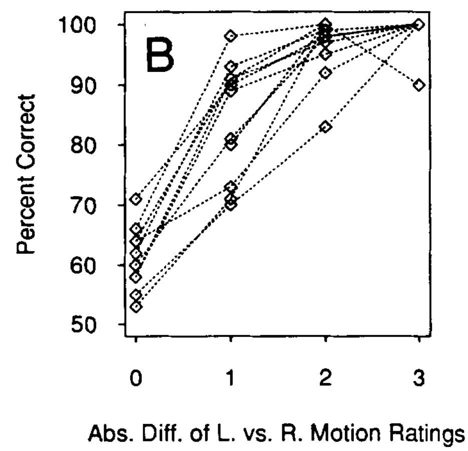


Figure 6. Accuracy in discriminating the direction of phase shift as a function of absolute difference between the rated strengths of leftward and rightward motion as averaged over all 11 subjects (Panel A) and for each subject individually (Panel B), averaged over all trials yielding the given absolute difference in rating, regardless of half-cycle and distance.

and 1.5. These three criterion levels were chosen to fall between chance performance (0) and the highest value attained by the lowest curve in Figure 5A, about 1.5, which again is about half of the highest possible value (3). Apparently, subjects were quite conservative with their confidence ratings, rarely showing complete faith in their discrimination judgments.

Of course, the time–distance relations plotted in Figure 5B are no longer based exclusively on objective judgments but depend in part on the subjective ratings of confidence in those judgments. Moreover, the slopes of these time–distance relations still increase, as in the previous Figures 2B and 3B, with level of the criterion. Nevertheless, by weighting the objective accuracy of phase-shift judgments by rated confidence, we have more closely approximated a linear dependence of critical time on distance.

Apparent Motion Asymmetry as a Mediator of Phase Discrimination

The similarity between the curves based on accuracy of phase discrimination (Figures 3 and 5) and the preceding curves based on subjective ratings of strength of apparent motion (Figure 2) support our proposal to use phase discrimination as an objective indicator of apparent motion. Under varied conditions of time and distance, the boundaries at which phase discrimination breaks down appear to correspond fairly closely to the boundaries at which apparent motion breaks down in accordance with Korte's third law.

But exactly what mediates this correspondence between experienced strength of apparent motion and judged direction of phase shift? Subjects cannot use a symmetric experience of motion to determine the asymmetric direction of phase shift. For example, in the case of long half-cycles, small interdot distances, and very small phase shifts, the strength of apparent motion in both directions might reach ceiling at the highest possible levels. Yet the motion's symmetry would provide no cue about the direction of phase shift. Only if apparent motion in one direction is discriminably stronger or qualitatively different from that in the other direction can motion cues per se be used to infer direction of phase shift.

With our phase-shifted displays, however, subjects often rated the apparent motion as appreciably stronger in one direction than in the other, a fact that was not preserved in the symmetrically averaged ratings used for the construction of Figures 2A and 2B. Such an asymmetry of experienced motion is to be expected because the operative variable of SOA has different values for the rightward and the leftward directions in our phase-shifted displays. Subjects might therefore have learned to use subtle but perceptible asymmetries between the leftward and rightward experiences of motion to determine the direction of phase shift when the rates of presentation were too fast for categorical analysis of the sequence of distinct visual displays. Many of our subjects reported difficulty in determining the exact sequence of visual events for rates of presentation in which the half-cycle times fell below 200 ms.

To see whether successful subjects might have used apparent motion asymmetries to discriminate direction of phase shift, we computed, instead of the average of the rated strengths of experienced leftward and rightward apparent motions, the absolute difference between the rated strengths of those two motions. Figure 6 shows how accuracy in phase discrimination increased with the absolute difference in rated strength of leftward and rightward motion averaged across the 11 subjects who met our accuracy criterion (Figure 6A) and separately for each of those 11 individual subjects (Figure 6B).

