Journal of Experimental Psychology:
Human Perception and Performance
1993, Vol. 19, No. 1, 63-80

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0096-1523/93/$3.00

Bistability and Hysteresis in the Organization of Apparent Motion Patterns

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In a paradigm for which 2 distinct patterns are perceived for the same stimulus, perceptual hysteresis (persistence of a percept despite parameter change to values favoring the alternative pattern) and temporal stability (persistence despite intrinsic propensities toward spontaneous change) are interdependent. Greater persistence during parameter change reduces temporal stability, slowing the rate of parameter change reduces hysteresis by increasing opportunity for spontaneous change, and increasing temporal stability (by enlarging the stimulus) increases hysteresis. Hysteresis results in the perception of parametrically disfavored patterns; a parameter can influence a percept without specifying it. The visual system thus exhibits time-dependent behavior analogous to dynamical behavior observed in other systems, both physical and biological, for which there is competition among alternative patterns that vary in relative stability.

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In this article we introduce a new methodology for studying perceptual hysteresis and report experimental results that demonstrate the interdependence of perceptual hysteresis and spontaneous perceptual reorganization. These results point to the importance of perceptual stability in describing the behavior of the visual system. In addition, this methodology provides a means for demonstrating that spatial geometry can have a nonspecifying influence on the organization of motion patterns by providing a context that affects the operation of visual mechanisms without defining the perceptual pattern produced by those mechanisms.

Perceptual stability is generally studied under conditions of multistability, that is, when more than one perceptual organization can be imposed on a stimulus (Attneave, 1971). It refers to the continued perception of a pattern despite the occurrence of intrinsic and extrinsic events that might result in the perception of an alternative pattern. A sufficiently stable percept can persist for an extended period of time, but eventually events arising within the visual system can be of sufficient magnitude for the stability to be lost, which produces a spontaneous reorganization in which the alternative pattern is perceived. Such reorganizations have been variously attributed to the intrinsic flexibility of organizational mechanisms, a kind of perceptual intelligence (Köhler, 1930/1971), neural satiation (Köhler & Wallach, 1944), stochastic influences (DeMarco et al., 1977; Taylor & Aldridge, 1974), and awareness of an alternative to the initial percept (Girgus, Rock, & Egatz, 1977). Regardless of the cause, the likelihood of a percept spontaneously changing can be characterized in terms of its temporal stability (low temporal stability implies a brief interval until there is a spontaneous change in organization).

A stable percept can persist despite changes in extrinsic stimulus parameters. This can be observed as both perceptual constancy and hysteresis. In experiments that demonstrate hysteresis, values of a critical parameter are gradually increased and decreased.[1] For example, Fender and Julesz (1967) gradually increased and decreased retinal disparity in studying the fusion of random stereograms. In studying the perception of coherent motion in random cinematograms, Williams, Phillips, and Sekuler (1986) gradually increased and decreased the proportion of dots whose direction of motion was selected (randomly) from a restricted range of possible directions. An initial percept is established at either extreme of these parameters, and gradual changes in the parameter's values eventually result in a change to the alternative percept. The general finding is that the initial percept persists even though the current value of the parameter might favor the alternative percept.

Hysteresis and multistability are essential temporal properties of percepts. Hysteresis carries the recent history of the percept into the present, and multistability reflects its immediately available future states. Nonetheless, perceptual hysteresis effects have been studied only minimally, and in particular there are no experimental studies that demonstrate the relationship between hysteresis, which reflects the persistence of percepts despite changes in extrinsic parameters, and temporal stability, which reflects the persistence of percepts despite propensities toward spontaneous change arising within the visual system (so perceptual reorganization occurs even when parameter values remain constant). This

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This research was supported in part by National Institutes of Mental Health (Neurosciences Research Branch) Grant MH 42900-01, Biomedical Research Support Grant RR 07258, and U.S. Office of Naval Research Contract N00014-88-J-1191.

We thank thank Stacey Pallo for suggesting Experiment 3, and Betty Tuller, Lewis Shapiro, Sao Luis Castro, Gunther Balz, and Shaul Hochstein for their careful reading of an earlier version of this article.

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[1] Psychophysicists have long been aware that their results depend on the direction of parameter change, but their concerns are more practical than theoretical. Thus, they recognize the potential "artifacts" inherent in the method of limits, for which parameter values are presented in sequential order, and avoid these problems through the method of constant stimuli, for which parameter values are presented in random order (e.g., Coren & Ward, 1989).

relationship is important because the two phenomena, though potentially separable, are functionally interdependent influences on the stability of perceptual patterns. That is, although it is logically possible for hysteresis to be observed under conditions in which there is very high temporal stability (no spontaneous change) and vice versa, we show in this article that hysteresis modifies the likelihood of spontaneous perceptual change, and we further show that the occurrence of spontaneous changes in organization modifies the magnitude of the hysteresis.

The initial objective of this study is therefore to establish the interdependence of hysteresis and temporal stability and to do so in the context of a paradigm that minimizes some of the experimental limitations and interpretive problems associated with earlier studies of perceptual hysteresis. One requirement is the systematic variation of stimulus parameters. Fisher (1967) reported hysteresis for a series of man–woman reversible figures, but it is difficult to assess the effect of gradually changing the value of a parameter for this example because different aspects of the figures change haphazardly from one figure to the next. Another, more difficult problem concerns the distinction between perceptual hysteresis and hysteresis in the subject's response; subjects continually responding to gradual changes in a parameter may persevere in their response even after their percept has changed. To limit this problem, Fender and Julesz (1967) and Williams et al. (1986) changed the values of their manipulated parameters very slowly. This solution, however, is too restrictive. It does not allow one to test the effect of rate of parametric change on perceptual hysteresis (as we do in Experiment 6) because rate of change also influences susceptibility to hysteresis in responding. Still another problem is decision uncertainty. Are hysteresis effects truly perceptual, or do subjects persist in an earlier decision while the varying parameter passes through values for which subjects are uncertain about what they are seeing? It is possible that the hysteresis effects obtained by Fender and Julesz (1967) and Williams et al. (1986) involve decisional as well as perceptual components.

Our second objective is to demonstrate that experimental paradigms assessing perceptual stability can provide evidence for a nonspecific perceptual influence of stimulus information. The specifying function of the stimulus has been articulated through ecological (Gibson, 1966, 1979) and computational (Marr, 1982) perspectives. We provide evidence that visual information can influence perception by providing a nonspecifying context that shapes the operation of intrinsic visual mechanisms without defining their final product. Nonspecifying stimulus information might favor one percept in relation to another, but the information in the stimulus is not sufficient to account for what is perceived. We show that when hysteresis is observed under conditions of high temporal stability, patterns are perceived that are not specified by the stimulus.

To provide evidence for a nonspecific influence of a manipulated parameter, it is necessary to know that subjects' responses are not based on the detection of the parameter alone. For example, in the Williams et al. (1986) study of hysteresis, the manipulated parameter was the proportion of dots whose direction of motion was selected from a restricted range of possible directions; when subjects reported that they perceived coherent motion, it was in the direction of the mean of this restricted range of directions. Subjects' reports of coherent global motion in this experiment might indeed have been due to a nonspecific influence of the manipulated parameter on intrinsic organizational processes; Williams et al. proposed intrinsic mechanisms involving nonlinear excitatory and inhibitory interactions among units that detect motion. If, however, their subjects were reporting nothing more than the detection of the strongest directional component in the display (Williams et al.'s parametric manipulation varies the prominence of this component), the influence of the manipulated parameter would have been specific rather than nonspecific. To demonstrate the nonspecific influence of the manipulated stimulus parameter in our experiments, we use a paradigm for which parameter values are not perceptually confusable with the motion patterns observed as values of the parameter are changed.

We study hysteresis, bistability, and spontaneous changes in perceptual organization through the use of a classical paradigm in which points of light are presented in corners of an imaginary rectangle, and apparent motion is seen in vertical or horizontal directions (Hoeth, 1968; Kruse, Stadler, & Wehner, 1986; Ramachandran & Anstis, 1985; von Schiller, 1933). Two point lights are presented at a time, one pair from two of the diagonally opposite corners of the rectangle and then after a brief delay a second pair from the other two diagonally opposite corners of the rectangle (following Anstis & Ramachandran, 1987, we refer to these stimuli as *quartets*, or *motion quartets*). Although the simultaneous perception of horizontal and vertical motion is a logical possibility for these stimuli, only one or the other motion direction is perceived. That is, parallel motions are seen either in opposite vertical or opposite horizontal directions (see Figure 1). The exclusivity of vertical and hori-

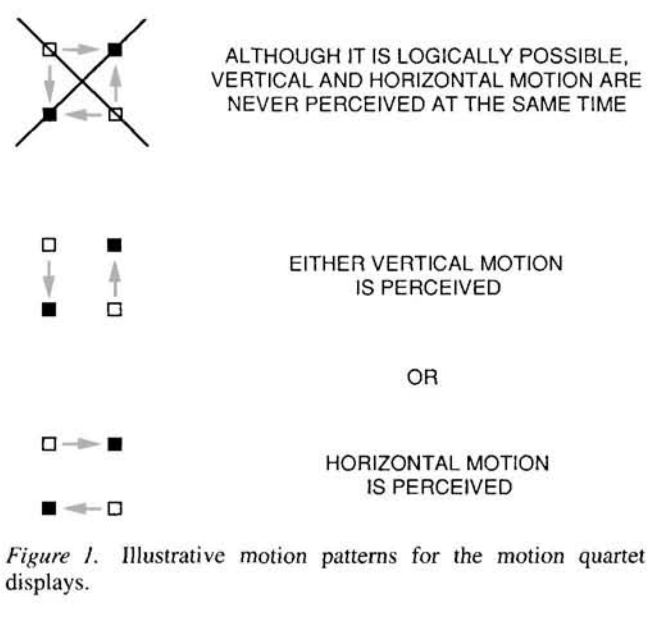

Figure 1. Illustrative motion patterns for the motion quartet displays.

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zontal motion implies that the two directional axes are mutually inhibitory for motion quartets.

