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Dynamical vs. judgmental comparison: hysteresis effects in motion perception

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Abstract—Perceptual comparison was investigated by gradually varying the relative length of two apparent motion paths, and independently determining when an initial percept was lost during the course of attribute change and when an alternative percept emerged. Dynamical comparison was indicated by a range of attribute values for which perception was bistable. Within this range, a percept that lost stability was immediately replaced by an alternative percept. Judgmental comparison was indicated by a range of attribute values for which perception was uncertain. When an initial percept was lost, an alternative percept did not immediately emerge because the alternatives being compared could not be distinguished. Differences in the effects of random noise on dynamical vs. judgmental comparison were demonstrated with computational simulations, and implications are discussed for motion energy models and solutions to the motion correspondence problem.

Keywords: Motion; apparent motion; motion quartet; judgment; dynamics; hysteresis; comparison.

INTRODUCTION

Comparison is intrinsic to the resolution of conflicting information in virtually every perceptual and cognitive domain. When comparisons are made with respect to a varying attribute dimension, they can be continuous or discrete (e.g. Foster, 1983). That is, they can entail discrimination (x is different from y; x is greater than y), or categorization (x indicates A; y indicates B). A related way in which comparisons can differ is with respect to whether they are dynamical or judgmental, a distinction that becomes apparent when the conditions favoring one perceptual outcome are difficult to discriminate from the conditions favoring another. Dynamical comparison then results in *bistability* (one outcome or the other is clearly perceived) and judgmental comparison results in *uncertainty* (the alternatives cannot be clearly distinguished).

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The particular domain in which the current study distinguishes between dynamical and judgmental comparison entails the perception of motion. As in most perceptual domains, difficulty in discrimination can arise because of limits in perceptual resolution and/or the masking of attribute differences by random noise. A new technique is implemented to experimentally probe the difference between dynamical and judgmental comparison, and computational simulations are presented to illustrate the implications of random noise for each. The experimental technique is based on the assessment of perceptual hysteresis. This is an important paradigm for studying perceptual comparison because, outside the laboratory, perceptual operations of any kind are always carried out in the context of the immediately preceding state of the visual system. Hysteresis methods provide such a context within an experimental setting. A dynamical basis for hysteresis implies that the immediately preceding state pre-disposes the continuation of an initial perceptual decision despite changes to attribute values that favor an alternative decision. Such hysteresis occurs as a result of competitive interactions between currently stimulated detectors and detectors that will be stimulated in the immediate future (Hock *et al.*, 2003). A judgmental basis for hysteresis implies that the predisposing state is a perceptual decision that precedes an interval during which changing attribute values make comparisons uncertain. Judgmental hysteresis would occur if the perceiver reports a change from the initial percept only after attribute values have changed sufficiently for the interval of uncertainty to have passed.

Developing experimental tools for distinguishing between dynamical and judgmental comparison is important for a number of reasons. One reason is that hysteresis is considered a signature characteristic of a dynamical system (Kelso, 1995), so the case for dynamics is enhanced if it can be established that hysteresis is not instead the result of judgment under uncertainty. A second reason for the importance of the dynamical/judgmental distinction is that the effects of random noise are beneficial in one case and detrimental in the other. Finally, the dynamical/judgmental distinction is important because it is directly relevant to core theories in motion perception. The comparison of motion energy in opposing directions is inherent in Fourier-based models of motion detection (Adelson and Bergen, 1985; van Santen and Sperling, 1985; Watson and Ahumada, 1985), and Ullman's (1979) minimal mapping solution to the motion correspondence problem compares the relative length or speed of alternative motions. Are the comparisons in these models dynamical or judgmental?

GENERAL METHOD

Hysteresis was measured using a modified version of the method of limits, and two response criteria were introduced in order to distinguish between dynamical and judgmental comparison. In the standard method of limits, values of a relevant attribute are gradually increased and decreased, and switches from an initial to an alternative percept are observed. The presence of hysteresis is indicated when switches occur at different attribute values for increasing (ascending) and decreasing (descending) trials. In the modified method of limits, which was originally developed by Hock *et al.* (1993), observers do not continually respond during the course of an ascending or descending trial. Such mid-trial responses are the source of response hysteresis in the standard method of limits; i.e. the tendency to continue repeating the same response despite changes in the percept. In the modified method, each trial varies with respect to how much the value of an attribute changes (each trial has a different end-point attribute value), and the observer's response is withheld until the end of the trial. In this way, when switches occur is determined by comparing trials with different end-points. For example, if there were no switches when the end-point attribute value was X, and there were switches when the end-point value was X + 1, it could be concluded that the switches occurred when the attribute value was X + 1. In this way, it is not necessary to measure response time and then guess when a switch was perceived by estimating the time required to generate a motor response. Hysteresis is indicated when the likelihood of a switch is different, depending on whether the same end-point attribute value is reached through an ascending or descending sequence.

Whether comparison is dynamical or judgmental was determined by varying the response that was made after each trial. For some blocks of trials, observers indicated whether there was a *change* to a different percept anytime during the trial (as in Hock *et al.*, 1993, 1997; Eastman and Hock, 1999). For other blocks, they indicated whether the initial percept was *lost* anytime during the trial. Dynamical comparison would be indicated if there is no difference in the switching points for the two kinds of response. That is, when one percept is lost, it would be replaced immediately by an alternative percept. In contrast, the two kinds of response would be expected to differ if comparison is judgmental. This is because attribute values at which the judgment first becomes uncertain (when it is reported that the initial percept is lost) are reached before attribute values for which a new percept emerges (when it is reported that the percept has changed).

The stimulus in Experiment 1 was the motion quartet, which is formed by simultaneously presenting two small elements in the diagonally opposite corners of an imaginary rectangle, then simultaneously presenting the two elements in the other diagonally opposite corners, then the first pair again, and so on (Hock *et al.*, 1993; Hoeth, 1968; Kruse *et al.*, 1986; Ramachandran and Anstis, 1985; von Schiller, 1933). As illustrated in Fig. 1a, the elements are perceived to move either horizontally or vertically, though never in both directions at the same time. The motion quartet varies with respect to the relative length of the vertical and horizontal motion paths, which is characterized by its aspect ratio (the vertical divided by the horizontal path length). Small aspect ratios favor the perception of vertical motion and large aspect ratios favor the perception of horizontal motion, with either motion pattern possible for intermediate aspect ratios. Hysteresis effects were assessed by continually increasing or continually decreasing the motion quartet's aspect ratio, using the modified method of limits to determine when there were switches between