The point plotted for each absolute difference in rated strength of motion is the percent correct phase discrimination for all trials yielding that absolute difference, regardless of the values of half-cycle time or interdot distance on each included trial. Despite variations in the overall heights of the curves for individual subjects, all these curves exhibit an increase that is orderly and perhaps essentially linear until they approach the ceiling value of 100% correct. The one point that failed to maintain monotonicity and 100% accuracy at a rating difference of 3.0 (at the right in Figure 6B) failed to do so because of a single incorrect response. (The heights of individual points in Figure 6B differ in reliability because they are based on different numbers of trials that resulted in a given absolute difference in ratings.)

Further information about the relation between accuracy of phase discrimination and asymmetry of rated strengths of motion is obtained by averaging over subjects but separating curves for different half-cycle times (Figure 7A) or for different interdot distances (Figure 7B). All the curves in Figures 6 and 7 appear consistent with the following account. First, subjects use whatever asymmetry they experienced to discriminate direction of phase shift. This is reflected in the roughly linear increases exhibited by the left portions of the curves in Figures 6B, 7A, and 7B. Second, when accuracy approaches the ceiling of 100% correct, it cannot improve further regardless of any further increase in asymmetry of experienced motion. This is reflected in the nonlinear flattening of the right portions of the curves in Panels A and B of Figures 6 and 7. Third, when the presentation rate is sufficiently slow that a subject can analyze the sequence of visual events during each cycle into either of two distinct patterns (e.g., left–blank–right or right–blank–left; see Figure 1), that subject can attain better than chance performance even when the apparent motion is so strong in both directions that motion asymmetry does not itself indicate direction of the phase shift. In Figure 7A, this is reflected in the fact that the curves for the longer half-cycles do not drop as low as 50% for zero absolute difference in rated left and right motions (at the left of the figure), but drop to only about 80% for half-cycles of 200 ms or more. Under these conditions, subjects may simply be registering the relative onset of the blank interval versus the onset of one of the dots and responding directly to the perceived phase relation without mediation by apparent motion.

Figure 7B provides perhaps the most striking evidence that asymmetry of apparent motion may serve as a mediator of phase discrimination in our task. The four curves plotted there lie virtually on top of each other, except for the single point plotted for a rating difference of 3 and an interdot distance of 3.6°. As we already noted, this one point, being based on relatively few trials, falls below the other points because of a single incorrect response. Otherwise, accuracy of phase discrimination appears to be completely explainable in terms of asymmetry of experienced motion.

Support for Korte's Third Law From the Absolute Motion Asymmetry Data

The objective phase discriminations appear consistent both with Korte's third law (see Figures 3B and 5B) and with the hypothesis that they were mediated by asymmetry in the experienced motion (see Figures 6 and 7). Accordingly, the absolute differences between the rated strengths of the leftward and rightward motions should also conform with Korte's third law (just as the averages of those ratings did; see Figure 2). Figure 8A plots the absolute difference between the rated strengths of leftward and rightward motion as a function of half-cycle time, again with points connected by cubic splines for purposes of interpolation. (Here, too, the nonmonotonicity of the top curve cannot be considered reliable.) After choosing four criterion levels for this measure of absolute motion asymmetry (viz., levels of 0.4, 0.5, 0.6, and 0.7), we plotted, as before, interpolated critical half-cycle values against distance for each of these four criterion levels. The resulting time–distance curves, displayed in Figure 8B, conform—as did the preceding Figures 2B, 3B, and 5B—with the linear form of Korte's third law. As in the case of the functions based on the average of the leftward and rightward ratings (Figure 2B), the functions based on the absolute difference between leftward and rightward ratings (Figure 8B) appear to converge to an intercept of about 100 ms for zero distance between the dots. Here, however, the slopes of the functions appear somewhat less dependent on the criterion level selected.