The parameter that varies in our experiments is the aspect ratio of the rectangular configuration of point lights. The aspect ratio is determined by dividing the vertical separation by the horizontal separation between the locations of the point lights (the horizontal separation remains constant throughout; we vary the aspect ratio by varying the vertical separation). When the vertical separation is small in relation to the horizontal separation, the perception of vertical motion is favored. When the vertical separation is large in relation to the horizontal separation, the perception of horizontal motion is favored. However, hysteresis observed under conditions of high temporal stability shows that this influence of stimulus geometry is easily altered. This forms the basis for our conclusions with regard to the nonspecific influence of stimulus geometry on the perceived motion patterns.

We report the results of two sets of experiments. The first four experiments (a) establish values of the parameter for which the motion quartets are bistable and provide evidence that the likelihood of spontaneous change (i.e., temporal stability) varies as a function of the manipulated parameter; (b) demonstrate that strong perceptual hysteresis effects can be obtained when stimulus change is unidimensional, and decisional and response-perseveration effects are minimized as experimental factors; (c) indicate that the obtained hysteresis is not the result of differences in trial duration; and (d) show that hysteresis is not the inevitable result of gradual parametric change. The last three experiments examine the interdependence of hysteresis and temporal stability. In Experiment 5, we show that when a percept persists even though the parameter changes to values that favor the alternative percept, the temporal stability of the percept decreases (i.e., the likelihood that the percept will undergo a spontaneous change increases). In Experiment 6, we provide evidence that the magnitude of the hysteresis is reduced when slowing the rate of parameter change allows more opportunity for the occurrence of spontaneous change, and in Experiment 7 we show that increases in temporal stability are correlated with increases in the magnitude of hysteresis.

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Experiments 1A and 1B

Randomly Ordered Presentations

Bistability in the perceptual organization of apparent motion (seeing two different motion patterns for the same stimulus) has been reported in many paradigms (e.g., Gerbino, 1981; Gorea & Lorenceau, 1984; Mather, Cavanagh, & Anstis, 1985; Pantle & Picciano, 1976) other than the motion quartets studied in this article. The purpose of this pair of experiments was to determine the range of parameter values, the aspect ratios of the configuration of point lights, for which motion quartets are bistable. The sequence of parameter values was random to provide a basis for determining (in subsequent experiments) whether the sequential change of parameter values extended the range of bistability. For each value of the parameter, we derived a measure of bistability (the relative likelihood of each motion pattern) and showed that this measure is related to the frequency of spontaneous perceptual change from one motion pattern to the other.

Method

The stimuli were point lights presented on a Macintosh II RGB monitor and viewed from a distance of 80 cm (maintained by a head restraint). Each point light corresponded to 1 pixel (visual angle 1.6 min). As indicated previously, points of light were presented at the four corners of an imaginary rectangle, one pair for two of the diagonally opposite corners of the rectangle and then after a brief delay a second pair for the other two diagonally opposite corners. Each display cycle comprised the following four-frame sequence: point lights for the left-diagonal corners of the imaginary rectangle for 195 ms; blank screen for 45 ms; point lights for the right-diagonal corners of the imaginary rectangle for 195 ms; blank screen for 45 ms.

The horizontal separation of the point lights was always 4 pixels (visual angle 6.4 min) in this and all subsequent experiments (other than Experiment 7); the vertical separation of the point lights varied from 2 to 8 pixels (3.2–12.8 min). The displays were tiny to minimize the effects of eye position on the perceived motion pattern (Ellis & Stark, 1978; Gale & Findlay, 1983). Nonetheless, vertical and horizontal motion were easily discriminated. The vertical separation of the point lights remained constant within a trial, regardless of the number of times each display cycle was repeated; it was either 2, 3, 4, 5, 6, 7, or 8 pixels (resulting in aspect ratios that varied from 0.5 to 2.0).

In Experiment 1A there were two blocks of 539 randomly ordered trials in each of four daily sessions. Each four-frame display cycle was presented either 1, 2, 3, 4, 5, 6, or 7 times per trial. For one block, subjects responded *yes* if they clearly saw vertical motion anytime during the trial; otherwise they responded *no*. For the second block of trials, subjects responded *yes* if they saw horizontal motion anytime during a trial. The order of each session's yes–vertical and yes–horizontal blocks was alternated on successive sessions and balanced across subjects.

Experiment 1B tested for spontaneous changes in the perceived pattern. The same stimuli were presented as before except that each four-frame display cycle was presented either 2, 3, 4, 5, 6, or 7 times per trial (two is the minimum number of display cycles that permits seeing a change in motion direction). Subjects responded *yes* if they saw both vertical and horizontal motion sometime during the trial (i.e., if they saw a change in motion direction); otherwise they responded *no*. There were two blocks of 462 trials in each of four daily sessions.

Two students at Florida Atlantic University (SP and JG) participated in this experiment. Their results closely matched those obtained in a pilot version of the experiment for a third subject. The subjects were naive with regard to the purpose of the experiment but had previous practice observing these stimuli and reporting spontaneous changes in the perceived motion pattern.

Results

In this as well as all of the subsequent experiments reported in this article, subjects never saw anything intermediate between vertical and horizontal motion (e.g., an oblique motion path). The two motion patterns were perceptually distinct. The proportion of trials in Experiment 1A for which subjects reported seeing horizontal motion and the proportion of trials for which they reported seeing vertical motion (judgments of horizontal and vertical were obtained in separate blocks of trials) are presented in the top panel of Figure 2. These data are averaged across trials with different numbers of display cycles because the same pattern of results was obtained regardless of the number of display cycles per trial.[2] The results demonstrate that vertical motion was seen for relatively small aspect ratios, horizontal motion was seen for relatively large aspect ratios, and both were seen for intermediate aspect ratios (1.0 and 1.25).

Another way in which bistability was demonstrated is through spontaneous changes in the perceived pattern while the stimulus display remained unchanged (Experiment 1B). Note that these spontaneous changes were perceptually abrupt. That is, there was no perceptual experience of an intermediate phase during which the subject was uncertain about what was seen. The quantitative results for Experiment 1B, which are presented in the middle panel of Figure 2, indicate that the proportion of trials for which there was at least one change in the perceived motion pattern increased with the number of times per trial that each display cycle was presented; a spontaneous change was more likely when there was more opportunity for one to occur.[3]

In the bottom panel of Figure 2, the proportions of trials with at least one spontaneous change (averaged across trials with different numbers of display-cycle repetitions) are shown together with a measure of bistability derived from the results of Experiment 1A. The latter measure is the difference in the proportion of yes–vertical and yes–horizontal responses (recall that these proportions were obtained in different blocks of trials). When this difference is relatively small (ignoring the sign of the difference), it indicates that both motion patterns are frequently perceived for the same value of the manipulated stimulus parameter. These data show that spontaneous changes from the initially perceived pattern to the alternative pattern occur primarily for aspect ratios of 1.0 and 1.25, which is where the stimuli are most clearly bistable. Thus, the results of Experiments 1A and 1B converge in indicating that the bistable boundary that separates the two motion patterns is relatively narrow when values of the stimulus parameter are presented in random order. If the spatial geometry of the quartet stimuli determines the perceived motion direction through a proximity rule in which motion correspondences are established over the shortest possible path (Ullman, 1978, 1979), the range of parameter values for which there is poor spatial resolution (so that both vertical and horizontal correspondences are possible) is very narrow.

Experiment 2

Modified Method of Limits

The purpose of this experiment was to show for the same stimuli as before that the motion pattern that is seen depends on how the stimulus parameter is changed over time. More specifically, we tested for hysteresis, which occurs when the values of a stimulus parameter are changed gradually and what is seen depends on the direction of change. Hysteresis is indicated when the transition from Pattern A to Pattern B, which is observed when the parameter is gradually increased, occurs at a higher parameter value than the transition from B to A, which is observed when the parameter is gradually decreased.

Method

Stimuli. In the introduction we discussed several potential methodological problems associated with the study of hysteresis. The first concerns the need to study perceptual changes that result from varying the values of only one stimulus parameter. In Experiment 2, we did this by increasing or decreasing the vertical separation between the point lights on consecutive display cycles within the same trial, thereby increasing or decreasing the aspect ratio of the rectangular configuration of point-light locations. Separate ascending trials (the vertical separation between the point lights increased by 1 pixel on consecutive display cycles) and descending trials (the vertical separation decreased by 1 pixel on consecutive display cycles) were presented within randomly ordered blocks of trials.

A second methodological problem concerns the potential for confounding perceptual hysteresis with hysteresis in responding. We minimized the problem in this experiment by introducing a modification of the psychophysical method of limits. Trials with descending series all began with an 8-pixel vertical separation (an aspect ratio of 2.0, which strongly favors the perception of horizontal motion) and ended with a vertical separation of either 7, 6, 5, 4, 3, or 2 pixels (endpoint aspect ratios of 1.75, 1.5, 1.25, 1.0, 0.75, or 0.5, respectively). For example, a descending trial with six display cycles proceeded through the following sequence of vertical separations: 8–7–6–5–4–3. Trials with ascending series all began with a 2-pixel vertical separation (an aspect ratio of 0.5, which strongly favors the perception of vertical motion) and ended with a vertical separation of either 3, 4, 5, 6, 7, or 8 pixels (endpoint aspect ratios of 0.75, 1.0, 1.25, 1.5, 1.75, or 2.0, respectively). For example, an ascending trial with five display cycles proceeded through the following sequence of vertical separations: 2–3–4–5–6. Thus, both ascending and descending series varied with regard to how deeply they probed into the range of aspect ratios that would lead to a transition from one pattern being perceived to the other. With this trial structure, subjects made one response to an entire ascending or descending run; they did not execute a response at each step in the gradually changing series, as in the standard method of limits procedure. Because there was no relation between when subjects saw the perceptual change and when they reported it through their response, observed

[2] Data for trials with only one display cycle are omitted from the final data tabulation because the brevity of these trials sometimes resulted in subjects being uncertain of what they had seen. This did not affect the overall pattern of results.