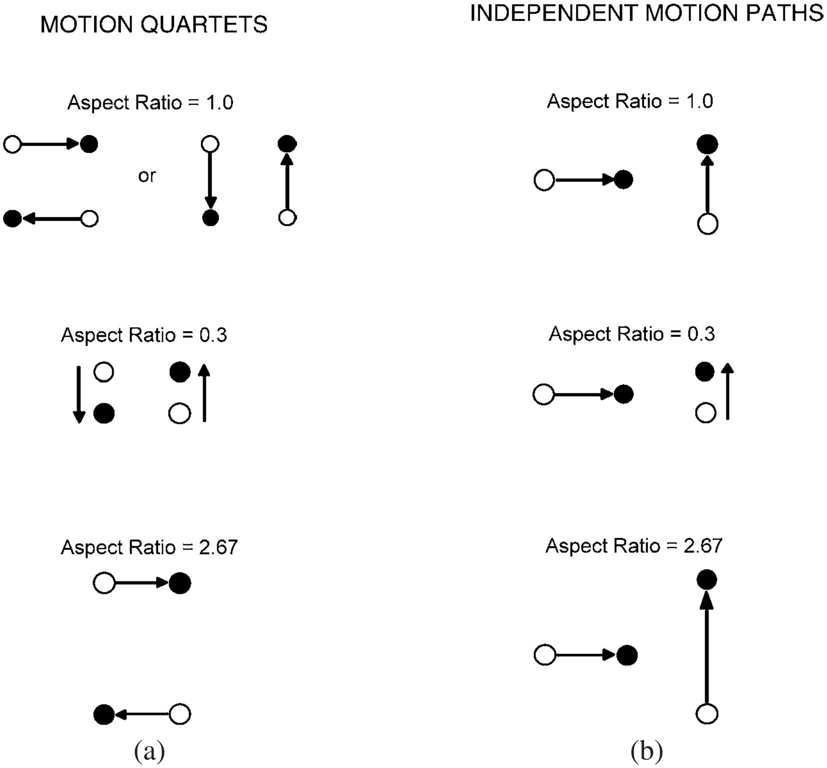

Figure 1. (a) Illustration of motion quartets in Experiment 1 and likely motion directions for a sample of aspect ratios (i.e. the vertical divided by the horizontal distance between element locations). (b) Illustration of spatially independent motion paths for stimuli in Experiment 2 with a corresponding sample of aspect ratios.

the initially formed and the alternative motion pattern (Percept Changed condition), or to determine when the initially formed pattern no longer was perceived (Percept Lost condition).

The stimulus in Experiment 2 also was composed of vertical and horizontal motion paths that differed in their relative length. In contrast with the motion quartet, for which the alternative motion paths shared common starting and ending locations, the horizontal and vertical motion paths in this experiment were spatially separate (Fig. 1b). Participants were required to compare the lengths of the two motion paths, with their aspect ratio varying as per the modified method of limits; i.e. Was the vertical path longer or shorter than the horizontal motion path at the start of the trial? Was there a point during the trial where the opposite was perceived? Hysteresis effects were assessed by continually increasing or continually decreasing the aspect ratio of the vertical and horizontal motion paths, and determining when there was a switch from one to the other of the motion paths being longer (Percept Changed condition), or when the motion path that was initially perceived as longer was no longer perceived as such (Percept Lost condition).

Dynamical comparison was anticipated for the motion quartets in Experiment 1 and judgmental comparison was anticipated for the spatially independent motion paths in Experiment 2. Dynamical and judgmental comparisons are alike in that there is a critical intermediate zone for which the attribute values specifying the alternative percepts are difficult to discriminate. This is a zone of bistability for dynamical comparison (one or the other of the motion patterns is perceived, as illustrated in Fig. 2a) versus a zone of uncertainty for judgmental comparison (the lengths of the motion paths are indistinguishable, as illustrated in Fig. 2b). In Fig. 2a, the aspect ratio is continually decreased; in Fig. 2b it is continually increased. The end-point value for a trial varies in the extent to which it reaches, penetrates, or passes through the intermediate zone where the vertical and horizontal motion paths are similar in length.

For dynamical comparison (Fig. 2a), large end-point values for trials with decreasing aspect ratio leave the initially established percept unchanged (horizontal motion is perceived), smaller end-point values bring the attribute into a range for which the initially established percept may or may not change (bistability), and still smaller end-point-values bring it into a range for which there always is a perceptual change (to vertical motion). What is crucial is that there is no region of uncertainty. When the initial percept is lost, it is immediately replaced by the alternative percept. For judgmental comparison (Fig. 2b), small end-point values for trials with increasing aspect ratio leave an initially established percept unchanged (the vertical motion path is longer), and greater end-point values bring the aspect ratio into a range for which the perceptual alternatives are difficult to distinguish. For the latter trials, the initial percept is lost and is not immediately replaced by the alternative percept. Only trials with still larger end-point aspect ratios bring the attribute into a range for which the initial percept is replaced by the alternative percept (the horizontal motion path is longer).

EXPERIMENT 1: MOTION QUARTET

Method

Stimuli. Stimuli were presented with a Power Macintosh 7300/180 computer on a Viewsonic 15GA monitor (screen luminance < 0.001 cd/m^2). The viewing distance was maintained by a head restraint at 35.8 cm. Each trial was composed of a sequence of between three and eight display cycles, with each display cycle composed of two 350 ms frames. During the first frame of each display cycle, two small squares (each 6×6 min; luminance $= 85.0$ cd/m^2) were located in the opposite corners of an imaginary rectangle, then on the second frame they were located in the other two opposite corners. The horizontal distance between element locations was fixed at 36 min while the vertical distance between element locations varied from 12 to 96 min. The aspect ratio of the motion quartet (the vertical divided by the horizontal distance between element locations) was either

