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Perceptual grouping in space and time: Evidence from the Ternus display

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We report three experiments investigating the effect of perceptual grouping on the appearance of a bistable apparent-motion (Ternus) display. Subjects viewed a Ternus display embedded in an array of context elements that could potentially group with the Ternus elements. In contrast to several previous findings, we found that grouping influenced apparent motion perception. In Experiment 1, apparent motion perception was significantly affected via grouping by shape similarity, even when the visible persistence of the elements was controlled. In Experiment 2, elements perceived as moving without context were perceived as stationary when grouped with stationary context elements. In Experiment 3, elements perceived as stationary without context were perceived as moving when grouped with moving context elements. We argue that grouping in the spatial and temporal domains interact to yield perceptual experience of apparent-motion displays.

As we move through the three-dimensional world, the image formed at the retina is fragmented in space and time due to occlusion. For example, a coffee cup may partly occlude a book lying on the table behind it, producing spatial fragmentation of the book; or a chair may temporarily be occluded by a table as an observer walks by, producing fragmentation in time of the chair. However, perceptual experience is coherent and continuous in space and time.

A major goal of perceptual theorists has been to explicate the principles and mechanisms of perceptual organization that give rise to perceptual coherence despite the fragmentary nature of the retinal image. This effort began with the Gestalt psychologists 80 years ago (e.g., Koffka, 1935; Wertheimer, 1912/1961, 1923) and has enjoyed a resurgence of attention recently (e.g., Kellman & Shipley, 1992; Nakayama, He, & Shimojo, 1995; Palmer & Rock, 1994).

"Perceptual organization" refers to the set of early visual processes that are responsible for grouping apparently distinct image regions into coherent and veridical representations of objects and surfaces arrayed in the local environment. For example, the book is experienced as being complete behind the cup because (1) the edges of the book on either side of the cup are collinear (an instance of good continuation); (2) the surface texture and color of the book on either side of the cup are the same (an instance of similarity); and (3) the boundary between the cup and the book is "owned" by the cup (because the cup is closer in depth and the boundaries remain stable relative to the cup but move relative to the book), allowing the book's surface to continue behind the cup (amodal completion). These properties all contribute to the perceptual completion of the book behind the cup.

Among the visual phenomena that have proven to be most useful in explicating perceptual organization mechanisms is apparent-motion perception. In apparent motion, a discontinuously displaced visual element is experienced as moving continuously through space: it is perceived as one element in motion rather than as two different elements that appear and disappear successively. The perception of motion depends on a number of factors, including displacement speed and acceleration (see, e.g., Metzger, 1934), the color and shape of the elements (e.g., Bosinelli, Canestrari, & Minguzzi, 1960), and the constellation of other elements in which the moving elements appear (e.g., Kolers, 1972). Apparent motion is of considerable interest to perceptual psychologists because it provides an especially clear window into the principles governing perceptual organization in vision.

A central question in studies of apparent motion has been the extent to which the grouping principles of similarity and proximity operating in space and time contribute to the perception of apparent motion. Within a single frame of elements, spatial grouping by proximity and similarity will depend on the appearance and locations of the elements. Effects caused by the configuration of elements within a single array will be referred to in this article as *spatial grouping effects* (which includes effects referred to in the literature as "context effects"). Across successive frames of elements, temporal grouping by proximity (in time) and similarity will also depend on the appearance and locations of the elements and, in addition, on the timing of the successive frames. The influence of proximity and similarity across time will be referred to as *temporal grouping effects* (because they de-

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pend in particular on the matching of individual elements across time). Both factors could, in principle, play important roles. However, current evidence about the importance of these various grouping factors is unclear.

