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FACTORS CONTROLLING THE COMPETING SENSATIONS PRODUCED BY A BISTABLE STROBOSCOPIC MOTION DISPLAY[1]

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Abstract—Two competitive sensations which are produced by a previously described bistable stroboscopic movement display were studied in a series of five experiments. In Experiment 1 each of the movement sensations was selectively adapted, a finding which supports the hypothesis that a different visual process underlies each of the two sensations. In Experiments 2–5 the relative dominance of the two sensations was controlled by the manipulation of five physical stimulus variables—frame duration, duration of the interval between frames, luminance of the interval between frames, contrast of stimulus frames, and degree of dark adaptation. Limiting conditions for the processes mediating the two competitive sensations were elaborated, and the implications of the findings for other studies of stroboscopic movement were discussed.

Key Words—apparent movement; bistable percept; perceptual organization; visual motion perception.

INTRODUCTION

Pantle and Picciano (1976) used a spatiotemporal display similar to one described by Ternus (1938) to study a bistable movement percept. With the display, competing sensations of stroboscopic movement are produced with a cyclic alternation of two stimulus frames. Frame 1 contains three black dots (A, B, C) arranged in a horizontal row on a white background. Frame 2 contains three identical dots (D, E, F), also arranged horizontally but shifted to the right such that the positions of dots D and E of Frame 2 overlap those of B and C, respectively, of Frame 1 (see Fig. 1). When stimulus conditions are appropriately selected, the spatiotemporal display gives rise to a bistable percept: either the observer perceives a group of three dots moving back and forth as a whole ("group movement") or he perceives the overlapping dots of each frame as stationary and a third dot moving back and forth from one end of the display to the other ("element movement"). The group and element movement sensations alternate spontaneously and involuntarily at a rate of about eight times per minute. Each sensation is exclusive of the other such that the percept experienced is never a mixture or combination of the two sensations. Since the external stimulus conditions which produce the bistable percept remain constant as the movement sensations alternate, the change of sensation must be due to a changeover from the operation of one internal mechanism to another, or by a change in the state of activity of some single mechanism. Since the two alternatives are functionally equivalent and indistinguishable psychophysically, we will hereafter use the neutral term "process" to refer to the mechanism or state of activity which underlies either sensation in order to avoid a commitment to a specific interpretation. Because the element and group movement sensations are mutually exclusive, it is clear that only one of the two processes (mechanisms or states of activity) is functional at any instant in time.

Assuming that a version of the two-process interpretation of the bistable phenomenon was correct, Pantle and Picciano (1976) attempted to cause either the element or group movement sensation to predominate by manipulating the stimulus characteristics of the bistable display so as to favor one or the other of the putative processes underlying the sensations. That is, they assumed that the number of element movement sensations reported by an observer in a series of short trials would be greater than the number of group movement sensations whenever stimulus conditions favored one of the underlying visual processes; and the number of group movement sensations would be greater than the number of element movement sensations whenever stimulus conditions favored the other visual process. Pantle and Picciano were able to achieve stimulus control over the movement responses elicited by their display by manipulating the duration of the dark interval between stimulus frames, the type of viewing (binocu-

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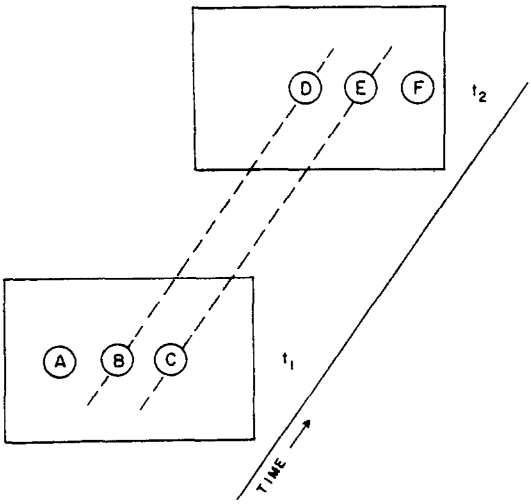

Fig. 1. A schematic representation of the spatiotemporal display used to study two competitive movement sensations.

lar or dichoptic), or the contrast of the stimulus frames.

In the first of the experiments reported in this paper, we attempted to selectively adapt one or the other of the movement sensations produced by the bistable display. In Experiments 2–4 we were able to extend the findings of Pantle and Picciano by obtaining still further stimulus control over the group and element movement sensations by the manipulation of a variety of independent variables. Thereby, we were able to establish a set of limiting conditions which apply to each movement sensation and to compare each set of limiting conditions to those for perceived movement produced with other types of displays. In Experiment 5 we demonstrated that a change in one internal state, namely light–dark adaptation, interacted with the processes which give rise to the element and group movement sensations.

EXPERIMENT 1

The hypothesis that the type of movement sensation produced by the display in Fig. 1 depends upon the predominance of one of two visual processes would be strengthened if it could be shown that each of the processes can be selectively adapted.

If the two-process hypothesis is true, adaptation to some stimulus (A) that weakens the response of the process which mediates the element movement sensation more than the process which mediates the group movement sensation will increase the proportion of group movement sensations reported afterward. If adaptation to another stimulus (B) weakens the response of the group movement process more than the response of the element movement process, the proportion of group movement responses reported afterward should decrease. The effect of stimulus A on the proportion of group movement sensations is opposite to that of adaptation to stimulus B. In Experiment 1 we employed two carefully chosen adapting stimuli in order to determine whether it is possible to shift the proportion of group movement responses in one direction with one adapting stimulus and in the opposite direction with the other adapting stimulus.

Method

Stimulus displays. Both adapting and test displays were spatiotemporal displays like those depicted in Fig. 1. Each of the two frames of a display was presented with one channel of a tachistoscope (Gerbrands Harvard Tachistoscope with Model 130S lamp drive module and Model 160A timer module). Each frame was a white index card on which three dots were drawn in black ink. The relative positions of the dots corresponded to those shown in Fig. 1. Each dot (diameter) subtended a visual angle of 25′ at the viewing distance of 81 cm. The center-to-center distance between any two adjacent dots was 1°. The luminance of the dots was 0.05 mL. The luminance of the white portion of each frame was 1.10 mL. Each frame subtended a visual angle of 6° 10′ vertically and 8° 45′ horizontally.

The duration of each stimulus frame in both adapting and test displays was always 200 msec. There were two different adapting displays. For one display, the element movement adapting display, the interval between stimulus frames (the interstimulus interval, called ISI hereafter) was 10 msec; for the other display, the group movement adapting display, the ISI was 80 msec. There were six test displays, each with a different ISI: either 20, 30, 40, 50, 60 or 70 msec.