[3] This observation is the basis for Hock and Voss's (1990) determination that the probability of a spontaneous perceptual reorganization can remain constant over time, which is contrary to Köhler and Wallach's (1944) neural satiation hypothesis.

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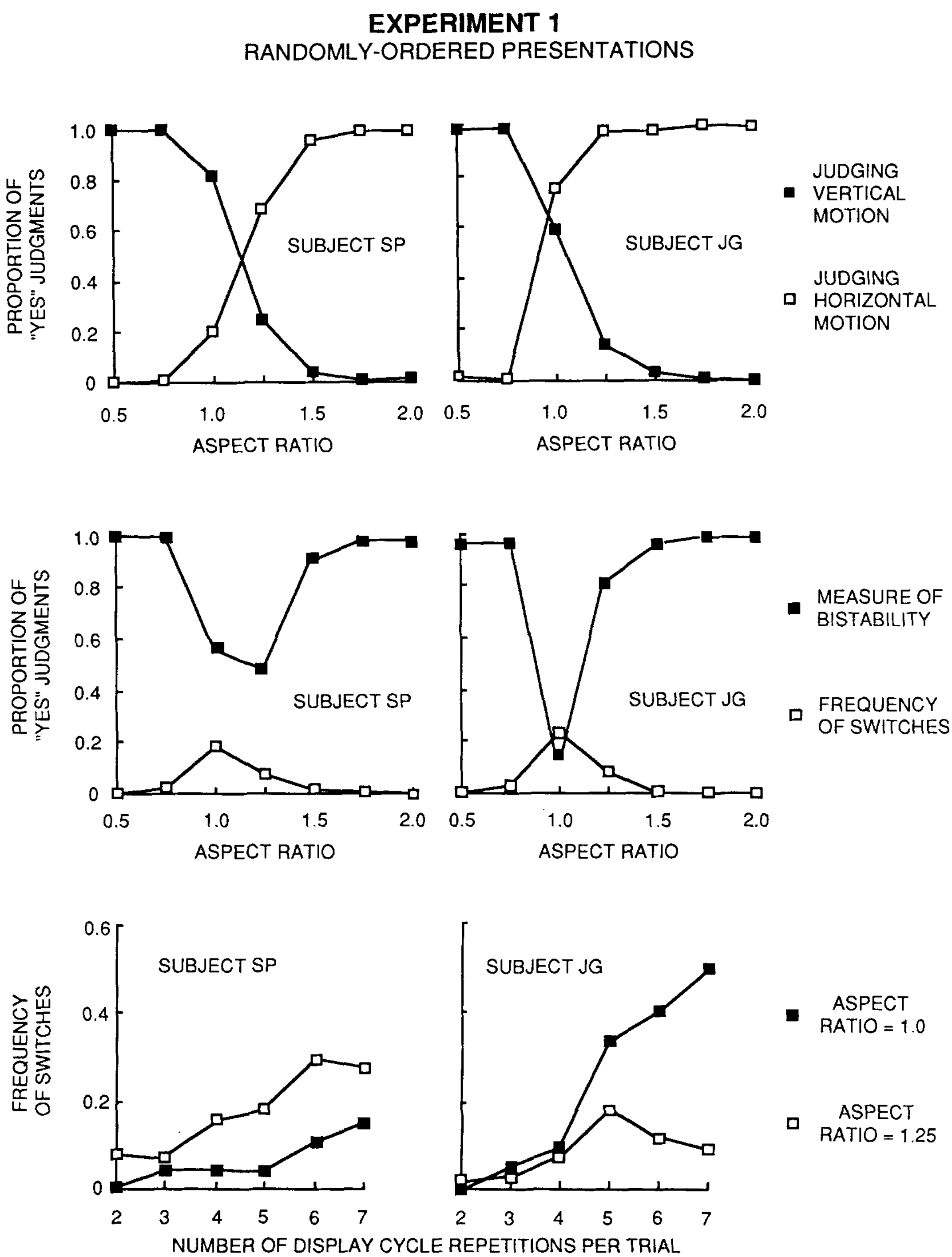

Figure 2. The top panel shows the proportion of yes–vertical and yes–horizontal responses in Experiment 1A as a function of the aspect ratio of the point-light configuration. The bottom panel shows the frequency of spontaneous changes in Experiment 1B as a function of the number of display cycle repetitions (to improve readability, data are omitted for aspect ratios for which the proportion of trials with a perceived change in motion direction is below 15% for all values of the number of display cycle repetitions variable). The middle panel shows the mean frequency of spontaneous changes in perceived motion direction graphed in relation to a measure of bistability (the difference in frequency of yes–vertical and yes–horizontal responses) as a function of aspect ratio.

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effects of parameter change involved perceptual hysteresis uncontaminated by response hysteresis.

The third methodological problem concerns the possibility that hysteresis can be due to subjects persisting in the same decision while the stimulus parameter passes through values for which they are uncertain of what they are seeing. Although there is no obvious way of completely eliminating this as a possibility, we believe that effects of decision uncertainty are minimized for the stimuli studied in this and the following experiments. This is because when the perceived motion pattern changed, either spontaneously or in response to changes in the stimulus parameter, there was rarely, if ever, an intermediate phase during which subjects were uncertain about what they were seeing. Subjects saw one motion pattern and then suddenly they saw the other motion pattern. If there were some moments of uncertainty, they were brief compared with the time scale (measurable in display cycles) at which spontaneous changes and hysteresis effects were observed.

Design. There were two blocks of 240 trials in each of four daily sessions. For one block, subjects responded *yes* if they saw vertical motion anytime during the trial; otherwise they responded *no*. For the second block of trials, subjects responded *yes* if they saw horizontal motion anytime during a trial. The order of each session's yes–vertical and yes–horizontal blocks were alternated on successive sessions and balanced across subjects.

Subjects. SP and GB, the latter also a student at Florida Atlantic University, participated in this experiment.

Results

For trials with descending series, all of which began with an aspect ratio of 2.0, yes–horizontal responses were made on 99.9% of the trials; this was also the case for yes–vertical responses for the ascending series, which began with an aspect ratio of 0.5. These results support our expectation for these aspect ratios that descending trials always begin with horizontal motion and ascending trials always begin with vertical motion (the very slight departures from 100% are probably due to occasional response errors).

The analysis of hysteresis therefore involved determining how often yes–horizontal responses were made for ascending trials, which began with vertical motion, and how often yes–vertical responses were made for descending trials, which began with horizontal motion. The results provide clear evidence for hysteresis (top panel of Figure 3). For ascending trials, switches from perceiving vertical to perceiving horizontal motion did not occur until the endpoint aspect ratio became relatively large. Conversely, for descending trials, switches from the perception of horizontal motion to the perception of vertical motion did not occur until the endpoint aspect ratio became relatively small (note the reversal of the axis for the descending series).[4] Thus, what is perceived depends on the direction of change. For example, when the endpoint aspect ratio was 1.25, only horizontal motion was seen on most of the descending trials, but only vertical motion was seen on most of the ascending trials. In contrast to the relatively narrow range of bistability observed when parameter values were randomly changed (Experiment 1), bistability was indicated in this experiment over almost the entire range of aspect ratios that had been studied.

Experiment 3

Modified Method of Limits With Variable Starting Points

In Experiment 2, both the ascending and descending trials varied with regard to the number of display cycles per trial. As a result, trials with relatively little change in aspect ratio were briefer than trials for which the change in aspect ratio was relatively large. Given our evidence for spontaneous changes in the perceived motion pattern when the parameter value remained constant (Experiment 1B), it could be argued that the apparent hysteresis obtained in Experiment 2 was due to differences in the duration of trials rather than differences in the direction in which the stimulus parameter was changed; trials lasting longer allow more opportunity for spontaneous changes. In the descending series, for example, the persistence of the initially horizontal pattern through the 1.25 aspect ratio (5-pixel vertical separation) might be due to the infrequent occurrence of spontaneous changes for relatively brief trials with only four display cycles (8–7–6–5). Perceptual change might be more likely to occur for descending trials with smaller endpoint aspect ratios simply because those trials happen to be of longer duration.

To rule out the possibility that the obtained hysteresis was an artifact of trial duration, this experiment included a set of trials with descending series that began with a relatively large vertical separation (12 pixels; aspect ratio of 3.0) and then decreased in separation down to and through the range of endpoint aspect ratios tested in Experiment 1. If the appearance of hysteresis is the artifactual result of differences in trial duration, then hysteresis would not be observed for these descending trials because there would be ample time for spontaneous changes to occur (as a function of trial duration) before the aspect ratio reached the range of values near the boundary between the two motion patterns.

Method

There were three sets of randomly mixed trials in this experiment, two descending and one ascending. For the ascending series, all trials began with a 2-pixel vertical separation (as before), for one descending series all trials began with an 8-pixel vertical separation (also as before), and for a new descending series all trials began with a 12-pixel separation. Endpoint vertical separations were either 3 to 7 pixels for the ascending series and either 7, 6, 5, 4, 3, or 2 pixels for both descending series. For all three series, the horizontal separation between the dots remained constant at 4 pixels, and the vertical separation changed in 1-pixel steps on consecutive display cycles. For example, a trial with eight display cycles in the new descending series proceeded through the following sequence of vertical separations: 12–11–10–9–8–7–6–5.

The subjects' response criterion in this experiment differed from that of Experiment 2. They now responded *yes* only when they saw both vertical and horizontal motion during the same trial (i.e.,

[4] Metzger (1941/1975) reported similar effects for the same kind of display. However, his description of procedures and results is scanty and nonquantitative.