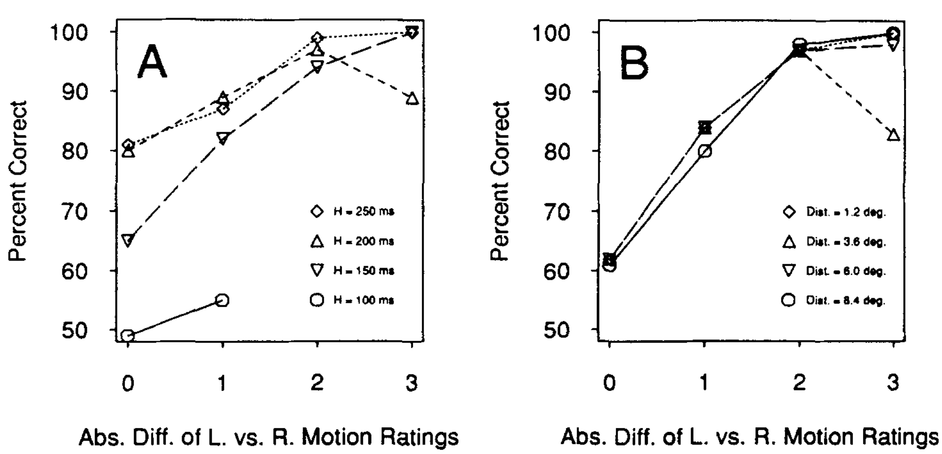


Figure 7. Accuracy in discriminating the direction of phase shift as a function of absolute difference between the rated strengths of leftward and rightward apparent motion averaged over subjects, but plotted separately for different levels of half-cycle duration (Panel A) and interdot distance (Panel B).

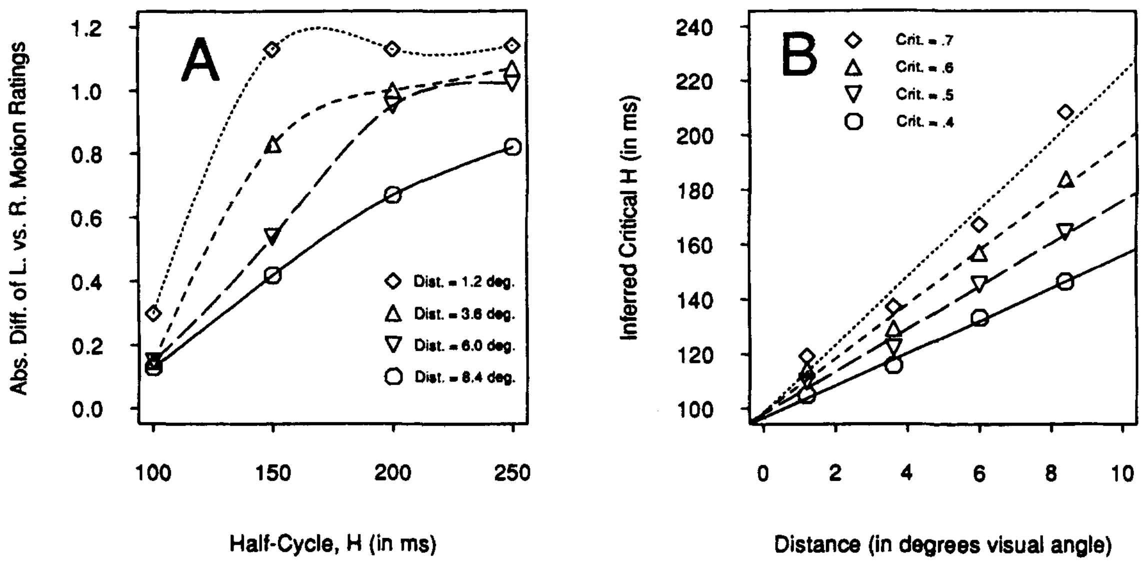


Figure 8. Panel A shows the absolute difference between the rated strengths of leftward and rightward apparent motion plotted as a function of half-cycle duration and interdot distance. Panel B shows the minimum half-cycle (interpolated from panel A) yielding a criterion level of confidence-weighted accuracy plotted as a function of interdot distance for each of four criterion levels.