Perceptual Grouping in Space and Time

To illustrate the roles of these two factors in apparent-motion perception, it is useful to consider a specific type of bistable apparent-motion display (the one we used in our experiments) known as a *Ternus display* (Ternus, 1926/1939).[1] The display consists of two partially overlapping frames of elements that are rapidly alternated for several cycles at a time (Figure 1). In the first frame, a row of horizontally arrayed elements is presented in locations a, b, and c for some duration *f* (say, 200 msec). The elements in Frame 1 disappear for a blank interstimulus interval (ISI) of variable duration. In Frame 2, the same number of elements appear in locations b, c, and d for duration *f*. (For convenience of expression, the locations of the elements will be indexed by the frame in which they appeared, so that element b_1 refers to the element in location b during Frame 1, element c_2 refers to the element in location c in Frame 2, and so forth.) Thus, elements b_1 and c_1 overlap with elements b_2 and c_2, respectively. Alternating presentation of the two frames induces a bistable percept of motion. Subjects report either *element motion*, in which the outermost element appears to hop back and forth from end to end (yielding a correspondence between a_1 and d_2 as shown in Figure 1), or *group motion*, in which the entire row of elements is perceived to move back and forth as a group (yielding correspondences between a_1 and b_2, b_1 and c_2, and c_1 and d_2, as shown in Figure 1). The percept is termed bistable because, at certain frame presentation rates, the percept changes spontaneously from group motion to element motion and back again.

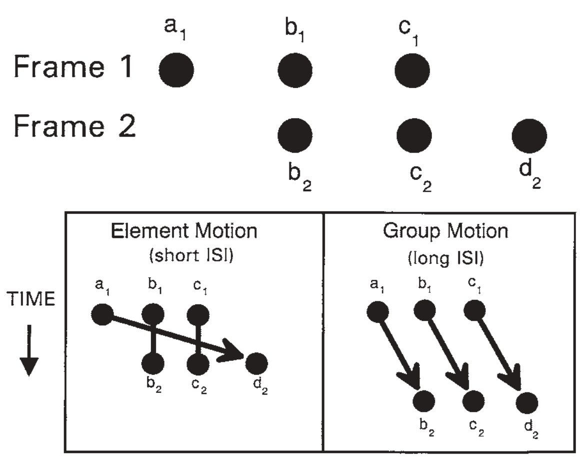

Figure 1. Bistable apparent motion (Ternus) display. Sequence of events on each trial. Three elements appear in locations *a*, *b*, and *c* during Frame 1 and in locations *b*, *c*, and *d* during Frame 2. The frames are separated by a blank interstimulus interval.

Bistable and ambiguous apparent motion displays like the Ternus display are especially interesting because they permit one to study grouping in space and time simultaneously. The sequence of events at the top of Figure 1 is perceptually ambiguous in that any element in Frame 1 might correspond to any of several elements in Frame 2. The solution to this *correspondence matching* problem can reveal aspects of perceptual grouping in space and time.

Pantle and Picciano (1976) showed that by varying the blank ISI between the two frames, it is possible to manipulate the relative likelihood of perceiving group or element motion. When the duration of the ISI is near zero, element motion is almost always perceived, and as the ISI increases, the probability of group motion percepts gradually increases until it approaches unity at ISIs of about 200 msec or more. Similar effects can also be obtained by varying frame duration (Petersik & Pantle, 1979).

Breitmeyer and Ritter (1986a, 1986b) clarified the mechanism responsible for this effect in a series of important experiments. They manipulated various factors that are known to influence the visible persistence of elements (e.g., the duration of persistence increases as the duration and contrast of the elements decreases; Coltheart, 1980). The probability of experiencing element motion at a given ISI was greater when the duration of persistence was longer. These results suggest that element motion will be perceived to the extent that the elements in the overlapping locations of the Ternus display (locations b and c in Figure 1) perceptually span the interstimulus interval, maintaining their continuity over time. This, in turn, increases the probability that the nonoverlapping elements in the display (in our example, elements a_1 and d_2) will be perceived as corresponding and therefore moving (see also Dawson, 1991; Dawson & Wright, 1994; Yantis, 1995; Yantis & Gibson, 1994).

How does the Ternus display reveal aspects of perceptual grouping? First, the appearance and spatial arrangement of elements within a frame will determine perceptual grouping of the constellation of elements across space at a given time, and the configuration so formed may influence motion perception. For example, to the extent that the elements in each frame of the display are closely spaced (contiguity) and similar in shape or color (similarity), they will tend to be grouped into a coherent configuration that may support group-motion percepts. Second, the appearance and spatial arrangement of elements across frames will determine perceptual grouping of the elements in time. For example, elements that appear in rapid succession (temporal contiguity) in adjacent locations (spatial contiguity) and that are similar in shape and color (similarity) in successive frames are likely to be grouped into a coherent spatiotemporal object (and thereby influence apparent-motion perception).