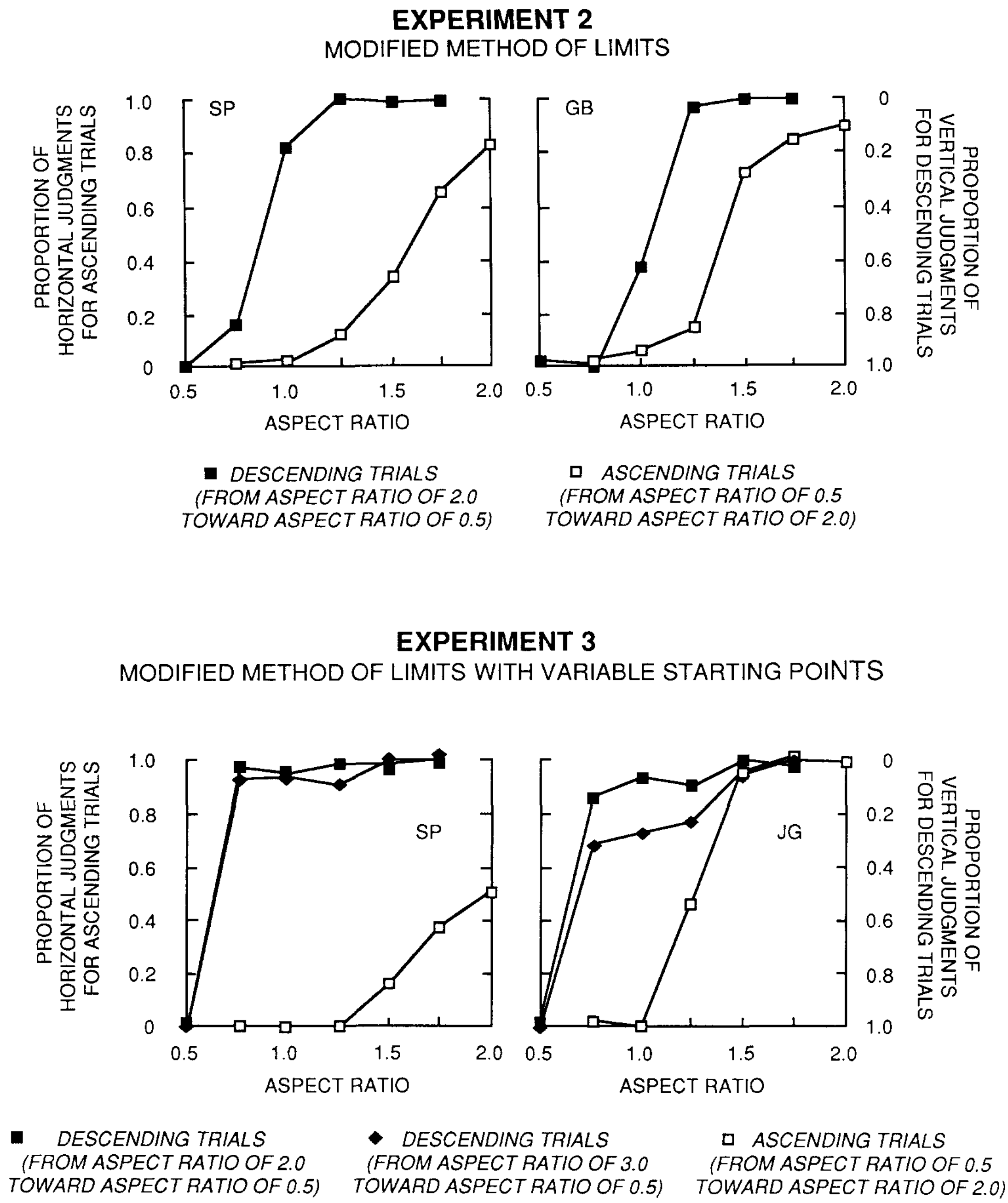

Figure 3. Hysteresis effects obtained in Experiments 2 (top panel) and 3 (bottom panel). (The aspect ratio is changed by 0.25 on successive display cycles by varying the vertical separation between the dots. The axis on the left side of each graph indicates changes from the perception of vertical motion to the perception of horizontal motion for ascending trials. The inverted axis on the right side of each graph indicates changes from the perception of horizontal motion to the perception of vertical motion for descending trials. SP, GB, and JG are the subjects.)

when they saw a change in motion direction). Because it was confirmed in Experiment 2 that the descending series always begins with the perception of horizontal motion (when the initial aspect ratio is 2.0) and the ascending series always begins with the perception of vertical motion (when the initial aspect ratio is 0.5), the new response criterion was logically equivalent to that of the previous experiment but allowed us to obtain more data for the measurement of hysteresis. There were two experimental sessions with two blocks of 252 trials per session. The subjects (SP and JG) were aware of the outcome of Experiment 2.

Results

The bottom panel of Figure 3 shows that hysteresis was obtained again. As in Experiment 2, gradually increasing

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and decreasing the values of the stimulus parameter expanded the range of values for which both motion patterns could be seen. For Subject SP, the results for the descending series starting with aspect ratios of 3.0 and 2.0 were virtually identical. For Subject JG, there was a small elevation in switches to vertical motion for the descending series beginning with the 3.0 aspect ratio, but the hysteresis was retained. The results therefore indicate that trial duration was not a factor in the hysteresis obtained with our modified method of limits procedure.

Experiment 4

Modified Method of Limits: Mixed Versus Blocked Ascending and Descending Trials

Although there are relatively few published reports of perceptual hysteresis, the robustness of the effect when it is observed (either formally or informally) may suggest that it is the inevitable result of gradually changing a critical stimulus parameter. In this experiment, we show that this is not the case by using the same stimuli that provided strong evidence for hysteresis in the preceding experiments. The only change is that we now restrict the direction with which the change can occur. That is, ascending trials, for which parameter values were gradually increased, were segregated from and presented in separate blocks from descending trials, for which parameter values were gradually decreased.

Method

The stimuli presented in this experiment were as first described in Experiment 2. There were three conditions, one with a block of 180 ascending trials (30 for each of the six endpoint aspect ratios), one with a block of 180 descending trials (again 30 for each of the six endpoint aspect ratios), and one with a random mixture of 180 ascending and 180 descending trials. The blocked–ascending, blocked–descending, and mixed ascending–descending conditions were tested on separate days to minimize interactions among them. The conditions were each tested twice, with the order varying for the three participating subjects. Data for the first 30 ascending and first 30 descending trials in each session were excluded from the final data tabulation. At the end of each trial, subjects reported whether they had seen a change in the perceived direction of motion anytime during the trial. Subjects HH, KE, and SP participated in this experiment; KE and SP were unaware of its purpose.

Results

The results of the mixed ascending–descending condition, presented in Figure 4, replicate the hysteresis obtained in the previous experiments. However, when the ascending and descending trials were presented in separate blocks, the magnitude of the hysteresis was reduced for all 3 subjects. When the data are averaged across subjects, there is no hysteresis for the blocked conditions.

The blocked design may reduce and even eliminate hysteresis because only one motion pattern is seen for the majority of trials in this condition. For example, there were many descending trials for which the perceived motion pattern remained horizontal throughout: 8–7, 8–7–6, 8–7–6–5, and as a result of hysteresis, 8–7–6–5–4 and perhaps some 8–7–6–5–4–3 trials. Despite randomization of order, various combinations of these horizontal-motion trials frequently occurred in relatively long sequences. Consequently, adaptation due to the repeated perception of the same motion pattern may have fostered perceptual switches to the non-adapted pattern (as in Kruse et al., 1986), potentially nullifying the hysteresis that contributed to the adaptation. Consistent with this account, we have found that hysteresis can be reinstated for the blocked conditions by interrupting the repeated perception of the same motion pattern (we added five display cycles with a 0.5 aspect ratio to the end of every descending trial, and we added five display cycles with a 2.0 aspect ratio to the end of every ascending trial; as a result, both horizontal and vertical motion were seen on every trial). That hysteresis can be eliminated and re-instated in this manner suggests that it depends on competition between alternative perceptual patterns and is not simply the result of decision or response biases operating within an ascending or descending series.

Summary of Experiments 1–4

The experiments reported thus far introduce a paradigm in which two distinctly different motion patterns are perceived. Values of a manipulated stimulus parameter favor one or the other of these patterns, and a relatively high rate of spontaneous change is observed at parameter values at the boundary of the two percepts. Because of the distinctiveness of these percepts (a consequence of the mutual inhibition of the vertical and horizontal motion directions for the motion quartets; see Figure 1), subjects rarely if ever are unsure of which they are perceiving. Perceptual changes, whether spontaneous or the result of parameter change, are therefore unlikely to have been influenced by decision biases in the presence of judgmental uncertainty. Perceptual hysteresis is observed through a modified version of the method of limits that eliminates response bias effects (a control experiment eliminates trial duration as a possible artifact of the method). Finally, a procedure has been introduced (blocked–ascending and blocked–descending trials) that eliminates hysteresis, probably as a result of adaptation that reduces the ability of the initial motion percept to compete with the (temporarily inhibited) alternative percept. If the observed hysteresis depends on response or decision bias rather than competition between alternative percepts, it would not have been eliminated by the blocking manipulation.