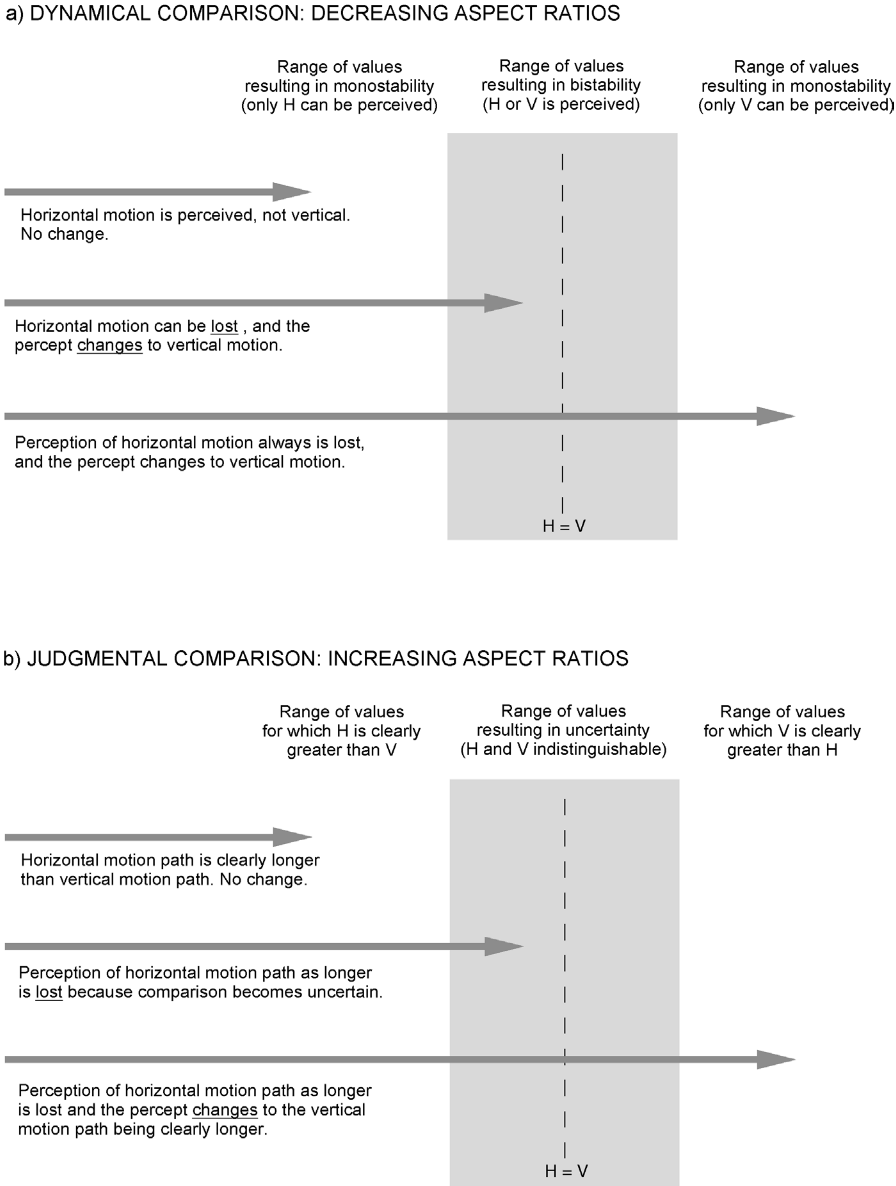

Figure 2. Diagram illustrating how dynamical and judgmental comparison differ with respect to how the end-point aspect ratio determines when an initial percept will be lost, and when an alternative percept will emerge. The key to the distinction is the presence of a zone of bistability for dynamical comparison versus a zone of uncertainty for judgmental comparison.

0.33, 0.5, 0.67, 1.0, 1.33, 1.67, 2.0, 2.33 or 2.67 deg. Ascending trials began with an aspect ratio of 0.33 for two display cycles, after which the aspect ratio increased during successive display cycles to a randomly determined end-point value (two examples: 0.33–0.33–0.5; 0.33–0.33–0.5–0.67). Descending trials began with an aspect ratio of 2.67 for two display cycles, after which the aspect ratio decreased during successive display cycles to a randomly determined end-point value (two examples: 2.67–2.67–2.33; 2.67–2.67–2.33–2.0).

Procedure. After each trial, participants indicated whether the first motion pattern they perceived was horizontal or vertical. In the Percept Changed condition, their second response indicated whether the initial percept was replaced by the alternative percept anytime during the trial. In the Percept Lost condition, their second response indicated whether they lost their initial percept anytime during the trial, irrespective of whether there was a change to the alternative percept. Participants responded by pressing designated keys on the computer keyboard.

Design. There were 16 distinctive trials, 8 ascending trials with 8 different end-point aspect ratios, and 8 descending trials with 8 different end-point aspect ratios. Each of these trials was repeated 5 times to form blocks of 80 trials (order was randomized within sub-blocks of 16 trials). Participants were tested for four blocks of trials during each of four testing sessions, two in the Percept Lost condition and two in the Percept Changed condition. The order of these blocks was counter-balanced over the four testing sessions.

Participants. The participants were two authors (LB and AH) and a Florida Atlantic University student (GH) who was naïve with respect to the purpose of the experiment.

Results

It can be seen in Fig. 3 that hysteresis was obtained in both the Percept Lost and Percept Changed conditions for all three participants. That is, the likelihood of perceiving the horizontal vs. the vertical motion pattern for intermediate end-point aspect ratios was different, depending on whether the aspect ratio was reached through an ascending or descending trial. When the initially established motion pattern was vertical (ascending trials; open circles or open squares), the vertical pattern persisted despite end-point aspect ratios being reached that favored the horizontal pattern. Conversely, when the initially established motion pattern was horizontal (descending trials; filled circles or filled squares), the horizontal pattern persisted despite end-point aspect ratios being reached that favored the vertical pattern (Note 1).

Hysteresis effects were quantified by probit analysis. For each participant, cumulative normal distributions were fit to the results for each of the eight blocks of ascending and each of the eight blocks of descending trials in order to find their 50%-thresholds. These were the end-point aspect ratios for which there was a switch from vertical to horizontal motion for half of the ascending trials, and the end-point aspect ratios for which there was a switch from horizontal to vertical motion for half