Subjects. Thirteen undergraduate psychology students volunteered for Experiment 1. Because the students had no prior practice in making psychophysical judgements, and because the demand on their concentration in the adaptation task was relatively great, they first participated in a perceptual adaptation task described by Pantle (1973). In that task we measured the time required for a sensation of stroboscopic movement of clusters of elements to adapt. Only the subjects (eight of the thirteen volunteers) whose adaptation times were consistent across a number of replications of the task during a practice (screening) session were retained for Experiment 1.

Procedure. Each experimental session was divided into two parts, one part in which the subject made judgements of element and group movement for test displays interspersed between periods of motion adaptation, and another part in which the subject was not adapted to motion (control condition).

The subject viewed an adapting display continuously for 5 min at the beginning of the adaptation part of each session. In any single session only one of the two adapting displays was used. Either the subject adapted to the display which produced the element movement sensation (ISI = 10 msec), or he adapted to the display which produced the group movement sensation (ISI = 80 msec). After the initial adapting period, the adapting display was interrupted for 5 sec every 15 sec. During the middle of the interruption (test trial), one of the five test displays was presented. The test display lasted for three cycles (one cycle: Frame 1—ISI—Frame 2—ISI), and afterward the subject indicated whether he had seen element or group movement. The cyclic alternation between adapting and test displays continued until each of the six test displays had been presented seven or eight times. The order of presentation of the test displays was random with the single constraint that no display was presented $n + 1$ times until each of the other displays had been presented n times.

The procedure which was followed during the control part of each experimental session was identical to that followed during the adaptation part of each session except that the subjects did not view the adapting display prior to the commencement of the test trials nor between the test trials. Instead they scanned objects outside the apparatus under ambient room illumination which produced approximately the same retinal illuminance as the adapting

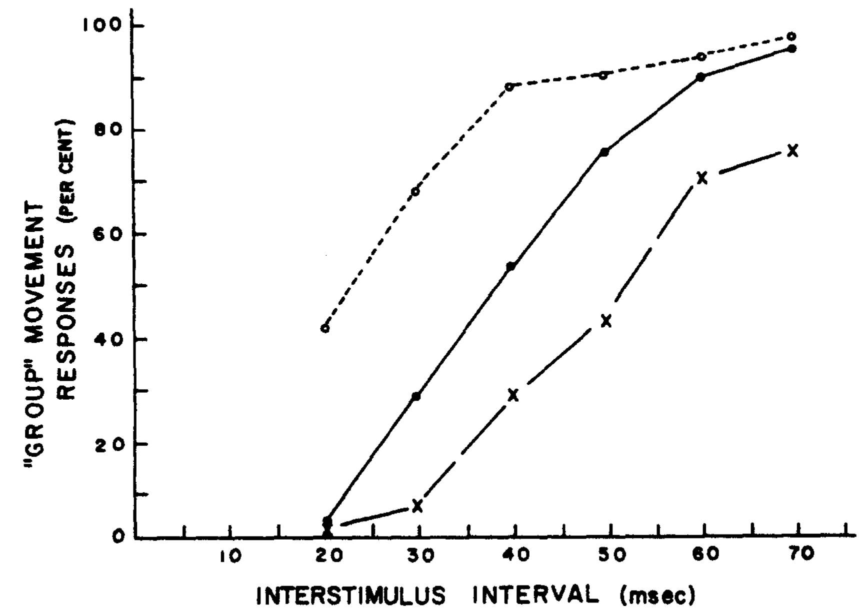

Fig. 2. Mean percentage of group movement responses as a function of the interval between stimulus frames (ISI) (Control function: solid line, filled circles; function obtained after adaptation to element movement: short-dash line, open circles; function obtained after adaptation to group movement: long-dash line, X's).

stimuli. The control condition provided baseline measurements which were used to assess the effects of element or group movement adaptation on the perception of the test displays. There was a 5-min break between the adaptation and control parts of each experimental session.

For each trial in all the sessions the subject directed his gaze toward the center of the stimulus display and at the same time attended to the entire display. No fixation point was provided. Each subject served in four experimental sessions. Over the four sessions a total of 30 judgments were obtained for each test display in the control condition. A total of 15 judgments were obtained for each test display while the subject was adapted to element movement, and a total of 15 while he was adapted to group movement. The order in which the subjects served in each adapting condition and the order in which the adapting and control conditions occurred within a session were counterbalanced across subjects.

Results and discussion

The percentage of group movement responses at each ISI was determined for each subject for each condition of motion adaptation and for the control condition. The pattern of results was the same in all important respects for the different subjects, and therefore each point plotted in Fig. 2 is the mean of the percentages for all eight subjects. Data obtained in the control condition are represented by the solid curve. The curve shows the mean percentage of group movement responses as a function of ISI. The function drawn with short dashes is the data obtained after adaptation to element movement; the function drawn with long dashes, data obtained after adaptation to group movement.

All three functions shown in Fig. 2 are monotonically increasing functions. As ISI was increased, subjects reported group movement sensations on a greater percentage of trials. A repeated measures analysis of variance of the percentage of group movement responses shows that the main effect of ISI is statistically significant, F (5, 35) = 117.53, $P < 0.001$. In the control condition subjects almost never reported group movement (i.e. they almost always saw element movement) at the shortest ISI studied (20 msec). At the longest ISI (70 msec), subjects saw group movement on nearly 100% of the trials. With an ISI of 40 msec subjects saw element movement on approximately half of the trials, and group movement on the other half. Relative to the control function, the function obtained after adaptation to group movement is depressed at all ISI's. The depression indicates that subjects saw group movement less often after adaptation to group movement. On the other hand, every point on the function obtained after element movement adaptation is higher than the corresponding point on the control function, indicating that subjects saw group movement more often (i.e. they saw element movement less often) after adaptation to element movement. The main effect of adaptation state is significant, F (2, 14) = 48.98, $P < 0.001$.

The main effect of adaptation state obtained in Experiment 1 demonstrates that the element and group movement sensations can be selectively adapted. After adaptation to the element movement display, the proportion of group movement responses increased, presumably because the process mediating the element movement sensation was weakened. After adaptation to the group movement display, the proportion of element movement responses increased, presumably because the group movement process was weakened. Although the effect of ISI on the type of movement seen in Experiment 1 and in the earlier experiment by Pantle and Picciano (1976) is clear, the interpretation of the effect is not straightforward. In Experiment 2 we take a closer look at the effect of temporal variables on group and element movement responses.