There may be competition between temporal grouping, on the one hand, and spatial grouping, on the other, that determines which percept is more likely to be observed in a bistable apparent-motion display. That is, the elements in the overlapping positions of the Ternus display are likely to be grouped with elements appearing in those same locations in the second frame, particularly with short ISIs (grouping by temporal proximity); as the ISI increases and the temporal distance between them grows, temporal grouping should weaken, leading to a decrease in element motion. Similarly, when the elements within each frame of the Ternus display are spatially proximal to one another (i.e., when the distances between adjacent elements are small), the elements are likely to be perceptually grouped within each frame, increasing the probability of group-motion percepts. Spatial and temporal grouping may then trade off in a systematic way to yield a family of psychometric functions relating element and group-motion percepts to ISI, interelement distance, and similarity.

Although a complete understanding of perceptual grouping in apparent motion requires an analysis of both spatial and temporal effects, these effects have been treated separately in most studies. We will therefore first review studies that focus on temporal grouping in apparent motion perception, and then separately review studies in which spatial grouping effects are assessed. Overall, the evidence is mixed, with some studies reporting spatial or temporal grouping effects and other studies concluding that no such effects exist. In the present paper, we will argue that interactions between grouping in the spatial and temporal domains determine the appearance of apparent motion.

Temporal Grouping Effects in Apparent Motion

In chapter 4 of his seminal 1972 book, *Aspects of Motion Perception*, Kolers noted that the Gestalt psychologists viewed the perception of form as a prerequisite for the perception of either real or apparent motion. He argued, however, that there was good evidence for the claim that the perception of form is a relatively late stage of visual processing, and that motion perception does not depend on form perception at all. In support of this claim, Kolers and Pomerantz (1971) reported several experiments in which observers were shown a shape, followed by a blank ISI, followed by the same or a different shape presented at a new location; the ISI ranged from 10 to 390 msec. Each time a sequence was presented, the observers were to judge whether they perceived smooth and continuous motion. The stimuli consisted of simple shapes, such as squares, circles, triangles, and outline arrowheads, matched for area. Within each trial, the two shapes were either identical (e.g., two circles) or disparate (e.g., a circle and a square, or an arrow and a triangle). The probability of perceiving smooth and continuous motion depended dramatically on the value of the ISI, but it did not depend upon whether the stimuli were identical or disparate in shape.

This is a test of what we have termed temporal grouping; on the basis of this experiment, Kolers (1972) concluded that similarity-based temporal grouping does not seem to affect the perception of apparent motion. "The classical argument is that the visual system perceives figures in different locations and infers motion to have occurred in order to resolve the disparity of figure location. What I have shown is that, to the contrary, the visual system responds to locations of stimulation and infers or creates changes of figure to resolve that disparity" (Kolers, 1972, p. 57).

Additional evidence subsequently accumulated in support of the conclusion that similarity-based temporal grouping is relatively unimportant in the perception of apparent motion. Navon (1976) used a more objective measure of perceived apparent motion (i.e., a judgment of the direction of motion rather than its "smoothness"). He presented shapes in a circular array of multiple shapes in which the direction of motion between successive frames was ambiguous. He found that local phenomenal identity had no discernible influence in disambiguating the perceived direction of motion; that is, motion was just as likely to be perceived between two different shapes as between two identical shapes. Navon concluded that similarity was irrelevant in perceiving apparent motion. Burt and Sperling (1981) came to a similar conclusion using rows of similar and dissimilar elements and a measure of the apparent direction of motion.

In one of his studies of the role of similarity in apparent motion perception, Kolers (1972) used heterogeneous Ternus displays, consisting of several squares and circles. Elements a_1 (the first element in the first frame) and e_2 (the last element in the second frame) had either the same or different shapes. If the similarity of the elements affects apparent motion, then a larger proportion of element-motion reports should have been observed when elements a_1 and e_2 were identical than when they were different. No such effect was observed, and Kolers took this as further evidence for the irrelevance of similarity in apparent-motion perception.