Observations From Postexperimental Interviews

In the postexperimental interviews, subjects attributed the difficulty in finding a reliable phase discrimination strategy to the often variable, ambiguous, or conflicting visual appearance of our rapidly cycling visual displays. As in previous work (see Shepard, 1984), the most frequently reported visual experiences changed with the rate of presentation given a particular interdot distance. At the fastest rates, the dots typically appeared to flicker on and off independently, without any discernable motion. At such rates, no subjects were able to discriminate between the two directions of phase shift. For the slowest rates, at the other extreme, a smooth back-and-forth motion of a single dot was typically experienced, but because the SOA was sufficiently long in both directions, the motion often appeared equally strong in both directions. The direction of phase shift in this case was probably based not on any asymmetry of experienced motion but rather on an analysis of the temporal order of the now relatively slow successions of left-dot, right-dot, two-dot, and no-dot visual fields (cf. Figures 1B and 1C).

The reported character of the visual experience was most variable for the intermediate rates. For rates of presentation that successively decrease from the fastest to the slowest rates just discussed, the asymmetric motions that were most often reported typically included some subsequence of the following successive forms: (a) One of the two flickering dots exhibited some incipient or partial movement toward the other dot, while the other dot continued to flicker in place. (b) One dot seemed to jump clear across to the position of the other dot and to "stick there," with little or no return motion in the opposite direction. (This very common percept allowed the easiest and most unambiguous phase discrimination.) (c) One dot appeared to move as if carried around on a horizontal rotating disk so that it passed in one direction in front of the display screen and disappeared behind the screen on the return trip, while the other dot remained stationary. (d) One dot appeared to move back and forth smoothly while the other dot flashed on and off at one end of this excursion only. These intermediate rates were too rapid to permit direct determination of the sequence of visual fields yet slow enough to give rise to some asymmetry in the experienced motion. Because these manifestations of asymmetry were so varied, however, subjects may have had to learn to interpret each manifestation as a different cue for the direction of phase shift.

General Discussion

Summary

In our experiment, the departure from a strict alternation between a left dot and a right dot always had the same absolute magnitude of 75-ms phase shift. Yet the accuracy with which subjects discriminated between the left-leading or right-leading directions of this objective phase shift systematically varied from a chance level of 50% to nearly 100% correct, depending on the spatial distance between the dots and on the rate of cycling (or, inversely, the duration of the half-cycles—a measure that would reduce to SOA itself if there were no phase shift). The critical half-cycle durations required to attain any specified criterion level of accuracy were highly correlated with subjective ratings of the experienced strength of apparent motion, and hence in accordance with Korte's law specifying the minimum time yielding good apparent motion for each distance of separation between the dots.

We are inclined to place greater emphasis on this qualitative agreement than on any precise, quantitative correspondence between the slopes we and others have estimated for the time–distance functions. Many of the earlier experiments that investigated the time–distance relation (e.g., Corbin, 1942; Exner, 1875; Korte, 1915; Neuhaus, 1930) used stimulus displays that differed from ours in one or more of the following respects: (a) the stimuli differed from ours in brightness, size, shape, duration, or viewing distance; (b) ISI was varied rather than SOA, sometimes with stimulus durations that were constant and very brief; (c) interstimulus distance was sometimes specified in terms of degrees of visual angle and sometimes in terms of linear distance in external space; (d) one-shot presentation of the two successive stimuli was used rather than continuing alternation. Additionally, diverse types of judgments were asked for, including judgments of subjective "simultaneity" versus motion, "successiveness" versus motion, "strength," "goodness," or "completeness" of motion, and so on. Finally (and especially in more recent studies), the alternately presented visual displays have been more complex, including multiple-element arrays (e.g., Braddick, 1974; Burt & Sperling, 1981; Ramachandran & Anstis, 1983, 1985) or two- or three-dimensional objects, and often inducing apparent motion that is rotational (e.g., Farrell & Shepard, 1981; Kolers & Pomerantz, 1971; Shepard & Judd, 1976; Wertheimer, 1912/1961) or that traverses a curved path (e.g., Anstis & Ramachandran, 1986; Brown & Voth, 1937; Farrell, 1983; Foster, 1976; Hecht & Proffitt, 1991; McBeath & Shepard, 1989; Proffitt, Gilden, Kaiser, & Whelan, 1988; Shepard & Zare, 1983).