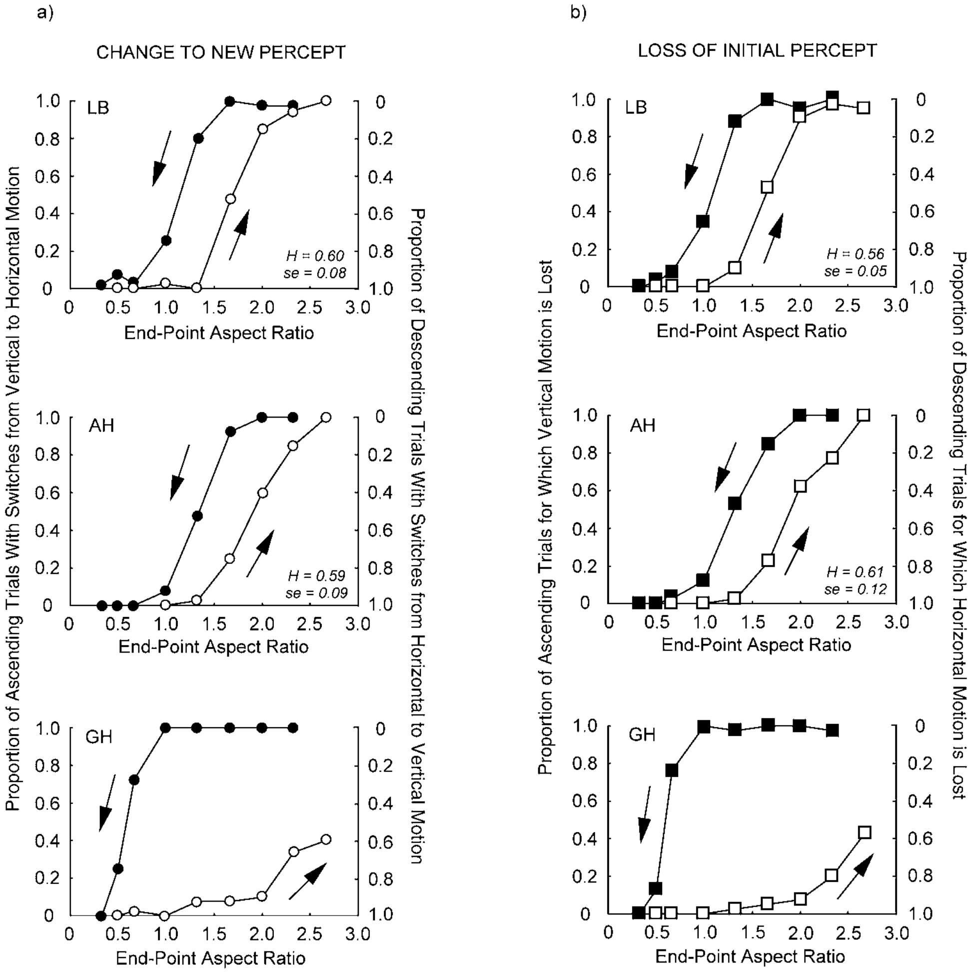

Figure 3. Experiment 1 (motion quartets): hysteresis effects based on participants indicating after each trial whether there was a change to an alternative percept sometime during the trial (a), or whether the initial percept was lost sometime during the trial (b). The axes on the left side of each graph indicate the results for ascending trials (open circles in the Percept Changed condition; open squares in the Percept Lost condition). The axes on the right side of each graph (note their inversion) indicate the results for descending trials (filled circles in the Percept Changed condition; filled squares in the Percept Lost condition). The independent variable is the end-point aspect ratio; e.g. for descending trials, the right-most data point is for a trial that begins with an aspect ratio of 2.67 and has an end-point aspect ratio of 2.33.

of the descending trials. The size of the Hysteresis effect (H) was the difference between these 50%-thresholds. Mean values of H are presented along with standard errors within each panel of Fig. 3, t-tests indicating that the mean H was significant for LB and AH in both the Percept Changed and Percept Lost conditions (the probit analysis could not be done for GH because there were too few vertical to horizontal switches for ascending trials).

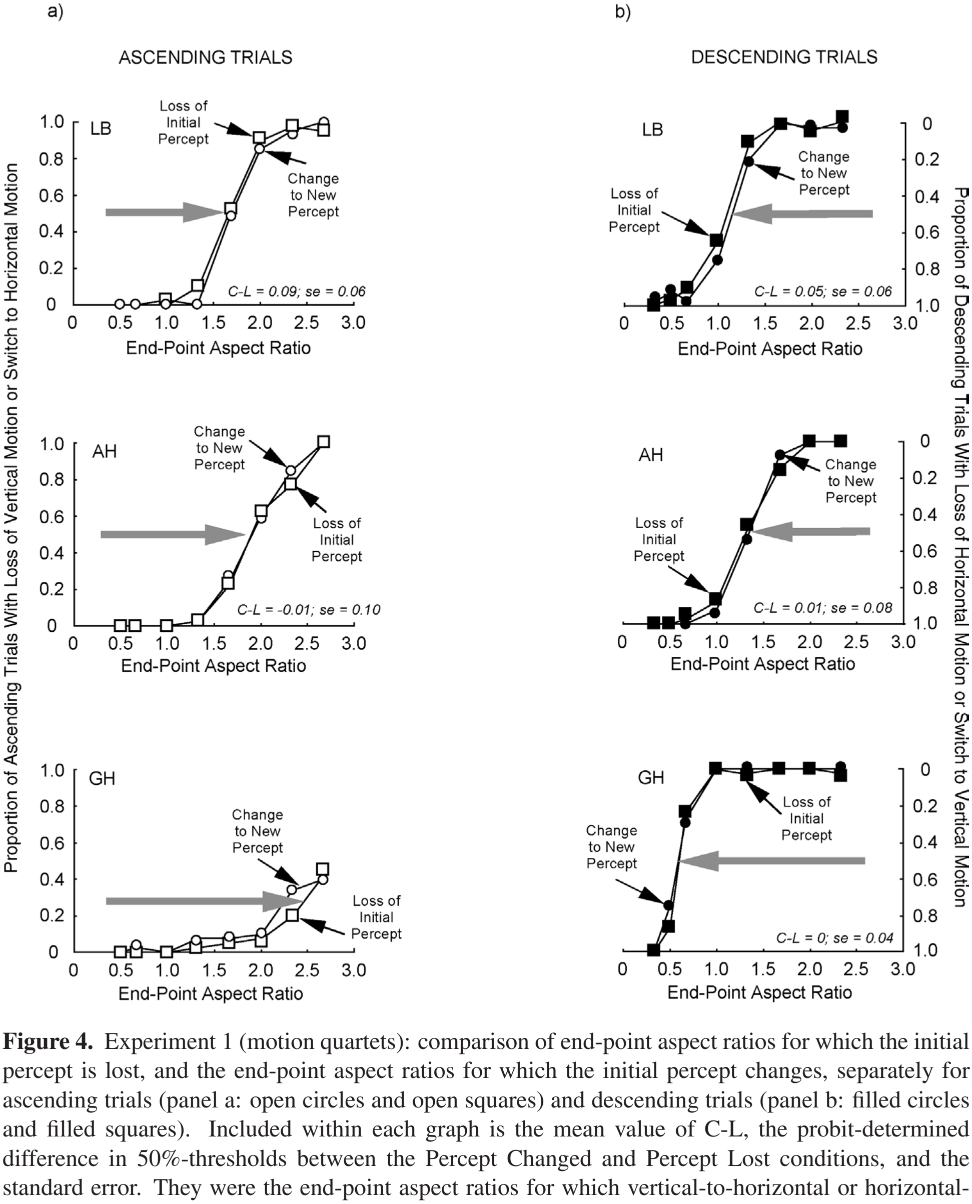

Figure 4. Experiment 1 (motion quartets): comparison of end-point aspect ratios for which the initial percept is lost, and the end-point aspect ratios for which the initial percept changes, separately for ascending trials (panel a: open circles and open squares) and descending trials (panel b: filled circles and filled squares). Included within each graph is the mean value of C-L, the probit-determined difference in 50%-thresholds between the Percept Changed and Percept Lost conditions, and the standard error. They were the end-point aspect ratios for which vertical-to-horizontal or horizontal-to-vertical switches occurred for half the trials.