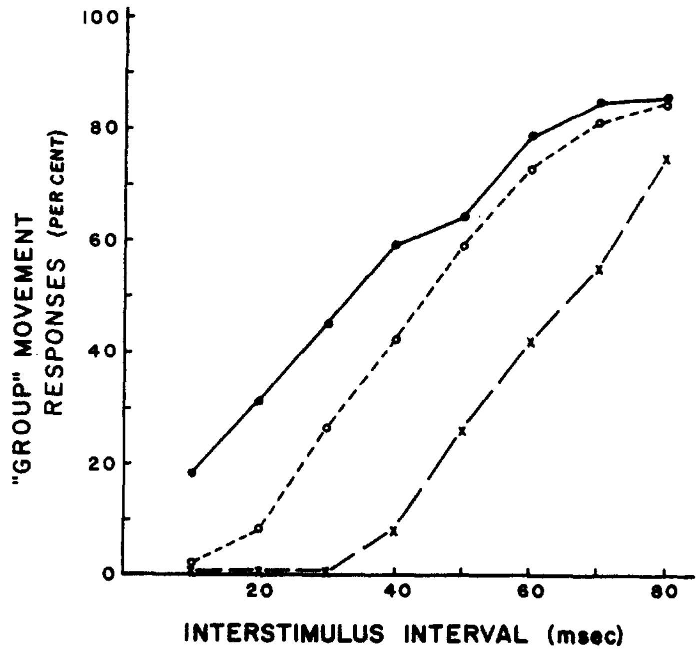

Fig. 3. Mean percentage of group movement responses as a function of the interval between stimulus frames (ISI) (Frame duration of 400 msec: solid line, filled circles; 200 msec: short-dash line, open circles; 100 msec: long-dash line, X's).

EXPERIMENT 2

Two aspects of the spatiotemporal display used in Experiment 1 change when the ISI is varied. Either aspect may have caused the variation in the proportion of element and group movement responses as ISI was manipulated. One aspect is the ISI *per se*, i.e. the amount of time that elapsed between stimulus frames. This aspect alone might be a critical one if the movement sensations depended upon the degree to which stimulation by successive frames was integrated. For example, if the element movement sensation depended more upon a process which integrated the stimulation produced by successive frames than did the group movement sensation, then an increase of the ISI *per se* would cause a decrease in the proportion of element movement responses, or equivalently, an increase in the proportion of group movement responses. The second aspect of the display which is altered by a change of ISI is its temporal periodicity. The shorter the ISI, the shorter is the period (the time it takes for the display to repeat itself). Temporal periodicity might be a critical variable if the movement sensations depended differentially upon rate of stimulation. For example, if the element movement process were tuned to a higher temporal frequency (periodic stimulation with a shorter period) than the group movement process, then the element movement sensation would be dominant when the ISI and temporal period are short, and the group movement sensation would be dominant when the ISI and the temporal period are long. In order to dissociate the effects of ISI *per se* and of temporal periodicity, and in order to shed some light on the processes underlying the effect of ISI, we conducted a second experiment in which both frame duration and ISI were varied.

[2] Of all the initial volunteers a total of four subjects were dropped from Experiments 2–5 because they could not see apparent movement or had difficulty maintaining a criterion which consistently distinguished between the two sensations. The subjects who were dropped from our experiments seem to number no more than those who do not report apparent movement with classical phi displays.

Method

Subjects. Eight introductory psychology students from Miami University served as subjects.[2] None of the subjects had previous experience making psychophysical judgments and all were naive with respect to the purpose of the experiment.

Stimuli and apparatus. The stimulus frames used in Experiment 2 were identical to those used in Experiment 1 and they were displayed with the same apparatus.

Procedure. Subjects served in four experimental sessions, each of which was conducted on a different day. During each experimental session, each subject saw a series of 120 stimulus sequences (trials)—5 replications of 24 conditions resulting from the factorial combination of 3 frame durations and 8 ISI's. The order of the conditions was random with the constraint that, for any one of the three possible frame durations, no individual ISI was repeated a third time until each of the other ISI's had been used twice. Furthermore, none of the eight ISI's was paired a second time with the same frame duration until it had been paired once with each of the other two frame durations. A single trial consisted of four complete cycles of the stimulus sequence with a particular combination of frame duration and ISI. Approximately 10 sec intervened between any two trials.

Results and discussion

The percentage of group movement responses for each experimental condition was determined for each subject. In all important respects, the pattern of results was the same for all subjects. The group results are summarized in Fig. 3, where the percentage of group movement responses is plotted as a function of ISI. A separate curve is plotted for the data obtained with each frame duration. Each data point is the average percentage of group movement responses for seven subjects.

There was a significant effect of ISI, $F(7, 42) = 66.96$, $P < 0.001$. The main effect of frame duration was also significant, $F(2, 12) = 15.84$, $P < 0.001$. At any ISI in Fig. 3, the point on the 400-msec curve is above the corresponding point on the 200-msec curve: likewise, any point on the 200-msec curve at a given ISI is above the corresponding point on the 100-msec curve. Thus, the number of group movement responses is greater for longer frame durations, irrespective of ISI.

Since both frame duration and ISI were shown to have a significant effect on the percentage of group movement responses, it is logical to ask how frame duration and ISI might be related in the generation of group and element movement sensations. The interaction of frame duration and ISI was significant in a repeated measures analysis of variance, $F(14, 84) = 3.17$, $P < 0.001$. Therefore, we conclude that the effects of frame duration and ISI are not simply additive.

It may be that the critical variable in the generation of group and element movement sensations is the overall cycle time (or period) of the stimulus sequence (where the period is equal to the duration of Frame 1 + ISI + duration of Frame 2 + ISI). If so, it would be expected that the percentage of group movement responses would vary whenever the period of the stimulus sequence varied. However, the results show that a *constant* percentage of group movement responses was obtained with *different* periods. For example, as can be seen in Fig. 3, subjects reported group movement sensations for 50% of the sequences which had a frame duration of 400 msec and ISI of 34 msec (period = 868 msec), a frame duration of 200 msec and ISI of 45 msec (period = 490), or a frame duration of 100 msec and an ISI of 68 msec (period = 336 msec). Similarly, 20% group movement responses were obtained for periods as different as 822, 452 and 294 msec. Thus, it is clear that any effect that temporal periodicity has on the type of movement seen cannot be independent of frame duration and ISI. Although there is no simple tradeoff of ISI and frame duration in the generation of group and element movement sensations, the results of the second experiment do indicate that an increase of either frame duration or ISI favors the group movement sensation, while a decrease of either frame duration or ISI favors the element movement sensation. Both variables help to define limiting conditions which are compared later to those for perceived movement with other types of displays.