In terms of milliseconds per degree of visual angle, the slopes implied by results from these quite different studies have been as high as 15 (Corbin, 1942), 29 (Neuhaus, 1930), and 39 (Shepard & Zare, 1983). Such slopes suggest slower apparent motion than do the slopes that we have here estimated based on our own objective phase discrimination task, which ranged from about 3.7 ms/° to about 10.6 ms/°, depending on the accuracy criterion chosen for the construction of the time–distance function. As we have noted, however, our conditions are not directly comparable to those used in these earlier studies. For example, the particularly high slopes reported by Shepard and Zare (1983) are to be expected in view of the effect of competing paths in the cases of curved or rotational apparent motion (see Farrell & Shepard, 1981; Shepard & Zare, 1983). Accordingly, the most useful comparison is, instead, with the results based on the subjective judgments that subjects gave concerning the strength of apparent motion with our own visual displays. The correspondence here appears much closer. The slopes based on the subjective judgments (Figures 2B and 8B) ranged from 3.6 ms/° to 14 ms/°, which entirely overlaps the range (of 3.7 ms/° to 10.6 ms/°) that we inferred from phase discrimination with the very same visual displays (Figures 3B and 5B).

This empirical agreement between the results from the subjective and objective measures obtained with the same visual display supports our proposal that accuracy of phase discrimination might be useful as an objective indicator of apparent motion. Our proposal also gains some theoretical plausibility from the notion that judgments of phase shift are largely mediated by asymmetries between the experienced strengths of apparent motion in the two directions. We suppose that such asymmetries are direct reflections of asymmetries in neural activity patterns attributable to the differing SOAs in the two directions of the phase-shifted display.

Of course, there are some drawbacks to the indirect, discrimination-based approach to apparent motion proposed here. More subject hours and more extensive data analyses appear to be required to achieve results comparable in stability to those obtained with subjective ratings (cf. the present Figure 3B with the somewhat more orderly Figures 2B and 8B). This drawback may be reduced if we are willing to weight the objective discrimination data by subjective confidence ratings (as in Figure 5B). Even so, as the half-cycle time becomes long, two things can weaken the usefulness of discrimination performance as a measure of apparent motion: First, the subject may become able to analyze the sequence of distinct visual displays making up each cycle (e.g., left dot, no dot, right dot, both dots, etc.) and hence no longer base phase discrimination on apparent motion. Second, performance may approach the 100% correct ceiling and hence fail to yield useful data over the full range relevant to the research issue (e.g., concerning Korte's third law). Still, despite these drawbacks, an objective discrimination-based index of apparent motion avoids some of the problems of bias and demand characteristics that can affect subjective ratings.