The Percept Lost and Percept Changed conditions are directly compared in Fig. 4 at aspect ratios for which Loss' or 'Change' was reported for 50% of the trials (this was not possible for GH's ascending trials). It can be seen that there was no tendency for the initially established percept to be lost at an aspect ratio prior to the one in which there was a change to the alternative percept. The size of the Changed-Lost difference (C-L) was determined separately for ascending and descending trials. Mean values of C-L are presented along with standard errors within each panel of Fig. 4, t-tests (one-tailed) indicating that the mean C-L difference was not significant for LB or GH. The virtual identity of the Percept Lost and Percept Changed results for the motion quartet was consistent with comparison being dynamic. A vertical/horizontal decision always was reached, even when the alternative attribute values being compared were difficult to discriminate.

EXPERIMENT 2: INDEPENDENT MOTION PATHS

As in Experiment 1, each display cycle was composed of two 350 ms frames, and each trial was composed of a sequence of between three and eight display cycles with different end-point lengths for the vertical motion path. During successive frames, a small 6×6 min square on the left side of the display was displaced horizontally by 36 min, back-and-forth on successive frames, and an identical square on the right side of the display was displaced vertically by 12 to 96 min, also back-and-forth on successive frames. The vertical motion path was 36 min to the right of the horizontal motion path, and the aspect ratio of the two motions again was either 0.33, 0.5, 0.67, 1.0, 1.33, 1.67, 2.0, 2.33 or 2.67 deg.

After each trial, participants indicated whether the horizontal or vertical motion path was longer at the start of the trial. In the Percept Changed condition, their second response indicated whether their initial percept was replaced by the alternative percept later in the trial. For example, if the horizontal path was initially perceived as longer, a percept change would be indicated if the vertical path was perceived as longer later in the trial. In the Percept Lost condition, participants' second response indicated whether the perceptual difference at the start of the trial was lost later in the trial, irrespective of whether or not there was a change to the alternative percept. In addition to the participants, all aspects of the experimental design, including the construction of ascending and descending trials, were as in Experiment 1.

Results

It can be seen in Fig. 5 that hysteresis was obtained for two of the three participants in the Percept Changed condition, and more significantly, for all participants there was less hysteresis (and even the reversal of hysteresis) in the Percept Lost condition. Values of H, the probit-determined difference between ascending and descending trials, are presented along with standard errors within each panel of Fig. 5. In the Percept Changed condition. t-tests indicated that H was significantly greater than zero for LB and AH, but the difference from zero was not significant for GH. In the Percept Lost condition, H was significantly greater than zero for LB, not significantly different than zero for AH, and significantly less than zero for GH.

As for Experiment 1, the Percept Lost and Percept Changed conditions are directly compared in Fig. 6 at aspect ratios for which Percept Lost and Percept Changed were reported for 50% of the trials. It can be seen for all three participants that the

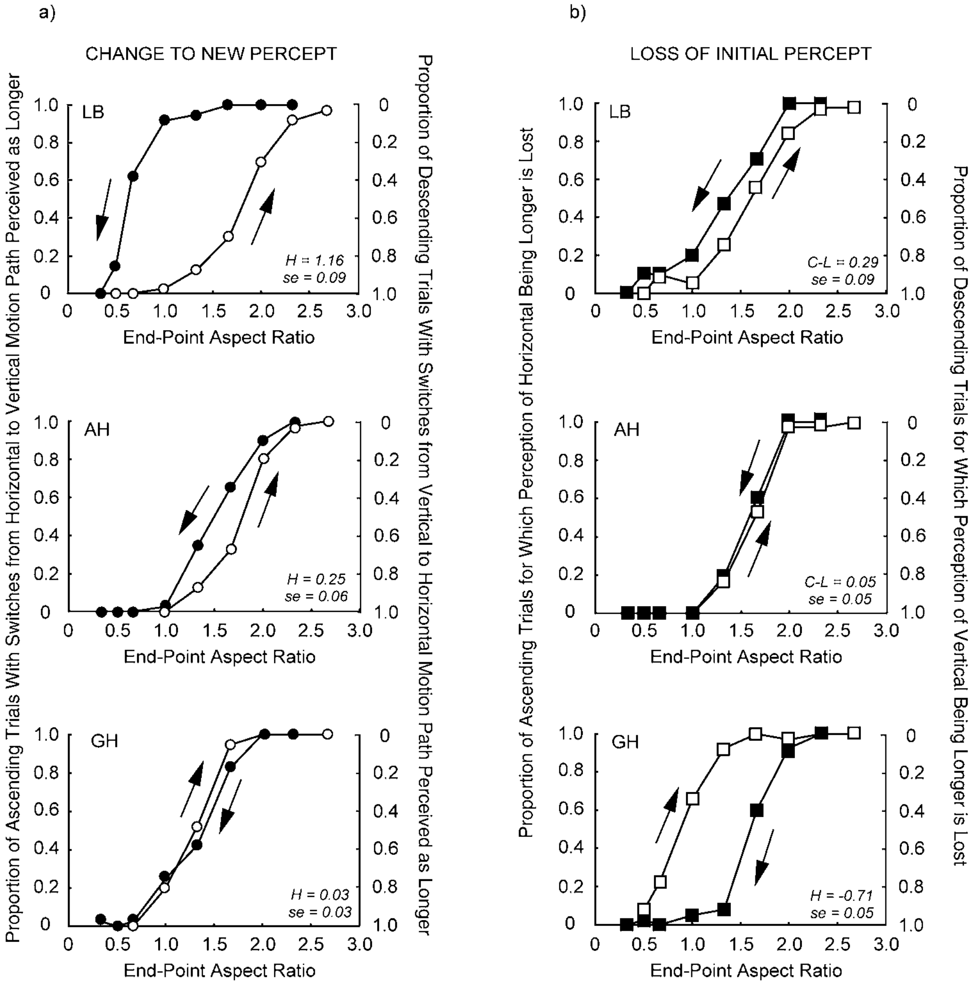

Figure 5. Experiment 2 (independent motion paths): hysteresis effects based on participants indicating after each trial whether there was a change to an alternative percept sometime during the trial (a), or whether the initial percept was lost sometime during the trial (b). The axes on the left side of each graph indicate the results for ascending trials (open circles in the Percept Changed condition; open squares in the Percept Lost condition). The axes on the right side of each graph (note their inversion) indicate the results for descending trials (filled circles in the Percept Changed condition; filled squares in the Percept Lost condition). The independent variable is the end-point aspect ratio; e.g. for descending trials, the right-most data point is for a trial that begins with an aspect ratio of 2.67 and has an end-point aspect ratio of 2.33.