Experiment 5

Modified Method of Limits: Trials With End Idles

The preceding experiments provide evidence within the same experimental paradigm for two factors that are related to the stability of the perceived patterns: their persistence despite propensities for spontaneous change arising within the visual system (temporal stability) and their persistence despite changes in the stimulus parameter to values favoring

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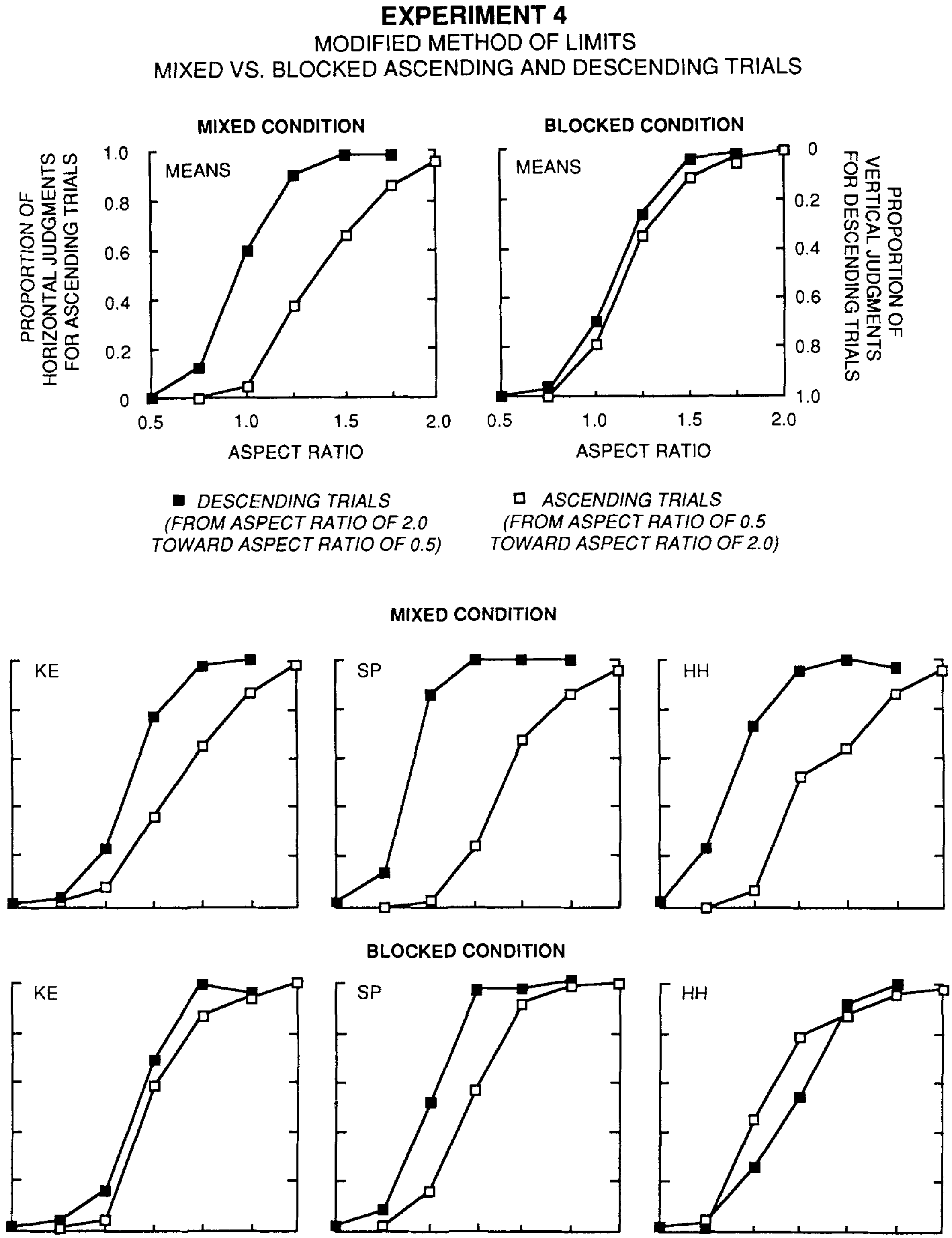

Figure 4. Hysteresis effects in Experiment 4 for the blocked–ascending, blocked–descending, and mixed ascending–descending conditions. (Means for the 3 subjects [KE, SP, and HH] are presented in the upper panel. Individual subject data are presented in the lower two panels.)

an alternative percept (hysteresis). This experiment links these two aspects of perceptual stability more directly. As in Experiments 2–4, values of the parameter were gradually increased or decreased toward an endpoint aspect ratio, the latter varying randomly from trial to trial. In this experiment we also included trials for which the stimulus parameter "idles" at the endpoint value. This allowed us to measure spontaneous changes in the perceived motion direction (i.e., changes occurring while the parameter "idles" at a constant value at the end of an ascending or descending run). Of

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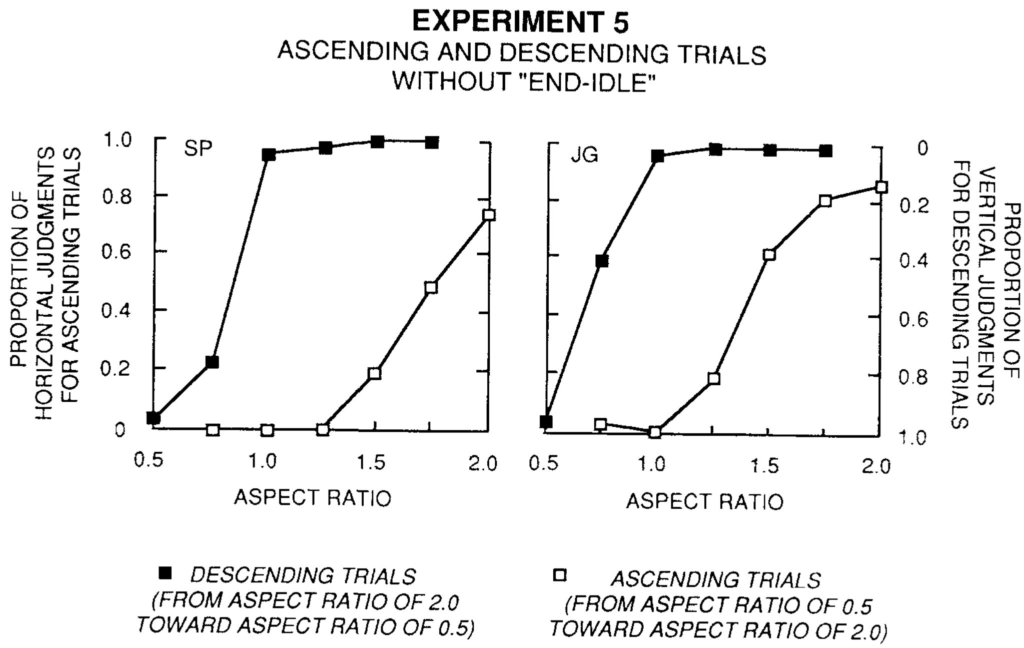

Figure 5. Hysteresis effects in Experiment 5 on the basis of trials for which the endpoint aspect ratio is presented for just one display cycle after gradually changing on preceding display cycles. (SP and JG are the subjects.)

interest is the effect of the initial percept persisting (while the parameter changes) on its temporal stability (the likelihood it will spontaneously change during the idle).

Method

Both ascending trials (the vertical separation increases by 1 pixel on consecutive display cycles) and descending trials (the vertical separation decreases by 1 pixel on consecutive display cycles) were presented in randomly ordered blocks of 240 trials (there were two such blocks in each of four daily sessions). Trials with descending series all began with an 8-pixel vertical separation (aspect ratio of 2.0), hence the perception of horizontal motion, and ended with a vertical separation of either 7, 6, 5, 4, 3, or 2 pixels; trials with ascending series all began with a 2-pixel separation (aspect ratio of 0.5), hence the perception of vertical motion, and ended with a vertical separation of either 3, 4, 5, 6, 7, or 8 pixels. In addition, the endpoint aspect ratios (the largest vertical separation in an ascending trial or the smallest vertical separation in a descending trial) were presented for either 1, 2, 3, or 4 display cycles. For example, a trial with nine display cycles might proceed through the following sequence of vertical separations: 8–7–6–5–4–3–3–3–3. Subjects responded by pressing the *yes* button only when they saw both vertical and horizontal motion during the same trial. Otherwise they pressed the *no* button. Subjects SP and JG participated in this experiment. They were unaware of its purpose.

Results

The results obtained when the endpoint aspect ratio was presented for just one display cycle replicated previously obtained evidence for hysteresis (Figure 5). The measurement of spontaneous changes was based on determining the proportion of trials for which the first perceptual change occurred during the idle (while the endpoint aspect ratio was held constant), not the preceding portion of the trial, during which parameter values were gradually increased or decreased. For each value of the endpoint aspect ratio, we first determined the number of trials with an idle for which subjects reported seeing a perceptual change (I) and then subtracted the number of nonidle trials for which subjects reported seeing a perceptual change (NI). We then divided the difference ($I - NI$) by the number of nonidle trials for which there was no perceptual change ($1 - NI$) to determine the proportion of trials for which the first perceptual change occurred during the idle.[5] This is our measure of spontaneous perceptual change.

As can be seen in Figure 6 (which includes the hysteresis data presented in Figure 5), the proportion of trials for which the first perceptual change occurred during the idle (i.e., when the first change was spontaneous) increased as a function of the extent to which the initially perceived pattern persisted. For example, Subject SP's results for nonidle trials indicate that she saw only vertical motion on all ascending trials with an endpoint aspect ratio of 1.25 and continued seeing only vertical motion, without change, for approximately half of the nonidle ascending trials with an

[5] As in Experiment 1B, the frequency with which at least one spontaneous change occurs during the idle increases as a function of the number of display cycle repetitions (2, 3, or 4). For purposes of this analysis, spontaneous changes are averaged across the number of display cycle repetitions.