EXPERIMENT 3

When an observer views a pair of random-dot patterns which are presented successively and which each contain a region of dots which is the same except for a uniform displacement, the region appears to move back and forth (Anstis, 1970; Bell and Lappin, 1973; Braddick, 1974; Julesz, 1971). Braddick (1973) found that the perception of movement of the random-dot cluster could be weakened if the interval between the pair of successively presented patterns was illuminated with uniform light rather than kept dark. In Experiment 3 we attempted to determine whether or not the presence of illumination of the interstimulus interval of our display would differentially affect the processes which give rise to the element and group movement sensations.

Method

Subjects. Ten students served as subjects in the experiment. All were naive about the purpose of the experiment and none had previous experience making psychophysical judgments.

Stimuli. Each member of a stimulus pair similar to those described in the previous two experiments was presented in one channel of the three-channel tachistoscope. The viewing distance was 81 cm, and at this distance the diameter of each black dot was 40′, with a center-to-center separation of 60′ visual angle between adjacent dots. The luminance of each black dot was 0.08 mL; that of the white background, 0.42 mL. The overall angle subtended by each stimulus frame was 6° 10′ vertically and 8° 45′ horizontally.

In addition, a plain white card was inserted into the third field of the tachistoscope for presentation during light-filled ISI's. The third field could be adjusted to one of six luminances between 0.00 mL and 2.40 mL.

Procedure. Each subject viewed 60 presentations of alternating stimulus frames (trials) during a single experimental session. ISI was held constant at 30 msec and stimulus duration was held constant at 200 msec. On any given trial the luminance of the blank field displayed during the ISI was randomly chosen from the six possible values under the constraint that no luminance would be repeated a third time until all other luminances had been presented twice. Each trial consisted of three complete cycles of the stimuli.

Results and discussion

The number of times that each subject reported group movement in each luminance condition was converted to a percentage and entered into a Friedman analysis of variance by ranks. The pattern of results was consistent across subjects, and the effect of ISI luminance on the type of movement reported by the subjects was statistically significant, $\chi^2(5) = 35.89$, $P < 0.001$.

The manner in which ISI affected the subjects' movement percept is shown in Fig. 4 where the mean percentage of group movement responses of all subjects is plotted as a function of the luminance of the uniform field during the ISI. The leftmost, circled point in the graph gives the mean percentage of group movement responses when the ISI was completely dark. The element movement sensation predominated. The mean percentage of group movement responses for ISI luminances that spanned the log unit from 0.03 to 0.3 mL remained approximately the same as that for a completely dark ISI. However, there was an abrupt change in the percentage of group movement sensations reported as ISI luminance was increased from 0.3 mL, a luminance lower than that of the stimulus frames, to 0.8 mL, a luminance higher than that of the stimulus frames. At the two highest ISI luminances, the group movement sensation predominated.

The influence of light in the ISI on the percentage of group movement sensations could possibly be due to a reduction in the effective contrast of the stimulus frames arising from temporal luminance summation.

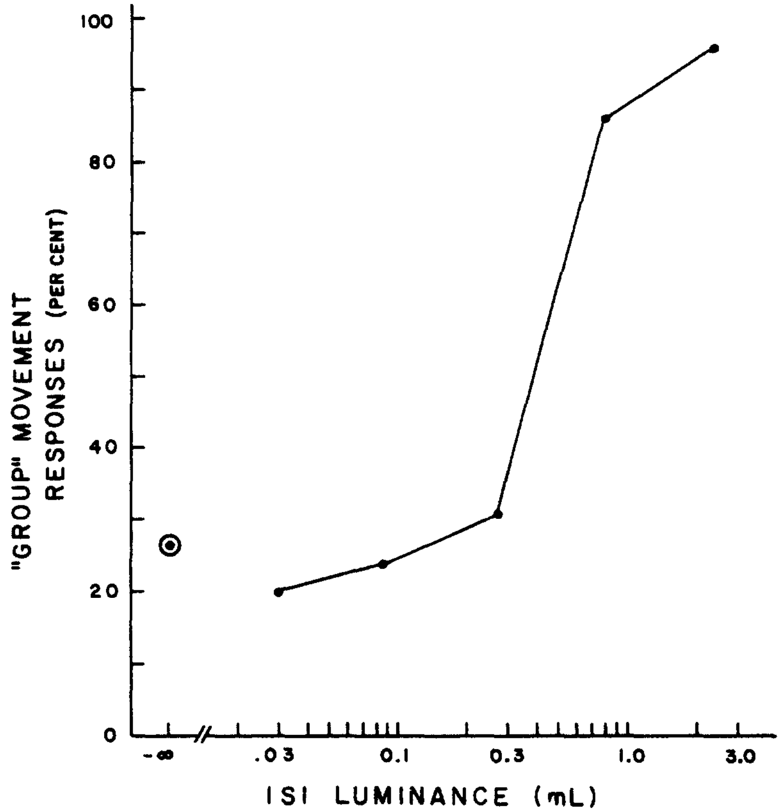

Fig. 4. Mean percentage of group movement responses as a function of the luminance of the interstimulus interval (ISI).

If the temporal integration of the luminance of a stimulus frame and the luminance of the uniform field of the ISI were complete, the effective contrast of a stimulus frame would be given by the following formula:

$$\hat{c} = \frac{\Delta L}{L_1 + (0.15)(L_2)}$$

where ΔL is the difference between the luminances of the dots and the background of a stimulus frame, L_1 is the background luminance of a stimulus frame, and L_2 is the luminance of the uniform field of the ISI. Assuming complete temporal integration, the effective stimulus contrasts for the ISI luminances of 0.00, 0.03, 0.09, 0.27, 0.80 and 2.40 mL used in the present experiment were 0.80, 0.79, 0.78, 0.73, 0.62 and 0.43, respectively. If the temporal integration were less than complete, which it most probably is over an interval of 230 msec (the total duration of a stimulus frame and an ISI), then the effective contrasts would be greater than the values computed above. In order to determine whether the effective contrast of the stimulus frames was the critical factor causing the changes in percentage of group movement sensations shown in Fig. 4, we directly manipulated the contrast of stimulus frames in another experiment.