initially established percept was lost at an aspect ratio prior to the one in which there was a change to the alternative percept (though the effect was very small for AH's descending trials). Mean values of C-L, the difference in 50%-thresholds based on probit analyses for the Percept Lost and Percept Changed conditions, are presented along with standard errors within each panel of Fig. 6. The mean C-L difference was

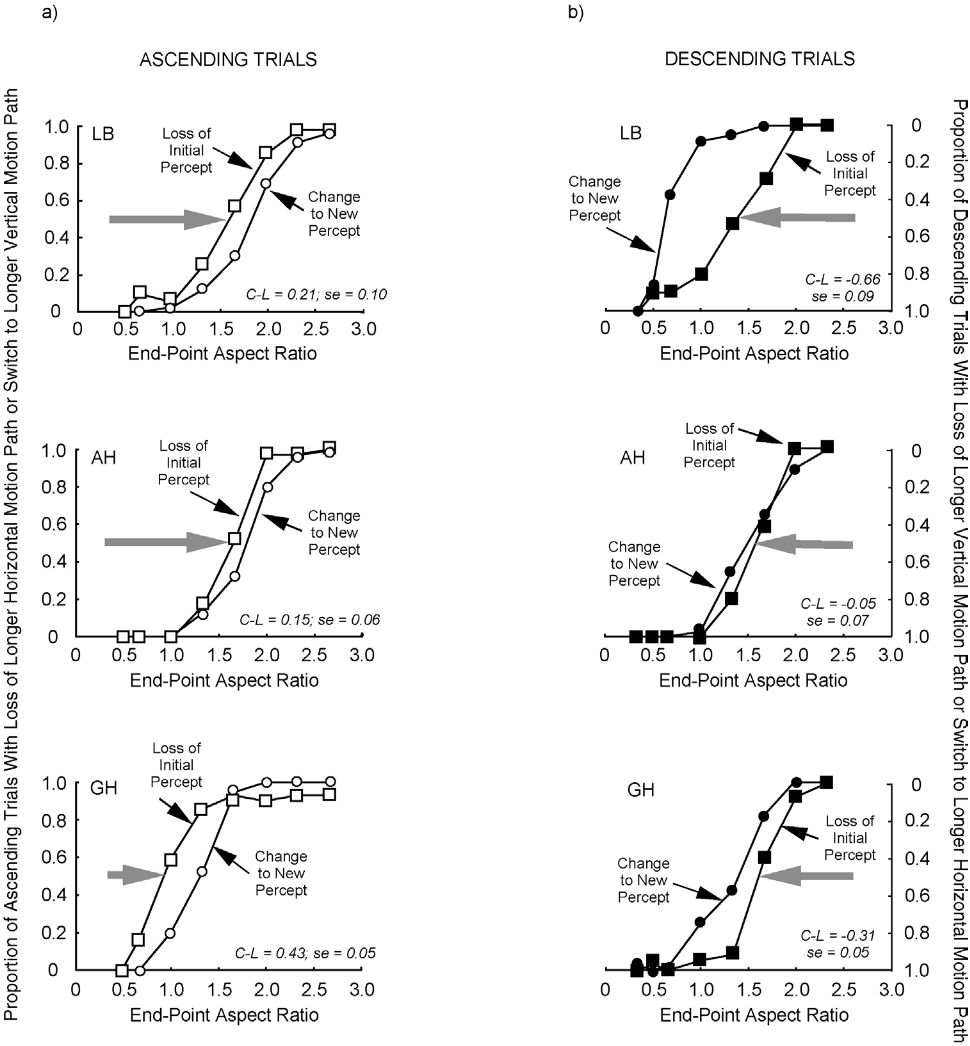

Figure 6. Experiment 2 (independent motion paths): comparison of end-point aspect ratios for which the initial percept is lost, and the end-point aspect ratios for which the initial percept changes, separately for ascending trials (panel a: open circles and open squares) and descending trials (panel b: filled circles and filled squares). Included within each graph is the mean value of C-L, the probit-determined difference in 50%-thresholds between the Percept Changed and Percept Lost conditions, and the standard error. They were the end-point aspect ratios for which vertical-to-horizontal or horizontal-to-vertical switches occurred for half the trials.

statistically significant (one-tailed *t*-test) in all cases except AH's descending trials. The results were consistent with both ascending and descending trials encountering a range of aspect ratios for which it could not be determined which of the two motion paths was longer. This absence of vertical/horizontal decision was consistent with judgmental comparison under conditions in which the alternatives being compared were difficult to discriminate.

COMPUTATIONAL SIMULATIONS: THE EFFECTS OF NOISE

The experiments described above distinguish between dynamical and judgmental comparison. An important implication of this distinction entails the influence of noise on the comparison process. When the alternatives being compared are similar, noise is likely to be detrimental to judgmental comparison; small differences in attribute values are increasingly difficult to discriminate in the presence of increasing levels of noise (Green and Swets, 1966). It is demonstrated in the simulations of Fig. 7 that this is the case even if a temporal integrator smoothes the effects of noise. The integrator used for the simulations is illustrated in Fig. 7a.