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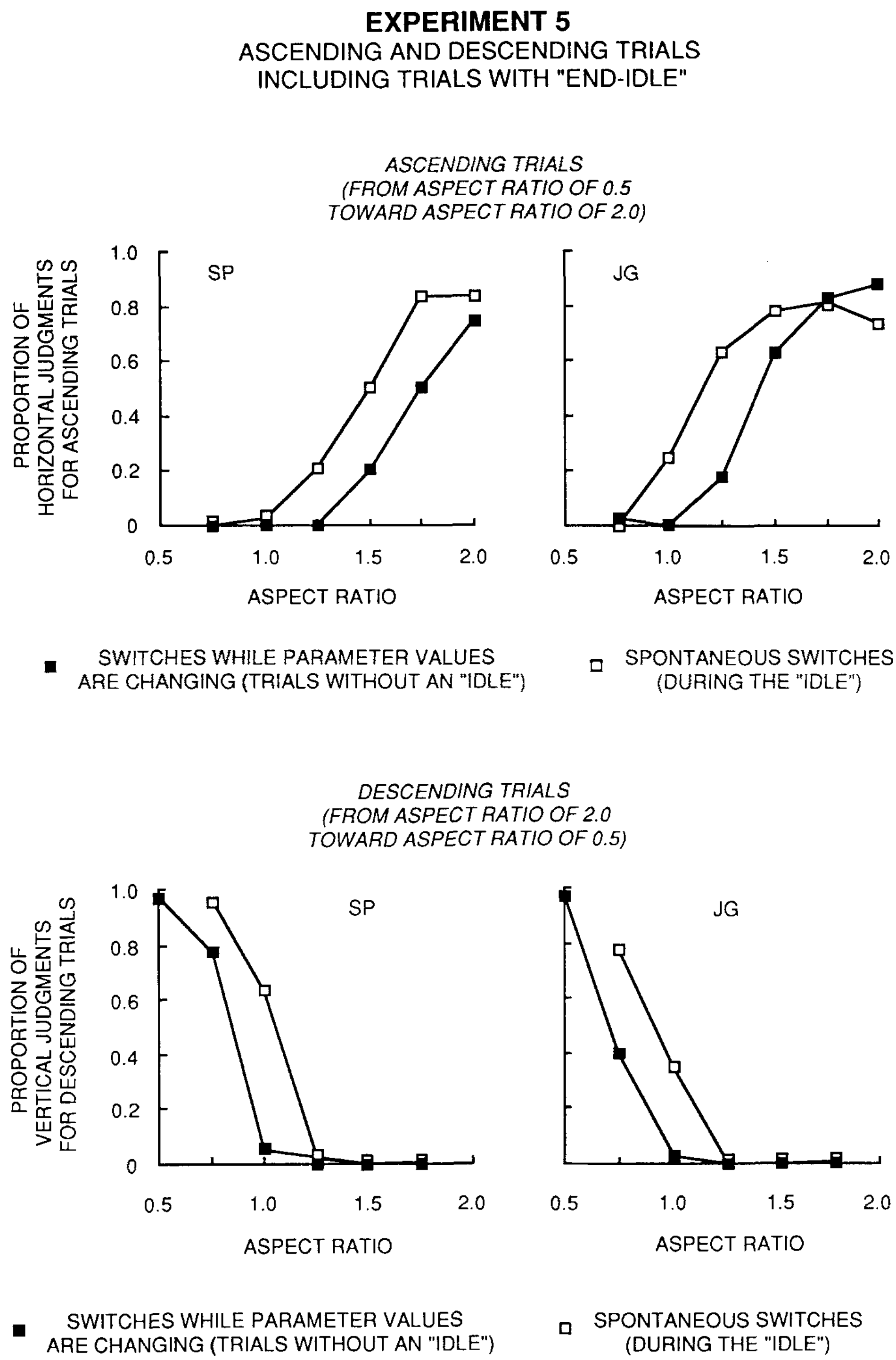

Figure 6. Further analysis of the results of Experiment 5. (One measure indicates the proportion of trials in which the first perceptual change occurs in response to gradual changes in aspect ratio [trials without an idle], and the other indicates the proportion of trials for which the first perceptual change is spontaneous [i.e., it occurs during the idle]. SP and JG are the subjects.)

endpoint aspect ratio of 1.75. Commensurate with this perceptual persistence, the likelihood of SP's first perceptual change being spontaneous (i.e., occurring during the idle) increased from about 0.2, when the stimulus idled at the aspect ratio of 1.25, to more than 0.8 when the parameter ascended further and idled at the 1.75 aspect ratio. That is, on trials in which the initial percept persisted until the idle period, her rate of spontaneous change during the idle

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increased dramatically as a function of how long the initial percept persisted. This interdependence of perceptual hysteresis, observed while parameter values were gradually changed, and the likelihood of seeing a spontaneous change in motion direction, observed when the stimulus parameter subsequently idled at a constant value (and not earlier in the trial), were obtained for both subjects for both ascending and descending trials.

Discussion

Gradually increasing and decreasing the aspect ratio of the motion quartet results in the persistence of the initially established percept, even though the values of the parameter that are reached favor the alternative percept. This, however, is not the only way for the disfavored pattern to be perceived. Sometimes it is perceived on the initial presentation of a motion quartet (providing the quartet's aspect ratio is not too extreme in either direction). When this happens, the results are consistent with those observed in this experiment. That is, the likelihood of spontaneous change increases as a function of how much the initial percept is disfavored by the parameter value (Hock & Voss, 1990).

Experiment 6

Modified Method of Limits: Vary the Rate of Parameter Change

Experiments 2–5 showed that the percept for a particular stimulus configuration depends on the direction of parameter change. In this experiment, we showed that it also depends on the rate of parameter change. When the rate of change is slowed, there is more opportunity for the initial percept, which is less stable because of its persistence under parametric change (Experiment 5), to give way to a spontaneous perceptual change relatively early in the ascending or descending series. The expected consequence is a reduction in the magnitude of the hysteresis. The modified method of limits procedure introduced in Experiment 2 is particularly suited to studying the rate of parameter change. Subjects did not respond until the conclusion of each trial, so we were not concerned about possible effects of the rate of stimulus change on response perseveration.

Method

As in the previous experiments, trials with ascending series (beginning with an aspect ratio of 0.5) and descending series (beginning with an aspect ratio of 2.0) were presented in random order. The fast rate of change was as in the previous experiments; the vertical separation was changed by 1 pixel on successive display cycles. A typical ascending series was 2–3–4–5–6. For ascending and descending series changing at the slow rate, the vertical separation remained the same for two consecutive display cycles and then changed by 1 pixel for the next two pairs of display cycles (except for the endpoint aspect ratio, which was presented for one display cycle as in the fast trials). A typical ascending series was 2–2–3–3–4–4–5–5–6. Subjects were presented two blocks of 288 trials in each of three daily sessions. They responded *yes* when they clearly saw both vertical and horizontal motion during the same trial and responded *no* otherwise. Subjects HH and GB participated in this experiment; GB was unaware of the rate manipulation and its purpose.

Results

The results presented in Figure 7 replicated the hysteresis observed in the preceding experiments and indicated, as predicted, that the magnitude of the hysteresis is reduced when the rate of parameter change is slowed. The reduction in hysteresis reflected the presence of intrinsic tendencies with opposing outcomes. Persistence under gradual parameter change maintained an initially established percept, but the likelihood of spontaneous change increased when the rate of parameter change was slowed.

Experiment 7

Modified Method of Limits: Vary the Size of the Motion Quartet

The rates of spontaneous perceptual change obtained in Experiments 1 and 3 indicate that our motion quartets are not as temporally stable as Ramachandran and Anstis's (1985). Differences in timing, the size of the quartets, or perhaps the presence of a central dot may all contribute to the contrasting results. In this experiment, we examined the effect of the quartets' size, and consistent with Ramachandran and Anstis's (1985) results, we found that the likelihood of a spontaneous change in organization is reduced (temporal stability is increased) when the quartets are enlarged. On this basis, we provide further evidence for the interdependence of hysteresis and temporal stability by showing that in addition to increasing temporal stability, enlarging the motion quartets increases the magnitude of the hysteresis.

Method

The small quartets are as in the preceding experiments; the horizontal separation between the dots was 6.4 min and the vertical separation varied from 3.2 to 12.8 min. The large quartets were enlarged by a factor of 10, which made them similar in size to Ramachandran and Anstis's (1985). Their horizontal separation was 1.07°, and their vertical separation varied from 0.53° to 2.13°.

As in the previous experiments, hysteresis effects were measured for trials with ascending and descending aspect ratios (the order of ascending and descending trials was random; there were no end idles), and spontaneous changes were measured for trials with constant aspect ratios (trial order was random for the latter, and there were always six display cycles per trial). There were four blocks of trials per session: Hysteresis and spontaneous changes were measured for both small and large quartets (the order of testing was counterbalanced over four experimental sessions). Subjects pressed the *yes* button if they saw a change in the perceived motion pattern anytime during the trial (otherwise they

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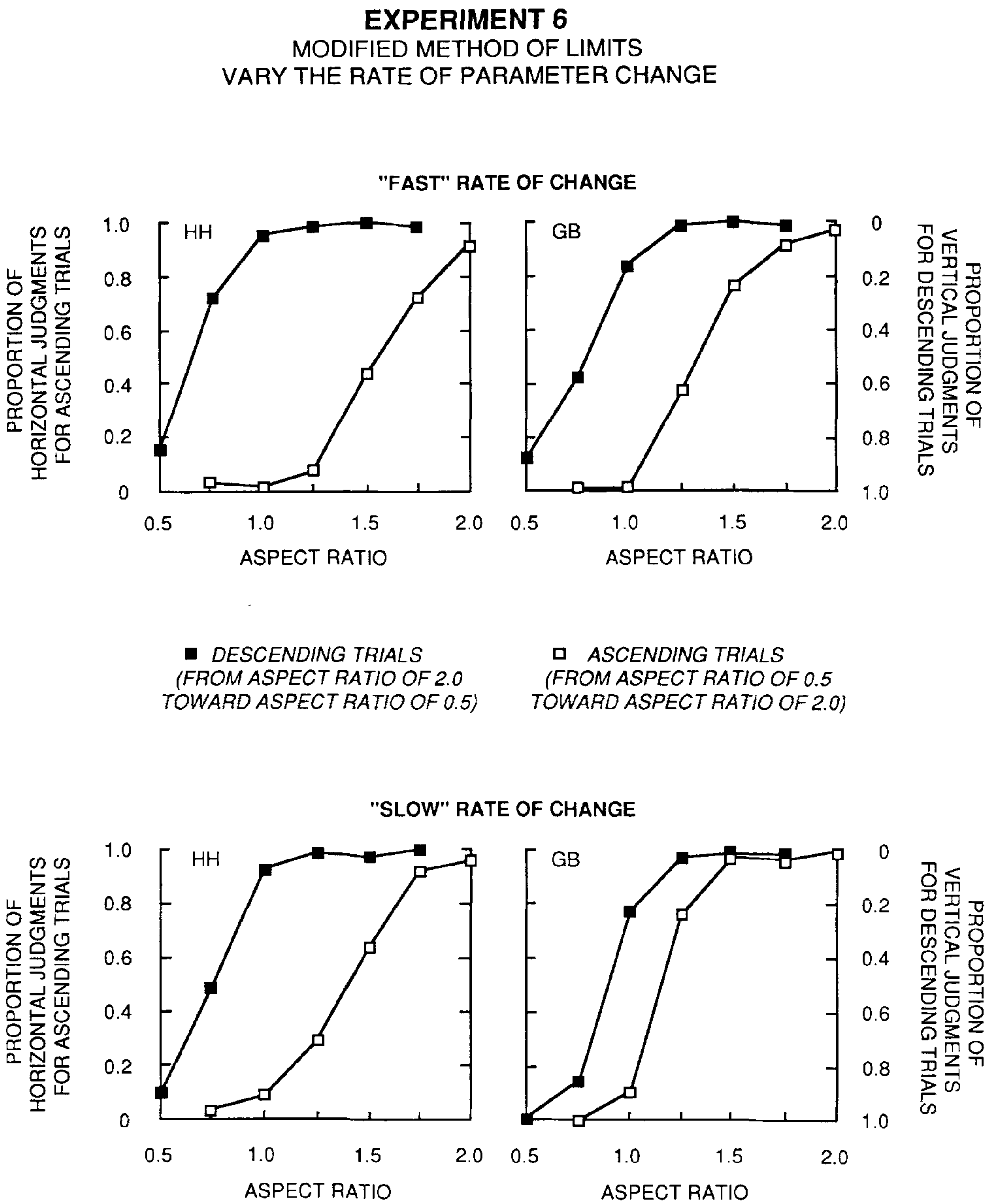