Petersik (1984) took advantage of the ISI effect in his studies of similarity in apparent-motion perception. He used a modification of the Ternus display in which the elements were letters. The letters in the two frames constituted the words MITE and ITEM, respectively. The letters I, T, and E appeared in the overlapping positions of the display, while the M was placed either in front of them or behind them (this can be seen as a variant of the experiment of Kolers, 1972, with heterogeneous shapes, reviewed earlier). With an ISI of 20 msec, subjects almost always reported element motion, so that the M was perceived as hopping back and forth over the stationary ITE group; this is what would be expected if similarity did indeed have an effect. However, with an ISI of 80 msec, subjects reported group motion. That is, they perceived the M as moving one location to the right and turning into an I, the I moving one location to the right and turning into a T, and so forth, as the group of letters hopped back and forth as a group. Thus, with a longer ISI, there was no effect of similarity. This result was taken as confirmation of previous claims that similarity does not affect the percept of motion, at least not under conditions that favor group motion.

Ramachandran, Ginsburg, and Anstis (1983) provided further evidence that similarity has little effect on apparent-motion perception relative to the low-spatial-frequency content of the elements. They presented subjects with displays in which the direction of apparent motion was ambiguous. Motion in one direction preserved element shape, and motion in the other direction preserved low-spatial-frequency content. Subjects reported always seeing motion in the direction that preserved low-spatial-frequency content.

The evidence reviewed so far is unanimous in suggesting that similarity of individual elements has virtually no effect in the perception of apparent motion. In the mid-1980s, however, evidence began to appear suggesting that similarity does sometimes influence apparent-motion perception. For example, Green (1986), using a paradigm similar to that of Ramachandran et al. (1983), showed that although low spatial frequencies are a major determinant of the percept of apparent motion, high spatial frequencies and the orientation of elements can also affect apparent-motion perception, provided that luminance changes are controlled. Earlier, Ullman (1979, 1980) had also reported an effect of element orientation on apparent-motion perception.

Werkhoven, Sperling, and Chubb (1993) used a modification of Green's paradigm and found no effect of differently or similarly textured patches on the direction of motion, but when orientation differences were introduced, similarity of the patches did have an effect (Werkhoven, Sperling, & Chubb, 1994).

Green's (1986) and Ullman's (1980) results seem to contradict earlier findings (e.g., Kolers & Pomerantz, 1971; Navon, 1976) in which figural details had no effect on apparent motion. Mack, Klein, Hill, and Palumbo (1989) argued that this apparent contradiction might be due to an effect of *directional set*. They observed that subjects who were shown ambiguous motion displays similar to those used by Navon (1976) tended to report the same direction of apparent motion over a number of trials. Similarity had a significant effect on initial trials, but on subsequent trials this effect seemed to be "swamped" by the effect of a directional set.

Shechter, Hochstein, and Hillman (1988) circumvented this "locking in" to a directional set by presenting a "correction trial" after every series of four equivalent responses. In the correction trial, the direction of motion was unambiguous and opposite to the direction reported in the previous four ambiguous-direction trials. Consistent with the directional set account of Mack et al. (1989), Shechter et al. (1988) observed a significant effect of similarity on apparent-motion perception.

Papathomas, Gorea, and Julesz (1991) showed that color similarity can also influence apparent-motion perception. They used a paradigm developed by Burt and Sperling (1981) in which rows of elements that were heterogeneous in color and brightness were presented and subjects were required to report the apparent direction of motion across successive frames. Color and brightness correspondence across frames could be consistent, uncorrelated, or in opposition. Color was shown to induce a clear sense of direction of motion when brightness-based direction of apparent motion was ambiguous. Color also was shown to contribute to brightness-based direction judgments if the two attributes were consistent, and, within a certain range of luminance values, color could dominate direction judgments even if the color and brightness correspondences were in opposition.