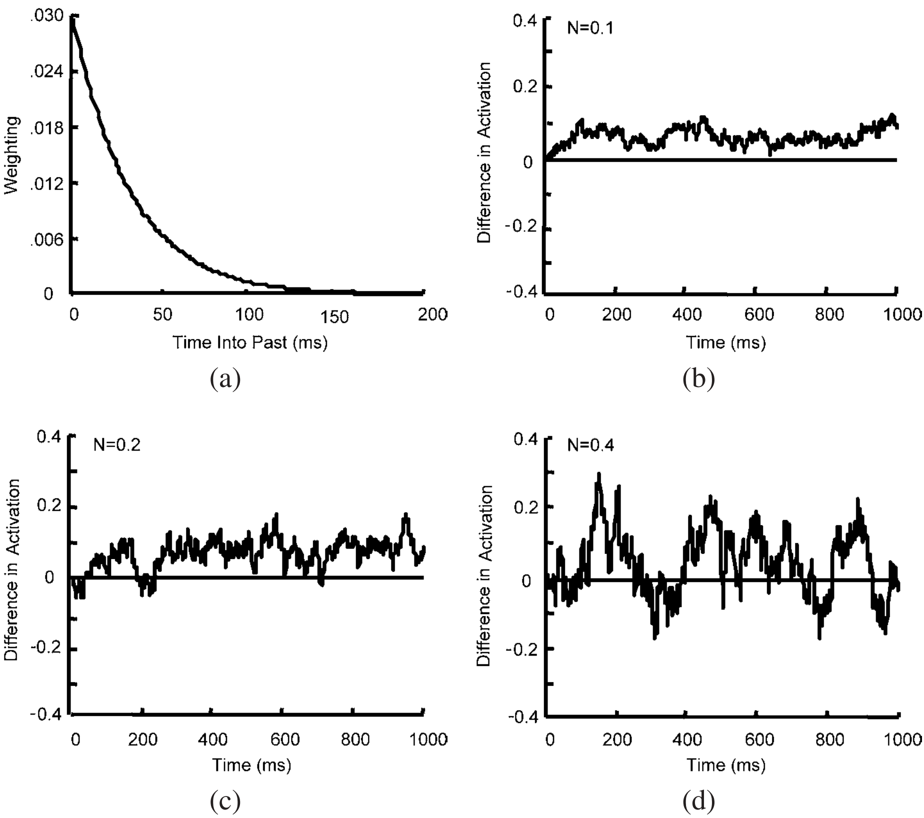

Figure 7. Implications of noise for judgmental comparison. (a) Current activation levels are temporally integrated with activation levels over a span of 200 ms, the contribution of preceding activation levels decreasing exponentially with how far back the integration reaches in time. (b, c, d) Computational simulations demonstrating how increased levels of noise (N) are harmful to judgmental comparison, despite the inclusion of a temporal integrator to smooth out the effects of noise.

It integrates the current activation levels of two detectors with activation levels that preceded it by up to 200 ms. The contribution of preceding activation levels decreased exponentially, depending on how far back in time they were relative to the current point in time (the coefficient of the exponential was −0.03). With this temporal integration, a difference in stimulus activation of 0.05 is consistently discriminated with a noise level of 0.1 (Fig. 7b), but the decision becomes increasingly muddled with increasing noise levels (Figs 7c, 7d).

In contrast, noise can be beneficial for dynamical comparison, particularly when equivalent attribute values are being compared. This is demonstrated in Fig. 8 by simulations based on a pair of detectors that mutually inhibit each other's activation. It can be seen in Fig. 8a that in the absence of noise, inhibitory competition is not sufficient to distinguish between equally activated alternatives; both can be equally above the threshold level required for perception (set at 0 for the simulations). However, even miniscule levels of noise can break this symmetry, resulting in a dynamical decision in which one alternative prevails (it is above threshold) and the other does not (it is below threshold), though with a preceding interval during which both alternatives are above threshold (Fig. 8b). Further increases in noise level can reduce the time interval during which both alternatives are above threshold, increasing the speed of the dynamical decision (Fig. 8c). Finally, still higher levels of noise can increase the speed of the dynamical decision to the point where only one of the alternatives rises above the threshold level required for perception (Fig. 8d).

DISCUSSION

Experiment 1 provided a clear case in which comparison is dynamical. Virtually identical results in the Percept Changed and Percept Lost conditions were consistent with an intermediate range of attribute values for which perception was bistable. When a percept was lost, it was immediately replaced by an alternative percept. The hysteresis that results from dynamical comparison for the motion quartet reflects a pre-disposition to continue with a previous perceptual decision because of the inhibitory influence of currently stimulated detectors on the detectors that will be stimulated in the immediate future (Hock *et al.*, 2003).

The significant difference between the Percept Changed and Percept Lost conditions in Experiment 2 was consistent with the presence of an intermediate range of attribute values for which the comparison of attribute values was uncertain. The hysteresis that results from this kind of judgmental comparison reflects a pre-disposition to continue with a previous perceptual decision because attribute values were encountered for which the perceptual alternatives were indistinguishable. However, other interpretations for the results of Experiment 2 cannot be ruled out. One possibility is that there was a third stable state for which the horizontal and vertical path lengths were perceptually equal. That is, there was dynamical competition among three perceptual alternatives. Another possibility is that dynamical competition can occur at the decision as well as the detector level. That is, judgmental

Dynamical Equations for the Simulations

$$\tau \mathrm{du_1/dt} = -\mathrm{u_1} + \mathrm{h} + \mathrm{S_1} - \mathrm{w}\sigma(\mathrm{u_2}) + \mathrm{N}\xi(\mathrm{t})$$
$$\tau \mathrm{du_2/dt} = -\mathrm{u_2} + \mathrm{h} + \mathrm{S_2} - \mathrm{w}\sigma(\mathrm{u_1}) + \mathrm{N}\xi(\mathrm{t})$$

σ represents the nonlinear, sigmoidal interaction:

$$\sigma(\mathrm{u}) = (1 + \exp^{-2(\mathrm{u}+2)})^{-1}$$

$\tau = 20$ ms is the time scale over which activation changes.
$\mathrm{h} = -2$ is the no-stimulus, resting level.
$\mathrm{S_1} = \mathrm{S_2} = 7$ is the activation effect of the stimulus.
$\mathrm{w} = 9$ is the coupling strength of the interaction.
$\xi(\mathrm{t})$ = Gaussian white noise with mean of zero and a standard deviation of 1.
N = Noise strength, which varies for each of the simulations.
(It modifies the standard deviation of the Gaussian noise).

(a)