Figure 7. Hysteresis effects in Experiment 6 when the aspect ratio is changed by 0.25 on successive display cycles (fast condition) or is repeated for two display cycles before being changed by 0.25 (slow condition). (HH and GB are the subjects.)

pressed the *no* button). There were 6 subjects in this experiment, 2 of whom had not participated in any of the preceding experiments.

Results

Means across the 6 participating subjects are presented in Figure 8. The upper panel indicates the proportion of trials for which there was at least one spontaneous change in the perceived motion pattern while the aspect ratio remained constant. The rate of spontaneous change was lower for the large compared with the small quartets for all 6 subjects. The effect of size, averaged over aspect ratio for each subject, was statistically significant, $t(5) = 7.19$, $p < .001$.

We obtained hysteresis for both small and large quartets for all 6 subjects (means are presented in the bottom two panels of Figure 8); hysteresis effects were obtained for all 8 subjects tested in Experiments 2–7. The method of measuring hysteresis for each subject was equivalent to determining the area between the ascending and descending curves on the hysteresis graphs (in the absence of hysteresis,

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the ascending and descending curves would overlap, so the area between them would be zero). For each aspect ratio, the frequency of seeing any horizontal motion during an ascending trial (the persistence of vertical motion would tend to keep this frequency low) was subtracted from the frequency of seeing only horizontal motion for descending trials (the persistence of horizontal motion would tend to keep this frequency high). These differences were summed over the endpoint aspect ratios (0.75, 1.0, 1.25, 1.5, and 1.75) that were common to ascending and descending trials.[6] On this basis, the magnitude of the hysteresis was significantly greater for the large quartets than for the small quartets for all 6 subjects. Although the difference was small for 3 of the subjects, the overall effect of quartet size was significant, $t(5) = 2.57$, $p = .05$. Subjects with the greatest increase in the magnitude of hysteresis for the enlarged quartets were those for whom the enlargement most reduced the frequency of spontaneous change.

Discussion

The results of this experiment suggest that intrinsic factors responsible for the occurrence of spontaneous change are less effective for the large quartets compared with the small quartets. Although the reasons for this are as yet undetermined, the greater temporal stability of the large quartets is correlated with an increase in the magnitude of the hysteresis. This is because the magnitude of the hysteresis is reduced when intrinsic fluctuations result in spontaneous perceptual change; greater temporal stability means that the occurrence of such spontaneous changes is less likely, so it becomes possible to observe something closer to the full hysteresis associated with gradual parameter change.

As a result of extensive hysteresis, perceptual patterns are seen at values for which they are rarely seen when a parameter value is selected randomly and held constant for the entire trial (as in Experiment 1). For example, for ascending trials with the large quartets, only vertical motion was seen for an average of 40% of the trials with an endpoint aspect ratio of 1.75 and for an average of 30% of the trials with an endpoint aspect ratio of 2.00. This was the case even though the vertical separation for these aspect ratios was much larger than the horizontal separation and was perceived as such. These percepts violate Ullman's (1978, 1979) "proximity rule" for motion correspondences, which specifies that in the absence of other constraints, motion follows the shortest path. Because of hysteresis, the violation of proximity occurs for vertical–horizontal disparities well beyond those that might be considered difficult to resolve (the resolution zone is indicated by the relatively narrow range of bistability when values of the parameter are presented in random order, as in Experiment 1). The spatial geometry of the motion quartet stimulus thus has a nonspecific influence on the perceived motion patterns. Although spatial proximities favor certain motion patterns in relation to others, this bias is readily reversed to accommodate the temporal qualities of the percept.

General Discussion

Perceptual stability refers to the continuation of a percept despite changes, both intrinsic and extrinsic, that might result in a perceptual reorganization in which an alternative pattern is seen. In this article, we examine two phenomena that reflect the stability of visual percepts: hysteresis and temporal stability. Hysteresis results from the persistence of a percept despite changes in a critical stimulus parameter to values that favor an alternative percept. Temporal stability is observed while stimulus parameters remain constant; stability is achieved despite propensities toward spontaneous change arising from within the visual system.

Experiments 1–4 establish our methodology (see the Summary of Experiments 1–4 section); Experiments 5–7 provide evidence for the interdependence of hysteresis and temporal stability. In Experiment 5, end idles are added to trials with ascending and descending changes in the aspect ratio (the endpoint aspect ratio of the quartets remains constant for two to four display cycles). We find that greater persistence (more hysteresis) during the ascending and descending segments of the trials results in less temporal stability (greater likelihood of spontaneous change) while the aspect ratio idles at the endpoint value. The rate of parameter change is varied in Experiment 6. We find that slower rates of change reduce the magnitude of the hysteresis, presumably because there is more opportunity for the occurrence of spontaneous changes (losses in temporal stability) during the ascending and descending runs. Such spontaneous changes work in opposition to the tendency of the percept to persist despite parameter change. In Experiment 7, we vary the size of the motion quartets and provide evidence for a direct relationship between temporal stability and hysteresis. Decreases in the likelihood of spontaneous change (increased temporal stability) are accompanied by increases in the magnitude of the hysteresis.

One possibility suggested by the aforementioned results is that the perceived patterns are stable because the visual system responds relatively sluggishly to changes in stimulus parameters or changes (fluctuations) that arise within the visual system itself. That is, what is perceived may depend on a running average of the current and immediately preceding responses of the visual system to intrinsic and extrinsic events. Another, more likely possibility derives from the observation that vertical and horizontal motion are

[6] An alternative to this procedure would be to fit each subject's ascending and descending data to a probit model, which involves the maximum likelihood estimation of the data based on a linear transformation of a cumulative normal distribution. The 50% point on the cumulative normal distribution would then provide a measure of the point of subjective equality (i.e., the aspect ratio for which there is an equal probability of seeing vertical and horizontal motion), and the difference in points of subjective equality between the ascending and descending trials would provide a measure of hysteresis. But the usefulness of probit analysis, which has the additional benefit of providing a measure of the slopes of the ascending and descending data curves, was limited by inconsistency in the extent to which our hysteresis data were satisfactorily fit by the cumulative normal distribution.

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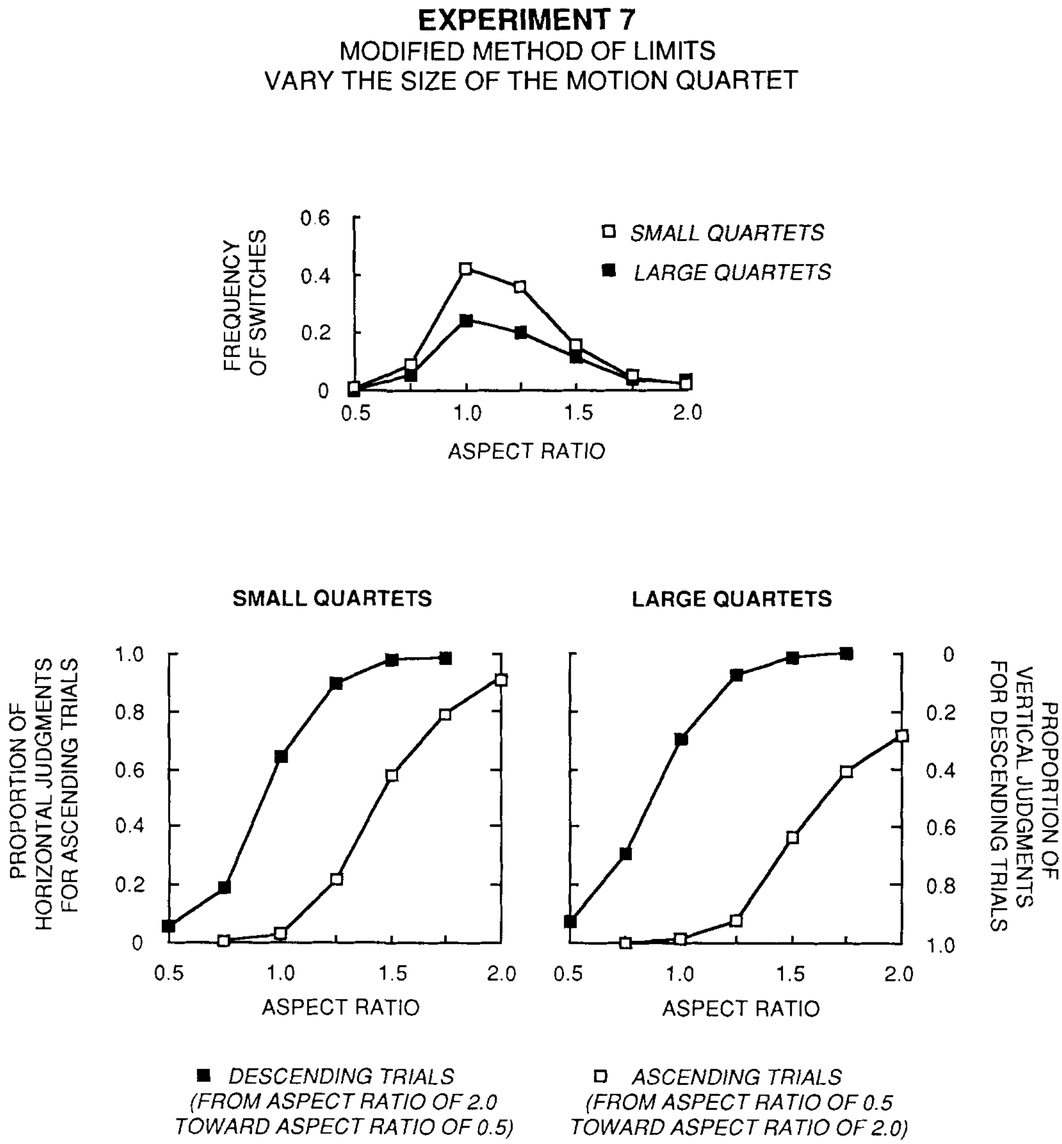