EXPERIMENT 4

Pantle and Picciano (1976) have shown that a reversal of stimulus contrast from one stimulus frame to the next (from black dots on a white background to white dots on a black background) eliminates element movement sensations in the element–group movement paradigm. It is possible, therefore, that changes in the magnitude (but not direction) of stimulus contrast alone will alter the proportion of element and group movement sensations in the element–group movement paradigm. Such a finding might be consistent with and support the "change of effective contrast" interpretation of Experiment 3. On the other hand, there is evidence from grating adaptation studies (see Sekuler, Pantle, and Levinson, 1978, for summary) that the response of at least one type of movement mechanism saturates at low stimulus contrasts (about 5 times threshold) and is independent of contrast for a wide range of suprathreshold values. If neither the element nor the group movement mechanism is affected by level of stimulus contrast, changes of stimulus contrast would not be expected to alter the proportion of element and group movement responses.

Method

Subjects. Twelve students served in the experiment. None had previous experience making psychophysical judgments and all were naive about the purpose of the experiment.

Stimuli. Four pairs of stimuli were used, all with dot spatial arrangements identical to those used in Experiment 1. However, each of the dots measured 9 mm in diameter with a center-to-center separation between adjacent dots of 15 mm. The visual angle subtended by each dot was approximately 38′. The center-to-center distance between adjacent dots was 1° 30′ visual angle. The luminance of the background of each pair of stimuli was 1.65 mL. The

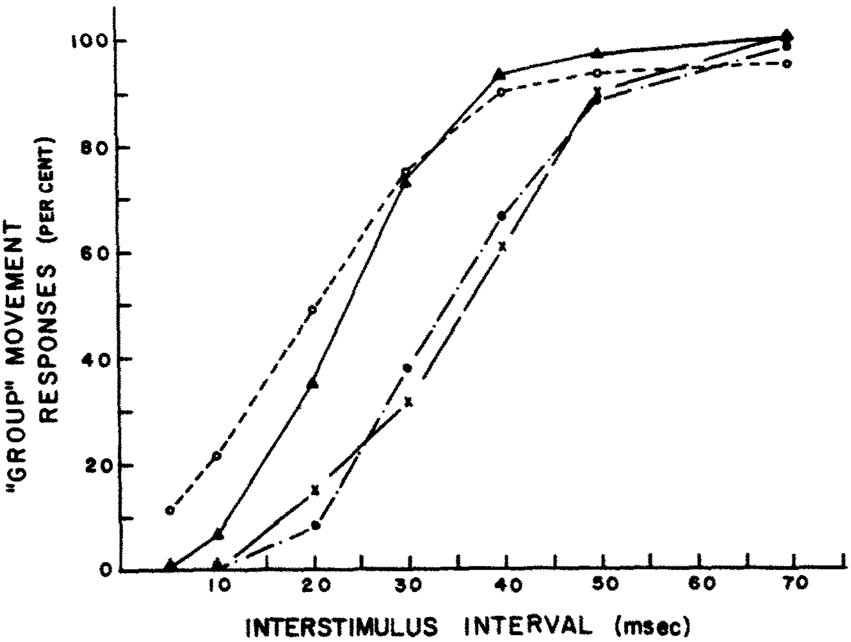

Fig. 5. Mean percentage of group movement responses as a function of the interval between stimulus frames (ISI) (Stimulus frames with dot contrast of 0.11: short-dash line, open circles; 0.23 contrast: solid line, filled triangles; 0.53 contrast: long-dash line, X's; 0.81 contrast: dot-dash line, filled circles).

luminance of the dots for different pairs of stimulus frames was varied. For one pair, the luminance of the dots was 0.30 mL; for another pair, 0.77 mL; for the third and fourth pairs, 1.28 and 1.49 mL, respectively. Thus, given a background of constant luminance, there were four pairs of stimulus frames with contrasts of 0.81, 0.53, 0.23 and 0.11, where contrast is defined according to the formula $C = \Delta L/L$. ΔL is the difference between the luminances of the dots and the background, and L is the luminance of the background.

The stimuli were matte photographs of white index cards with dots drawn in black ink. Different exposure times were used to produce pairs of photographs (stimulus frames) with the different contrasts. Each pair of stimuli was presented with two channels of a three-channel tachistoscope.

Procedure. Subjects served in four experimental sessions conducted on separate days. During any particular session, stimulus frames of a single chosen contrast were used for testing. During the session there were 35 trials—five at each of seven ISI's between 5 and 70 msec. Stimulus duration was held constant at 200 msec and ISI was randomly selected with the constraint that no single ISI was repeated a third time until all others had been used twice. The order in which the four conditions of stimulus contrast were presented to the subjects was counterbalanced across subjects.

Results and discussion

Each function in Fig. 5 shows, for a single stimulus contrast, the mean percentage of group movement responses as a function of ISI. Each point on a curve is based on 60 responses, five for each of twelve subjects. Again there was a significant main effect of ISI, $F(6, 66) = 129.67$, $P < 0.001$. The present result extends the earlier findings of Pantle and Picciano (1976) in showing that the effect of ISI is present for low, as well as high, contrast stimuli. The main effect of stimulus contrast was also significant, $F(3, 33) = 19.44$, $P < 0.001$. Subjects reported a greater percentage of group movement sensations at lower contrasts. Except for the 70-msec ISI where the percentage of group movement responses is near 100 for all stimulus contrasts, points on the curves for contrasts of 0.11 and 0.23 fall above corresponding points on the curves for contrasts of 0.53 and 0.81 at all ISI's.

The changes in the percentage of group movement responses obtained in the present experiment with reductions of stimulus contrast are in the *direction* required to account for the results of Experiment 3. However, the range of absolute stimulus contrasts over which reductions of stimulus contrast affected the percentage of group movement responses in Experiment 4 does not coincide with the range of effective stimulus contrasts over which reductions affected the percentage of group movement responses in Experiment 3. In Experiment 3 a change of effective stimulus contrast from 0.73 to 0.62 increased the percentage of group movement responses from 31% to 86%. In Experiment 4, an even larger reduction of stimulus contrast from 0.81 to 0.53 produced no change in the percentage of group movement responses. The curves for these two contrast levels in Fig. 5 completely overlap. Not until the contrast was reduced to 0.23 or 0.11, a few times threshold levels for the conditions of the experiment, was there any effect of stimulus contrast on the type of movement seen by the subject.

Two conclusions are warranted by the data: (1) at near threshold contrasts the process underlying the group movement sensation more readily dominates the process underlying the element movement sensation than it does at high contrasts; (2) some process other than temporal integration and reduction of effective stimulus contrast must be responsible for the effects of ISI illumination in Experiment 3.[3] Like ISI and frame duration, ISI illumination and stimulus contrast are variables that can be used to define limiting conditions for the element and group movement sensations. Again, the limiting conditions will be compared later with the limiting conditions for perceived movement with other types of displays.