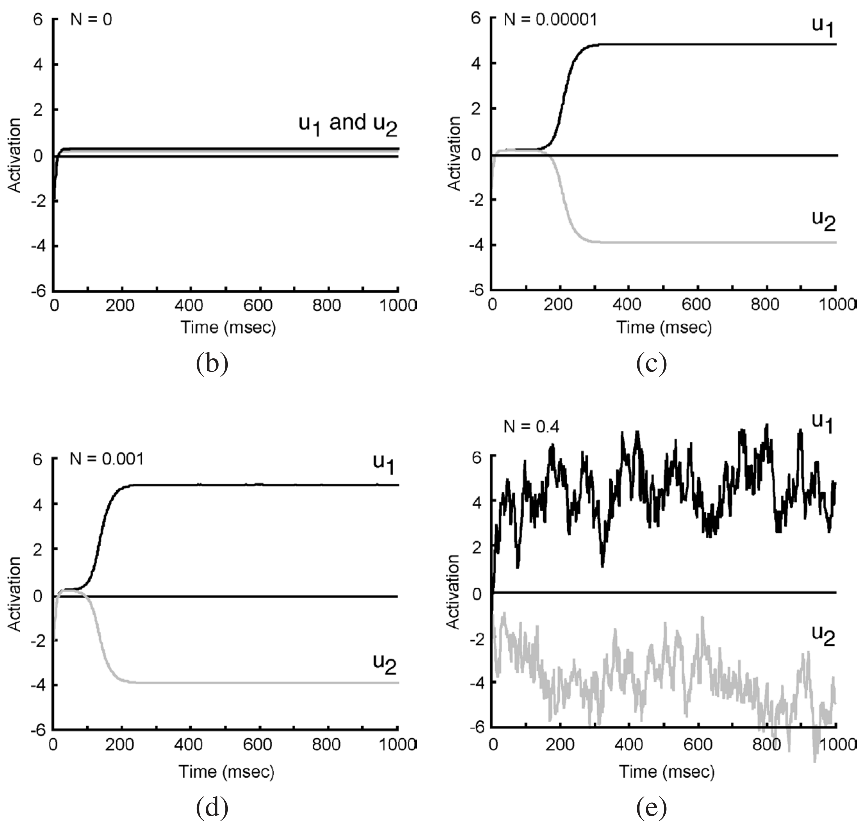

Figure 8. Implications of noise for dynamical comparison. (a) The dynamical equations and parameter values used in the computational simulations. (b, c, d, e) Simulations demonstrating how increased levels of noise benefit dynamical comparison. Although the activation variables u_1 and u_2 prevail equally often in the simulations, only those simulations for which u_1 predominates are presented in the figure.

comparison in Experiment 2 might have entailed inhibitory competition between alternative decisions (Busemeyer and Townsend, 1993; Usher and McLelland, 2001) rather than the simple determination of whether the horizontal or vertical motion path was longer.

We conclude, therefore, that our experimental technique of using the modified method of limits together with percept-changed/percept-lost response criteria can provide strong supportive evidence for dynamical comparison (as in Experiment 1), and can also indicate when comparison might not be dynamical (as in Experiment 2). It should be noted that distinguishing between dynamical and judgmental comparison in this way remains valid even if adaptation were to nullify hysteresis effects resulting from dynamical comparison (Hock *et al.*, 1993; Gephstein and Kubovy, in press), and even if a liberal response criterion were to eliminate percept-changed hysteresis effects for judgmental comparison (as for subject GH in Experiment 2).

To date, there have been numerous reports of hysteresis effects in perception. In addition to motion quartets (Hock *et al.*, 1993; Ramachandran and Anstis, 1985), they include hysteresis for a reversible figure (Fisher, 1967), binocular fusion (Fender and Julesz, 1967), coherent motion of random cinematograms (Williams *et al.,* 1986), single element apparent motion (Hock *et al.*, 1997), motion vs. position perception (Eastman and Hock, 1999), and speech perception (Tuller *et al.*, 1994). The results of Experiment 2 indicate that hysteresis in at least some of these studies might have been the result of a conservative judgment strategy in which participants, faced with a range of attribute values for which comparison is uncertain, withhold reporting change to an alternative state until values are reached for which their decision is certain. Hysteresis may not always be a defining signature of a dynamical system in perception, and perhaps not in other domains as well.

Computational simulations following the two experiments reported in this article indicate that the dynamical/judgmental distinction has another important dimension. That is, in contrast to judgmental comparison, noise benefits dynamical comparison by speeding decisions and preventing the activation for one of the alternatives being compared from rising above the threshold level required for perception. It is significant, given its importance for dynamical comparison, that noise is not included in Fourier-based models of motion detection (Adelson and Bergen, 1985; van Santen and Sperling, 1985; Watson and Ahumada, 1985). As discussed earlier in this article, whether motion is perceived in a particular direction is determined in these models by comparing the motion energy in that direction with the motion energy in the opposite direction. The assumption that motion will not be perceived when there is equal motion energy in opposite directions has led to the expectation of perceptual stationarity for counterphase gratings (Adelson and Bergen, 1985), which simultaneously and equally stimulate motion detectors with opposing directional selectivity (Levinson and Sekuler, 1975). The fact that stationarity usually is not perceived for this stimulus (Gorea and Lorenceau, 1984; Kelly, 1966; Kulikowski, 1971; Levinson and Sekuler, 1975) suggests that the dynamical comparison of motion signals in opposite directions, together with symmetry-breaking random noise, will provide a more complete account for the perception of motion (and nonmotion) for counterphase gratings (Nichols and Hock, 2002).

Random noise also is absent from Ullman's (1979) minimal mapping solution to the motion correspondence problem, which is based on the comparison of the relative length or speed of alternative motion paths. (Alternatively, Gilroy, Hock and Ploeger (2001) have argued that the comparison is based on the relative activation of the detectors responding to the alternative motions.) The absence of noise implies that splitting and fusion would occur for the motion quartet when motion strength is equated on the basis of the relative lengths of the horizontal and vertical motion paths. The fact that this is never observed again points to a dynamical account with symmetry-breaking noise, an account that has been provided in detail by Hock *et al*. (2003).

In conclusion, hysteresis is an important setting for investigating perceptual comparison because it entails the comparison of changing stimulus values within the context of the immediately preceding state of the visual system. Our results demonstrate that the experimental distinction between dynamical and judgmental comparison is central to the interpretation of hysteresis effects: Are they due to competitive interactions or conservative response criteria? Additionally, differences between dynamical and judgmental comparison bring to light different ways in which the visual system responds to random noise. Dynamical decisions can benefit from noise, whereas judgmental decisions must be reached despite the presence of noise. It would not surprise us if further investigations based on the dynamical/judgmental distinction indicate that implicit decisions (decisions embedded in relatively low-level mechanisms) are usually dynamical, being reached immediately over a range of stimulus values for which perception is bistable. In contrast, we anticipate that explicit decisions (decisions based on conscious choices) will usually prove to be judgmental, and thus strongly shaped by stimulus conditions in which discrimination is uncertain. Finally, the distinction between dynamical and judgmental comparison is at least partially related to Foster's (1983) distinction between discrete/categorical and continuous/fine-grained processes. The comparison of motion path lengths is implicit for the motion quartets of Experiment 1. Stimulated motion detectors are differentially activated by motion over different path lengths (Gilroy *et al*., 2001), and categorically different percepts emerge from dynamical, *nonlinear* interactions among the stimulated detectors (Hock *et al*., 2003). In contrast, the comparison of path length for the independent motion paths of Experiment 2 is explicit, judgments depending on an essentially *linear* process for which fine-grained discriminations result in uncertainty rather than bistability.

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NOTE

1. Hock *et al.* (1993) obtained similar hysteresis effects when they controlled for the difference in total duration for trials with different end-point aspect ratios.

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