Application of the Objective Phase Discrimination Method and Integration With Other Existing Subjective Methods

Ours is not the first attempt to establish a more objective measure of apparent motion. Burt and Sperling (1981), for example, developed a path-selection paradigm in which apparent motion might be seen along any of several paths in an ambiguous, multistimulus display. Burt and Sperling expressed dissatisfaction with previous subjective, qualitative measures of apparent motion. Yet their path-selection paradigm still required subjective ratings concerning the relative strength of motion over one specified path compared with another and hence did not yield an objective measure based on responses that could be considered right or wrong. A path-selection procedure could, however, be made to yield an objective measure by requiring subjects to make discriminations concerning the relative distance or timing between stimuli lying along different competing paths. Such discriminations, like our phase discriminations, would have an objectively correct answer and might be mediated by motion percepts, as we suggest. Where our phase discrimination task may be most suitable for investigating apparent motion in traditional two-stimuli situations, such a path-selection paradigm may be more suitable for investigating more complex, multistimulus displays.

A related alternative to simple quality-of-motion rating measures for apparent motion was explored by Ramachandran, Ginsburg, and Anstis (1983). When they presented one stimulus in a first frame and two stimuli differing from each other in the second frame, they found that apparent motion was experienced from the first stimulus to whichever of the two later stimuli was perceived as more similar to the first in certain respects. How this competition paradigm could be made into an objective discrimination task is unclear, however, in the absence of an objective specification of stimulus similarity.

Following Ivry and Cohen (1990), our phase-shift method could be integrated into the visual search task of Treisman and Gelade (1980). Subjects could be asked whether all pairs of alternating dots in a large display have the same phase relation (which they objectively would on half the trials), or whether one pair "pops out" as having a different phase relation (which it would on the other trials). Distance between dots within a pair, phase difference between dot pairs, and number of dot pairs per display could be manipulated; latency to make the correct or incorrect judgment could be measured. Because different phase relations can induce asymmetric strengths of apparent motion in one direction versus the other, the direction specificity of motion detectors and the automaticity of motion direction perception could be tested.

Preferential looking paradigms developed for testing the motion perception of human infants (e.g., Freedland & Dannemiller, 1987) typically present strictly alternating, apparent motion stimuli as targets and static stimuli as controls. Incorporating phase-shifted displays into preferential looking paradigms would not provide objective performance data of the sort presented here, but might allow a more finely graded range of stimulus conditions among those eliciting strong bidirectional apparent motion, those eliciting unidirectional motion, and those eliciting no motion. Such a method might allow investigation in infants of the existence of direction-specific motion perception and preferences for certain apparent motion directions.

Although we have focused here on the time–distance relation known as Korte's third law, the method of phase discrimination might also be used to study other lawful aspects of apparent motion and related subjective phenomena. For example, the particular features used to establish object identity in apparent motion could be investigated by changing object features across trials; higher phase discrimination accuracies might indicate stronger (asymmetric) apparent motion, hence a stronger object identity. The phase discrimination task could similarly be used with path-guided apparent motion (Shepard & Zare, 1983) to assess the relative efficacy and naturalness of different shapes and lengths of paths.

We are aware of only one other study that manipulated phase relations in apparent motion. Gilden, Bertenthal, and Othman (1990) varied the phase relations between alternating sets of stimulus dots and an alternately appearing single test dot. In a variant of the illusory occlusion phenomenon first demonstrated by Ramachandran, Inada, and Kiama (1986), the apparent motion of the test dot is entrained to the apparent motion of the other dots, such that the test dot seems to disappear beneath a nearby occluder. Gilden et al. found that subjectively rated strength of illusory occlusion decreased monotonically as phase shift increased from 0° to 162°. Their desynchronization phase shift differs from our asymmetric alternation pattern for just two stimuli, but both methods illustrate the utility of breaking the symmetry of presentation timing in studies of apparent motion.

More generally, discrimination-based methods might facilitate the extension of the study of apparent motion and the laws governing its occurrence to other perceptual continua and sensory modalities having different phenomenology but yielding the same phase discrimination performance. The objective character of the phase discrimination task also opens the possibility of its being taught (e.g., by operant conditioning) to animals of other species. This might facilitate not only the demonstration of apparent motion in nonhuman species, but also the noninvasive study of the full variety of motion perception systems that have evolved in so many different species to fill so many different adaptive functions.

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