EXPERIMENT 5

It is generally held that, in humans, vision with high levels of illumination is mediated primarily by cones and that vision with low levels of illumination is mediated primarily by rods. This principle manifests itself during the course of dark adaptation after exposure to a bright flash of light. During dark adaptation there is a changeover from cone vision to rod vision. If there were a different input of rods and cones to the processes mediating the element and group movement sensations, then one would expect a change in the proportion of element and group movement sensations produced by a constant spatiotemporal (element–group movement) display during dark adaptation. There are other reasons for expecting that the level of light–dark adaptation may influence element and group movement sensations. Physiological experiments show that the response characteristics of visual neurons in the cat change with the level of light–dark adaptation (Barlow, Fitzhugh and Kuffler, 1957; Zacks, 1975), and Breitmeyer (1973) has shown psychophysically that the temporal frequency response of movement-sensitive mechanisms studied with gratings shifts to lower frequencies as dark adaptation increases.

Method

Subjects. Five subjects, including the authors, participated in Experiment 5. All subjects were experienced psychophysical observers.

Apparatus and stimuli. A three-channel Maxwellian-view system was used in the experiment. Two stimulus channels provided the two individual stimulus frames of the element–group movement display, and the third channel provided a bright adaptation field. In one of the stimulus channels, a collimated light beam was passed through a photographic transparency to produce one of the stimulus frames of the element–group movement display. The second stimulus channel provided the second stimulus frame. The retinal illuminance of the dots in each stimulus frame was approximately 110 td; the retinal illuminance of the background of each stimulus frame was 1100 td. Each dot subtended a visual angle of 53′, and the center-to-center distance between a pair of adjacent dots was 1°31′. Each stimulus frame as it appeared to the subject was circular with a diameter of 12°37′.

The two stimulus frames were presented in alternate succession to the subject by means of an episcotister placed at a focal point in the optical paths of both stimulus channels. A variable-speed motor in combination with a multi-ratio speed reducer allowed the subject to control the speed of rotation of the episcotister, and thereby the rate of alternation of the stimulus frames. As the speed of rotation was increased, both the duration of each stimulus frame and the interval between them (the ISI, which was completely dark) decreased. Both of these decreases were shown to produce a lower percentage of group movement responses in Experiment 2. The ratio of frame duration to ISI duration remained the same for all rates of alternation of the stimulus frames.

The adaptation field provided by the third channel was spatially uniform, was circular with a diameter of 12°37′, and had a retinal illuminance of 58,000 td. A stop was placed at a focal point in the adaptation channel to insure that the image of the source formed in the plane of the subject's pupil did not exceed the diameter of the subject's pupil.

All three channels were combined by beam-splitters prior to the final lens of the optical system. The final lens formed three superimposed images of the two sources in the plane of the subject's right eye. A chin rest was used to stabilize the subject's head position. The retinal locations of each stimulus frame and of the adaptation field were concentric.

Procedure. The general plan of the experiment was to have each subject set the rate of alternation of the stimulus frames at a point (hereafter point of equilibrium) which produced an optimal bistable percept while viewing the element–group movement display at regular intervals following light adaptation. In general, the point of equilibrium[4] is defined as that speed of rotation of the episcotister which yielded a sensation of spontaneous alternation between element and group movement sensations of approximately the same probability and strength. At rates of alternation which were too slow, group movement predominated; at rates which were too fast, element movement predominated. The subject adjusted the alternation rate by changing the speed of the motor which controlled the speed of rotation of the episcotister in the two stimulus channels. All subjects practiced setting their own equilibrium points until they were able to complete the adjustment within 10–15 sec.

Each subject served in three experimental sessions. At the beginning of each session, the subject dark adapted for approximately 2 min. Next, the subject viewed the adaptation field alone with his right eye for a 90-sec interval. Following 90 sec of light adaptation, the experimenter occluded the adaptation field and the subject made his first setting of the point of equilibrium. After finding his

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[3] It is possible that the change in the proportion of element and group movement responses as a function of ISI luminance is related to changes in temporal luminance transients produced by the display. If the background luminance of the stimulus frames were equal to the ISI luminance, the only spatiotemporal change of intensity that would occur during a stimulus sequence would be that produced by the appearance of the dots during a stimulus frame and their disappearance during the ISI. This matched condition was not one of the conditions of Experiment 3. Either the ISI luminance was less than the background luminance or it was greater, the result of which was that the intensity of the whole stimulus field was modulated (flickered in square-wave fashion) during a stimulus sequence. It is interesting that the element movement sensation predominated whenever the stimulus frames constituted the bright phase of the modulation cycle, and the ISI, the dark phase; and that the group movement sensation predominated whenever the stimulus frames constituted the dark phase of the cycle, and the ISI, the light phase. Stated in another way, the element movement sensation predominated when the pattern signal produced by the stimulus frames was part of an "on"-transient associated with an increase of illumination over the whole visual field; the group movement sensation predominated when the pattern signal produced by the stimulus frames was part of an "off"-transient associated with a decrease of illumination over the whole visual field.

[4] The point of equilibrium corresponds to the ISI value where any of the functions which relate percentage of group movement responses and ISI in previous experiments cross the ordinate value of 50%.

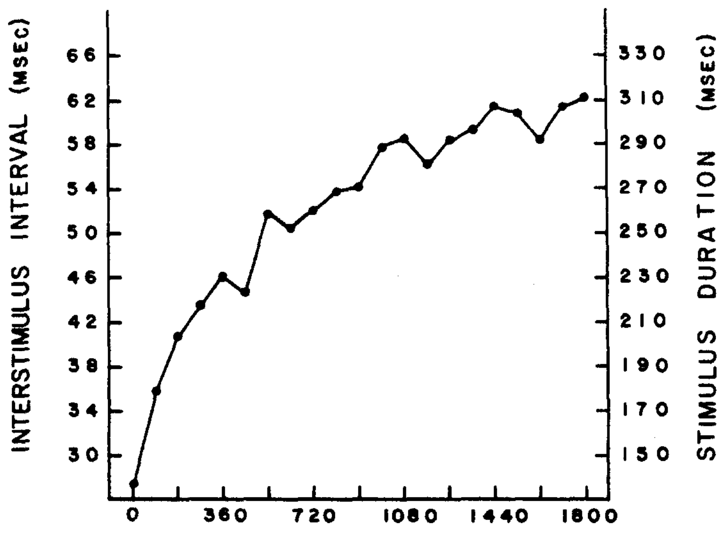

Fig. 6. The interstimulus interval (left-hand ordinate) and corresponding frame duration (right-hand ordinate) required to produce spontaneously alternating movement sensations as a function of dark adaptation time.

point of equilibrium, the subject turned away and faced a dark wall (0.0014 mL) until the next time he was required to set his point of equilibrium. Exactly 90 sec after the *beginning* of the first adjustment of his point of equilibrium, the subject made a second adjustment. This sequence of events continued so that the subject set his point of equilibrium every 90 sec over a period of 30 min of dark adaptation. Thus, during any single session, each subject made 21 settings of his equilibrium point.