To summarize, recent evidence suggests that similarity does influence correspondence matching in certain apparent-motion displays (e.g., Green, 1986; Papathomas et al., 1991; Shechter et al., 1988). In these situations, motion is observed more often between similar elements than between dissimilar elements. However, this effect does not seem to be completely general; no effect of similarity in the Ternus display has yet been reported, and existing evidence still speaks against it.

Spatial Grouping Effects in Apparent Motion

The evidence concerning the effect of spatial grouping on apparent-motion perception has been inconsistent. Some studies suggest that there is a significant effect of spatial grouping, while others suggest that there is little or no effect.

Ramachandran and Anstis (1983, 1985) showed observers a display containing multiple spatially dispersed bistable apparent-motion stimuli (i.e., ambiguous dis-

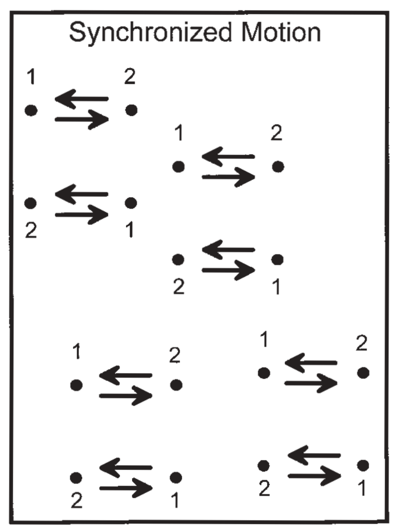

Figure 2. Display used by Ramachandran and Anstis (1985, Figure 2). Elements labeled "1" are presented in the first frame; elements labeled "2" are presented in the second frame. Apparent motion between the dots was observed either in the horizontal direction (as shown here by the arrows) or in the vertical direction, but appeared the same in all conceptual squares. (From "Perceptual Organization in Multistable Apparent Motion," by V. S. Ramachandran and S. M. Anstis, 1985, *Perception*, *14*, pp. 135–143, Figure 2. Copyright 1985 by Pion, Limited, London. Adapted with permission.)

plays that appear to exhibit either vertical or horizontal motion; see Figure 2). They found that these apparent-motion stimuli interacted such that all of them appeared to exhibit the same direction of apparent motion (i.e., all the stimuli in the display appeared to exhibit either vertical motion or horizontal motion during any given short interval). Furthermore, in several experiments, Ramachandran and Anstis showed that the path of apparent motion could be influenced by the surrounding context, suggesting that spatial grouping effects were important in apparent-motion perception.

In one experiment, however, Ramachandran and Anstis (1985, Experiment 4) found that a continuously moving context (i.e., stimuli that move continuously through space rather than in successive frames as in apparent motion) had only a slight influence on the perception of a bistable apparent-motion display in the center.

Ramachandran and Cavanagh (1987) showed that a displaced context with low-spatial-frequency content could "capture" dynamic noise with high-spatial-frequency content, which then appeared to move in the direction of the context. Coherently moving dots and gratings with a high-spatial-frequency content were also affected by a context with a low-spatial-frequency content.

In addition, Williams and Sekuler (1984), Chang and Julesz (1985), Anstis and Ramachandran (1986), and Dawson (1987) have also observed effects of unambiguous motion context on the perceived direction of ambiguous motion (in these studies, the spatial frequency content of the ambiguously and unambiguously moving elements were the same).

Petersik and Rosner (1990) investigated the effect of stationary and apparently moving context on bistable apparent motion using a modification of the Ternus display. In this study, unlike in the previous ones, a moving context appeared that was always ambiguous (Figure 3). Their display contained two rows of dots and, in four of the six conditions, connecting lines were drawn between the middle elements of the upper and lower rows. The upper row was a standard Ternus display, and the lower row provided a stationary or moving context. When present, the lines either remained stationary (panels C and D) or shifted from frame to frame (panels E and F). The influence of the lower context row on the upper test row was investigated.