Figure 8. Frequency of spontaneous switches and hysteresis effects in Experiment 7 for small and large motion quartets, shown as a function of the size-independent aspect ratio.

mutually inhibitory for motion quartets, so one or the other is perceived but never both at the same time (see Figure 1). If the stability of a perceptual pattern formed for the motion quartets is the result of the inhibition of the alternative percept, the interdependence of hysteresis and temporal stability would follow from the additional assumption that the amount of inhibition varies according to the extent to which the aspect ratio favors the alternative percept. Hysteresis would then result because levels of inhibition changed more slowly than the stimulus parameter (the aspect ratio); temporal stability would result from the inability of all but the largest intrinsic fluctuations to overcome the inhibitory bias and produce a switch to the alternative pattern. Increasing losses of temporal stability when there is more and more persistence of the initial percept (Experiment 5) follows from the reduction in inhibition of the alternative percept with changes in the aspect ratio. As the inhibitory bias is reduced, smaller and smaller fluctuations could overcome the bias, resulting in a loss of temporal stability. Slowing the rate of parameter change allows more opportunity for the occurrence of an intrinsic fluctuation large enough to override the inhibition of the alternative pattern, reducing the magnitude of the hysteresis (Experiment 6). Conversely, increasing temporal stability (by enlarging the quartets) decreases the likelihood of their being an intrinsic fluctuation large enough to override the inhibition of the alternative pattern, increasing the magnitude of the hysteresis (Experiment 7).

Characterizing the perceptual stability of the motion quartets in terms of the mutual inhibition of alternative motion directions suggests that perceptual pattern formation for the quartets is analogous to pattern formation in physical and

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biological systems (Haken, 1977/1983, 1981), in particular systems in which there is competition among alternative patterns that vary in their relative stability (Kelso, 1984; Kelso & Schöner, 1987; Landauer, 1962, 1978; Schöner & Kelso, 1988). The time-dependent behavior of these and many other systems has been described in terms of nonlinear dynamics, that is, nonlinear laws of motion (e.g., Gurel & Rossler, 1979). A similar description applies naturally to our experimental observations.

The essential idea is that multistability in perception is represented by coexisting attractors that are stable solutions of collective-variable equations of motion. This means that the system is attracted to one of these solutions (the perception of vertical vs. horizontal motion) if it is initially in one of their basins of attraction. Spontaneous changes among the attractors can occur strictly as a result of random fluctuations, provided that a fluctuation is sufficiently strong to put the system into the alternative basin of attraction (this is followed by the relaxation of the system to the new attractor). The likelihood of this happening is linked to the relative sizes of the basins of attraction, which in turn depend on the relative stability of the attractors; in general, the stabler attractor has the larger basin of attraction, and switching into this state is more likely than switching out of it. When the experimental parameter is varied, the stability of the attractor corresponding to the initial percept decreases while the stability of the attractor corresponding to the alternative pattern increases. Hysteresis is observed under parameter change because the initial percept persists even when the parameter value results in the alternative pattern being relatively more stable. This is because the initial pattern retains some measure of temporal stability, despite its shrinking basin of attraction. However, additional parameter change further reduces this basin of attraction, commensurately increasing the likelihood that a random fluctuation will be sufficiently strong to put the system into the alternative, more stable basin of attraction.

Describing the stabilities of percepts in this way suggests that the temporally dependent behavior of the visual system might be consistent with some rather general dynamical laws of nature. Indeed, our experiments provide evidence that is consistent with what is predicted by a recent application of dynamical theory to motion quartets (Schöner & Hock, 1992): Loss of temporal stability is observed at the boundaries of hysteresis (Experiment 5), and the magnitude of the hysteresis depends on both the rate of parameter change (Experiment 6) and the level of intrinsic fluctuations (Experiment 7). However, the appropriateness of characterizing the behavior of the visual system dynamically requires generalization of these results to other perceptual phenomena and more analytic experimental testing. For example, temporal stability in the presence of intrinsic, random fluctuations is achieved in dynamical theory through the operation of fast-acting restoring forces that counteract the effect of the fluctuations. On this basis, we would expect temporal stability for the motion quartets to be decreased by conditions that decrease the transient or phasic responsiveness of the visual system. Also predicted by dynamical theory is the existence of a limit to the magnitude of the hysteresis. At this limit, which can be approached only when temporal stability is very high, the slope of the hysteresis function is expected to become very steep, indicating that perceptual change occurs because the initial percept is no longer possible (rather than because a random fluctuation arises within the visual system).[7]

These experimental predictions emerge only if one takes the conceptual step from characterizing the perceptual stability of the motion quartets in terms of the mutual inhibition of alternative motion directions to a more general formulation in which pattern formation for the quartets is described in terms of nonlinear dynamics. However, experimental support for these predictions would not demand a dynamical theory of perception. Rather, it would provide further evidence that any theory of perception must account for the dynamical behavior of the visual system.

Thus, at least two kinds of theory are important. One that is currently undergoing rapid development concerns concepts that capture the universal, lawful nature of dynamical phenomena across model experimental systems in a wide variety of physical and biological domains (e.g., Haken, 1977/1983; 1981). The experimental results reported in this study indicate that the visual system is a potential candidate for addition to the roster of systems whose time-dependent behavior is consistent with dynamical theory. Another kind of theory is more attuned to the long-term goal of perceptual theory, which is to predict what is perceived and how the perceiver behaves under a specific set of circumstances. We are not proposing that nonlinear dynamics constitutes such a theory. What we are proposing is that a successful theory of perception would have to account for, and is therefore constrained by, the intrinsic dynamics of the visual system.

Our results demonstrate one way in which constraints of this kind influence perceptual theory. In our experiments, we have introduced conditions with relatively high temporal stability and gradually changed a critical parameter over a wide range of values. As a result of hysteresis, motion patterns are seen that are not specified by the spatial geometry of the quartets (e.g., vertical motion is seen for large aspect ratios). Thus, the generality of Ullman's (1978, 1979) assertion that correspondences in motion perception are specified or determined by the relative closeness of the elements (i.e., motion follows the shortest path) is constrained by the intrinsic stability of percepts. Although other investigators (Schecter & Hochstein, 1989; Schecter, Hochstein, & Hillman, 1988) have shown that nonspatial features such as shape, size, and luminance can compete with proximity in establishing motion correspondence, no such competing stimulus features are introduced into the present study. The issue is therefore not one of resolving multiple sources of specifying information, which is the concern of Cutting's (1986) theory of directed perception. Hysteresis and temporal stability are properties of the percept, not the stimulus, and as such can take precedence over stimulus geometry in establishing motion correspondences. We

[7] This prediction points to the importance of being able to measure the slopes of the ascending and descending data curves (see Footnote 6).

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conclude, therefore, that the role of the motion quartet's stimulus geometry is nonspecific. Values of nonspecific parameters provide a context or medium for the operation of intrinsic visual mechanisms that favor certain percepts but do not determine what is perceived.

This conclusion stands in contrast to the more typical treatment of stimulus parameters as specifying what is perceived through either the detection of features (e.g., Marr, 1982) or higher order stimulus structure (Gibson, 1966, 1979). The nonspecific, contextual function of stimulus information has generally been conceptualized in terms of top-down processes (e.g., Lindsay & Norman, 1977) that clarify detected stimulus information when it does not satisfactorily specify the source of the information, perhaps through the biasing of a hypothetical decision stage of processing (Green & Swets, 1966). A potential virtue of introducing dynamical concepts into perceptual theory is that nonlinear dynamics explicitly incorporates a nonspecific role for stimulus information in terms of control parameters that affect the relative stability of attractor states (e.g., Haken, Kelso, & Bunz, 1985; Kelso, 1984). Consistent with our observation that what is seen is not specified or defined by the spatial geometry of the quartets, Schöner and Hock's (1992) application of dynamical theory to the perception of motion quartets successfully predicts our experimental evidence for the interdependence of hysteresis and temporal stability on the basis of stimulus geometry having a nonspecific influence on the perceived motion pattern.[8]

In conclusion, the results of the experiments reported in this article point to the theoretical importance of perceptual stability. Through the examination of perceptual stability, we can observe dynamical features of the visual system that are common to a wide range of physical and biological domains and can also observe how intrinsic perceptual mechanisms can override stimulus geometry in influencing perceived patterns of motion. Much remains to be learned about how perceptual stability emerges from the mechanisms through which visual information is processed and how what may prove to be universal dynamical laws are realized in these mechanisms.

[8] Related formulations have been proposed by Kawamoto and Anderson (1985), who provided a neural network model in which satiation (loss of temporal stability) is built into synapses, and Ditzinger and Haken (1989, 1990), who addressed adaptation and spontaneous switching in terms of an attention parameter. Schöner and Hock's (1992) approach differs from theirs in the central importance of stability as a property of the percept.

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Received July 27, 1990
Revision received March 6, 1992
Accepted March 6, 1992 ■

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