Following each adjustment of the point of equilibrium by the subject, the speed of the episcotister was set at a random point for the next trial. At the completion of the experiment each subject had made a total of 63 bistable point settings, 3 at each of the 21 delays after the adaptation field was extinguished.

Results and discussion

The results of Experiment 5 are summarized in Fig. 6. The function gives the rate of alternation corresponding to the point of equilibrium as a function of the time after the adaptation field was turned off. Since ISI and stimulus duration both changed when the subject varied alternation rate, the point of equilibrium is expressed both in terms of ISI (left-hand ordinate) and stimulus duration (right-hand ordinate). Each datum point is the mean of 15 estimates of the point of equilibrium, 3 for each of 5 subjects. As can be seen in the figure, the subjects had to increase the stimulus duration and ISI (the period of alternation of the stimulus frames) in order to maintain the point of equilibrium as time in the dark increased. An analysis of variance showed that the change in the point of equilibrium is statistically significant, F (20, 80) = 19.14, $P < 0.001$. The change in the point of equilibrium is most easily understood in the following way. If the subjects did not change the alternation period as dark adaptation progressed, the element movement sensation became predominant, i.e. grew in strength relative to the group movement sensation. Since an increase of either stimulus duration or ISI favors the group movement sensation, the subjects increased the alternation period in order to preserve the balance between the group and element movement sensations as dark adaptation progressed.

It is not possible to draw any firm conclusions about the neural origin of the change in the point of equilibrium with dark adaptation. However, two likely candidates are that the change in the equilibrium point is the result of (1) a change in response properties of the processes which underlie the group and/or element movement sensations (Zacks, 1975), and (2) a change from a cone- to a rod-dominated movement system.

DISCUSSION

In Experiments 1–5 a bistable movement display which was first studied systematically by Pantle and Picciano (1976) was examined in more detail. It was discovered that a number of new variables can be manipulated to favor one of the stable states evoked by the display. Specifically, the group movement sensation could be made increasingly dominant over the element movement sensation by (1) increasing the duration of the frames of the display, (2) increasing the illumination of the interval between stimulus frames from dark to light, (3) reducing stimulus contrast, and (4) increasing the level of light adaptation of the subject. Unlike many other bistable phenomena, the element–group movement phenomenon is interesting in that it has been possible to identify a variety of variables which can be manipulated to bring it under stimulus control.

With stimulus conditions held constant, our suprathreshold display is bistable. There are spontaneous abrupt changes between two mutually exclusive sensations. As we stated in the introduction, the changes of sensation must be due to competition between two perceptual processes. *Across different stimulus conditions*, different proportions of element and group movement occur, but the character (quality) of the sensations does not change. For this reason it seems most parsimonious to assume that the change of stimulus conditions does nothing more than favor one of the processes which compete even when stimulus conditions are held constant. Given that this conclusion is valid, the variables which cause either the element or group movement sensation to predominate can be used to describe the limiting conditions for the operation of the processes mediating the respective sensations. In the next two sections we compare the limiting conditions summarized above for the element and group movement sensations with those that have been discovered for perceived movement with other types of displays.

Characteristics of processes capable of mediating movement sensations

The ϵ-process. When a subject is alternately presented with a pair of random-dot patterns, each of which contains a region of dots that are identical (100% correlation) except for a uniform displacement, the region appears to move back and forth as a whole (Anstis, 1970; Bell and Lappin, 1973; Braddick, 1973, 1974; Julesz, 1971). Braddick (1973, 1974) studied the effects of a variety of variables on the ability of subjects to perceive the movement of correlated areas of random-dot patterns. Four of these variables have also been manipulated in Experiments 3 and 4 or in the experiments conducted by Pantle and Picciano (1976). The variables are ISI, ISI luminance, stimulus contrast, and type of viewing (binocular or dichoptic). Any manipulation of the four variables which decreases the ability of subjects to perceive the movement of correlated areas of random-dot patterns also produces fewer reports of element movement sensations with the element–group movement display. The element movement sensation and the sensation of the movement of a correlated area in random-dot patterns share the same set of limiting conditions. Given such similar behavior, it is likely that both movement percepts depend upon a common process (hereafter called the ϵ-process). Braddick's experiments (1973, 1974) make it clear that the ϵ-process depends upon a local matching of the intensities of points in successive stimulus frames.

Outside the limiting conditions which give rise to the perception of the movement of correlated areas of random-dot displays, subjects see no movement. They perceive only the flashing or flicker produced by the successive frames. However, outside the limiting conditions which give rise to the element movement sensation with the element–group movement display, subjects do perceive movement—movement of a different kind (i.e. the group movement sensation). One major difference between the random-dot display and the element–group movement display, then, appears to be that the bistable display reflects the existence of two visual processes in competition (the ϵ-process and some other process) while the random-dot display isolates only the ϵ-process.

The γ-process. The stimulus conditions which were shown in Experiment 2 to favor the group movement sensation are the same as those required to obtain stroboscopic movement of clusters of elements investigated by Pantle (1973) and Ramachandran, Madhusudhan Rao, and Vidyasagar (1973). The favorable conditions are long frame durations (preferably greater than 100–200 msec) and long ISI's (preferably greater than 50 msec).

Besides having the two limiting conditions in common, the group movement sensation and the cluster movement sensations of Pantle and Ramachandran *et al.* are phenomenologically similar and place similar processing requirements on the visual system. In the cluster movement studies, subjects perceived a cluster of elements defined by a global form cue to move as a whole. In the Pantle study two stimulus frames were alternated, and each frame contained a cluster of rectangular elements whose orientation differed from that of background elements. In the Ramachandran *et al.* study two stimulus frames were alternated, and each frame contained a cluster of elements (dark and light points) whose tendency to occur in runs was different from that of background elements. In each study the cluster was located in a different position in each frame. When the frames were alternated, subjects perceived the cluster of elements defined by the global form cue to move back and forth as a whole. This was true despite the fact that the positions of the elements within the cluster and within the background were random, and they were different from one frame to the next. The internal structure of the cluster did not have to remain the same in order that the identity of the cluster be retained or its movement perceived. In the present studies the average brightness of the area encompassed by the group of three dots in each frame was less than that of the remainder of the stimulus frame, and the brightness difference provided a global form cue by which the dots as a group could have been segregated from the background. Inasmuch as the three dots are perceived to move as a group, local brightness differences which defined the individual dots were unimportant,[5] as was the local position information in the cluster movement studies. Indeed, in a series of experiments to be reported elsewhere (Pantle and Petersik, 1978), slight perturbations were introduced in the spatial positions of individual elements of the frames of an element–group movement display, and the perturbations did not affect the group movement sensation.