In the conditions with stationary connecting lines (Figures 3C and 3D), Petersik and Rosner (1990) observed fewer group motion responses than in the conditions in which the lines were absent, and in the conditions with shifting lines (Figures 3E and 3F), they observed a greater proportion of group motion responses than in the control conditions. This provided evidence that the connecting lines influenced apparent-motion perception, possibly by virtue of grouping by contiguity (Palmer & Rock, 1994). However, Petersik and Rosner found no effect of whether the context elements moved or not, and concluded that context did not influence apparent motion unless it was physically connected with the moving elements.

We have reviewed two sets of experiments: those in which temporal grouping effects in apparent motion were assessed and those in which spatial grouping in apparent motion were assessed. There is considerable evidence that similarity-based temporal grouping influences apparent motion in some paradigms, but there is evidence against such an influence in the Ternus display. When apparent-motion elements are accompanied by a context, then in some studies the context has been shown to have an effect via spatial grouping; in other studies, no such effect was found. One goal of this article is to provide new evidence that will clarify this apparently inconsistent pattern of results and show that the results can be accounted for by the spatiotemporal grouping hypothesis put forth above.

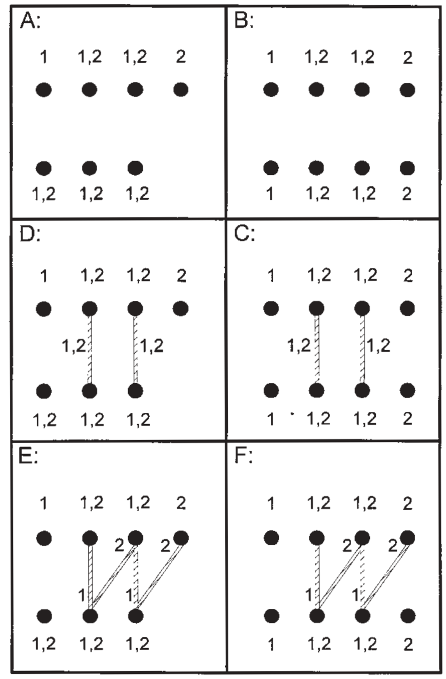

Figure 3. Displays used by Petersik and Rosner (1990). Elements labeled "1" are presented in the first frame, the elements labeled "2" are presented in the second frame. In Conditions C and D, the connecting lines remain stationary; in Conditions E and F, the top termini shift from frame to frame. In Conditions A, C, and E, context elements remain stationary; in Conditions B, D, and F, they are displaced. Copyright 1990 by Psychonomic Society, Inc. Adapted with permission.

EXPERIMENT 1

As we noted in our review of the literature, a number of experiments have shown an effect of similarity on apparent motion in certain displays. However, neither Kolers (1972) nor Petersik (1984) found an effect of similarity in the Ternus display.

There is reason to believe, however, that the design of these experiments may have prevented them from revealing similarity effects in the perception of the Ternus display. In Kolers (1972, p. 82, Arrays 32 and 33), the first element in the first frame never matched the first element in the second frame in either condition, and this may have hampered the percept of group motion in both conditions.

Moreover, the elements within each frame were dissimilar in both conditions, and this may have hampered the percept of group motion in both conditions as well. Hence, the design of the Kolers experiment may not have maximized differences due to shape between conditions and may not have been optimal for observing the effects of similarity on the percept of group versus element motion in the Ternus display.

In Petersik (1984), the Ternus display was made up of letters that formed a word. The coherence of the elements within a group (a word) was ensured in element motion but not in group motion. The experiment successfully demonstrated that group motion does occur at the expense of the coherence of the word. However, if a condition had been included in which the letters could not be grouped into a word, then a potential effect of the grouping of the string of letters could have been revealed more easily.

The purpose of Experiment 1 was to determine whether grouping (in this case, of squares and circles) could affect the perception of element and group motion in the Ternus display. In each trial, subjects were shown Ternus displays consisting of two elements (see Figure 4); the elements either had the same shape (the homogeneous condition) or different shapes (the heterogeneous condition) within each frame.

In the homogeneous condition, the elements were the same within and between frames, which should maximize the spatial grouping of the elements within a frame, and thus favor the percept of group motion. In the heterogeneous condition, the elements were different within and between frames (the positions of the square and circle were reversed between frames). In this case, the spatial grouping of the elements within each frame should be weaker than in the homogeneous condition. If grouping is important in the Ternus display, then the probability of group motion percepts should be greater in the homogeneous condition than in the heterogeneous condition for at least some ISIs.