Given the similar phenomenological characteristics of the group movement sensation and the cluster movement sensations described by Pantle and Ramachandran *et al.*, and given their similar behavior in the face of the manipulation of a few variables, it is reasonable to conclude that they depend upon a common process (hereafter called the γ-process) which is preceded or accompanied by global form processing. When the limiting conditions for cluster movement in the experiments of Pantle and Ramachandran *et al.* are exceeded, as happens when frame duration or ISI is too short, only local movement of elements or the flicker produced by the successive frames is perceived. Data from studies which focus upon the perception of movement of clusters of elements

[5] A global form process which acted like a low-pass, spatial frequency filter could preserve the low-frequency components which define the group of dots as a whole and remove the high-frequency components which define the individual dots.

defined by global form cues reflect only the one process (the γ-process), a process which has different functional properties than the ϵ-process isolated in studies of the movement of correlated areas in random-dot displays.

Implications of the present results for other studies of movement processes and for other multistable phenomena

Our results have a number of implications for research on form and movement processes. First, the idea that movement sensations can originate from either of two visual processes changes the perspective from which a number of current problems in movement perception are viewed. The following are but a few examples. In a series of experiments Navon (1976) attempted to determine the role that figural properties of a stimulus play in the perception of its motion. In order to provide some evidence on this question, Navon devised a display in which the preservation of figural identity, if operative, would bias an observer's percept toward one of two possible outcomes; i.e. one outcome would be favored over the other if the movement process was affected by figural constancy. With his spatiotemporal display, Navon found that figural identity failed to bias perception, and he took his result as evidence that the form properties of a stimulus are irrelevant to its perceived motion. If Navon's procedure and display isolated only the γ-process, then his results are not surprising. The percepts of the subjects in Navon's experiments are like the cluster movement sensations (Pantle, 1973; Ramachandran *et al.*, 1973) and the group movement sensation which we described in this paper and attributed to the γ-process. In all these cases, including that of Navon, a whole is perceived to move, and the internal or local form details of the whole are irrelevant to the movement impression. There is evidence that, under the appropriate conditions, the γ-process may even inhibit the transmission of information about the exact form or shape of a moving stimulus (Breitmeyer, Love and Wepman, 1974). The movement sensations in Navon's experiments probably originate only in the γ-process because the positions of the stimulus elements in the successive frames of his display were more than 20′ apart, and because he used a long ISI. The ϵ-process was precluded from playing a role in Navon's experiments because its operation requires that the elements in successive frames of a display be less than 20′ apart. The upper limit (20′) on the spatial displacement tolerated by the ϵ-process is derived from the results of an experiment by Braddick (1974) in which it was shown that the perception of the movement of a correlated area in a random-dot display occurs only when the correlated area is not shifted by more than about 20′ regardless of dot or element size.[6] With our element–group movement display, a second movement sensation (the element movement sensation) originating from the ϵ-process is possible because the groups of elements in the separate frames overlap spatially and are within the 20′ limit of displacement.

Based upon the discussion above, it might be expected that two different movement sensations could be produced by the alternation of almost any two complex forms in the same location (or nearly identical locations) of the visual field if the temporal characteristics of the sequence are varied and favor either the ϵ- or γ-process. Shepard and Judd (1976) presented two perspective views of three-dimensional objects in alternation in the same spatial location. With a frame duration of 400–500 msec (like that which favored the group movement sensation in Experiment 2), Shepard and Judd's subjects perceived the object to move as a rigid whole throughout its entire trajectory. With a frame duration of 100–150 msec (like that which favored the element movement sensation in Experiment 2), Shepard and Judd's subjects perceived motion of a nonrigid or noncoherent sort. Different parts of the object appeared "to move independently or to deform into other noncorresponding parts". Shepard and Judd view the lower duration limit for the perception of rigid, coherent movement as some kind of minimum time necessary for a relatively automatic construction of an internal representation of a three-dimensional stimulus. Below the limit, the construction process presumably breaks down and a sensation of nonrigid incoherent movement results. We suggest that the sensation of rigid, coherent movement and the sensation of plastic, noncoherent movement described by Shepard and Judd are mediated by the same processes as underlie our group and element movement sensations, respectively, i.e. the γ- and ϵ-processes. If this hypothesis is correct, one would expect that the rigid, coherent movement described by Shepard and Judd could be weakened by any of those manipulations which lessened the tendency of our subjects to see group movement. For example, after adaptation to a very bright light, the number of times that nonrigid, incoherent movement is reported for frame durations of 100–400 msec with Shepard and Judd's display should decrease and the number of times that rigid, coherent movement is reported should increase.

The general strategy we have employed to elucidate the response properties of the mechanisms underlying our bistable phenomen ought to be applicable to other forms of multistability as well. But in order to be successful one needs to find those variables which permit one to achieve stimulus control over the various stable states. Ginsburg (1971) has shown how it is possible to bias some multistable phenomena toward a given stable state by spatial filtering. With his results as clues as to the nature of the competing processes which may underlie some forms of multistability, it may be possible to discover those variables which permit one to bring the phenomena under stimulus control.

Finally, in a further series of experiments in which spatial parameters of an element–group movement display were manipulated (Pantle, 1977; Pantle and Petersik, 1978), it was found that the spatiotemporal

[6] Braddick himself (1974) suggested that "a low-level motion detecting process with a very limited spatial range may underlie the occurrence of perceptual segregation in random-dot arrays. A second higher process may lead to the perception of motion from the succession of two more widely separated stimuli...." Different evidence has led us to the same conclusion, but we have attempted to describe the response properties of the two processes more fully and labeled them the ϵ- and γ-processes, respectively.

response properties of the processes mediating the element and group movement sensations at least parallel those of sustained and transient visual mechanisms described in other psychophysical and physiological experiments (see Sekuler *et al.*, 1978, for summary). For this reason further research concerned with the properties of the ϵ- and γ-processes, and with the competition between them, might be beneficial for future theories of form and movement perception.

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