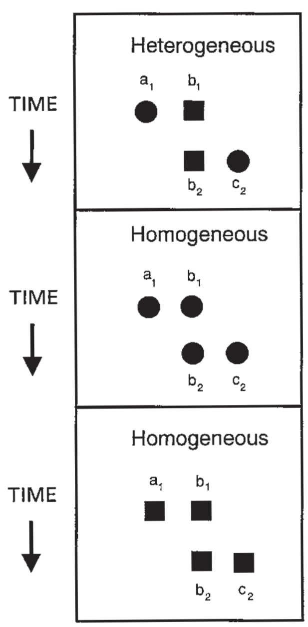

Figure 4. Displays used in Experiment 1. The first panel shows an example of a display used in the heterogeneous condition; the middle and last panels show examples of displays used in the homogeneous condition. Elements labeled "1" are presented in the first frame, and elements labeled "2" are presented in the second frame.

Method

Subjects. Ten undergraduates at the Johns Hopkins University served as subjects in partial fulfillment of the requirements of an introductory psychology course. All subjects had normal or corrected-to-normal visual acuity. The subjects took part in one 1-h session and were naive as to the purpose of the experiment.

Apparatus and Stimulus Materials. Stimuli were presented under low ambient room illumination on a 21-in. Taxan UV1150 color monitor controlled by an Artist Graphics XJS-1280 graphics board in a 386-based computer. The refresh rate was 60 Hz (i.e., 16.67 msec per frame), noninterlaced. Stimuli consisted of white circles and squares of 73.0 cd/m^2 on a black background of 1.5 cd/m^2 (measured with a Lite Mate system 500 photometer on a 5.2º square test patch). From a viewing distance of 60 cm (controlled by a chin-rest), the squares were 1.38º of visual angle on a side and the circles had a diameter of 1.55º of visual angle. These dimensions yielded elements with identical areas of 1.9º square of visual angle; the equal areas ensured comparable visible persistence durations. The interelement distance was 1.7º of visual angle (measured center to center).

Design. We completely crossed the homogeneity condition (homogeneous vs. heterogeneous) with ISI (0, 17, 33, 50, 67, 100, 133, 167, 200, and 300 msec), yielding a 2 × 10 design. Subjects participated in one session with three blocks of 160 trials. Within each block, each of the 20 different conditions occurred eight times in a random order. Thus, we obtained 24 observations from each subject under each combination of ISI and homogeneity condition.

Procedure. In each trial, the subjects were shown Frame 1 for 200 msec, followed by the appropriate ISI, Frame 2 for 200 msec, and another blank ISI. This sequence was repeated for four cycles. During the ISI, the screen was entirely black. The intertrial interval was 1 sec. Subjects were asked to keep their eyes on the center of the screen, but to pay attention to the entire display.

Before the presentation of the experimental trials, each subject was shown a sequence of example trials. First they were shown trials with an ISI of 0 msec and then trials with an ISI of 300 msec. The example stimuli were either homogeneous or heterogeneous, chosen on a random basis. After each example trial, the subjects were asked to report, without prompting, what they had seen. The presentation of examples continued until the subjects described their percepts in a way consistent with element motion in the presentations with an ISI of 0 msec and with group motion in the presentations with an ISI of 300 msec. These descriptions occurred spontaneously in all subjects after just a few exposures to the example trials. After the subjects had described their percepts in this way, they were told that we would label the perceived motion in the former case *element motion* and the perceived motion in the latter case *group motion*.[2]

Responses were unspeeded. The subjects responded by pressing one of two keys on a custom response box: they pressed the left key to indicate that they perceived element motion and the right key to indicate that they perceived group motion.

For half of the subjects, squares were presented in the homogeneous condition; these subjects constituted the square group. For the other half of the subjects, circles were presented in the homogeneous condition; these subjects constituted the circle group. In the heterogeneous condition for both groups, the left element in the first frame and the right element in the second frame were circles; the middle element in both frames were squares.

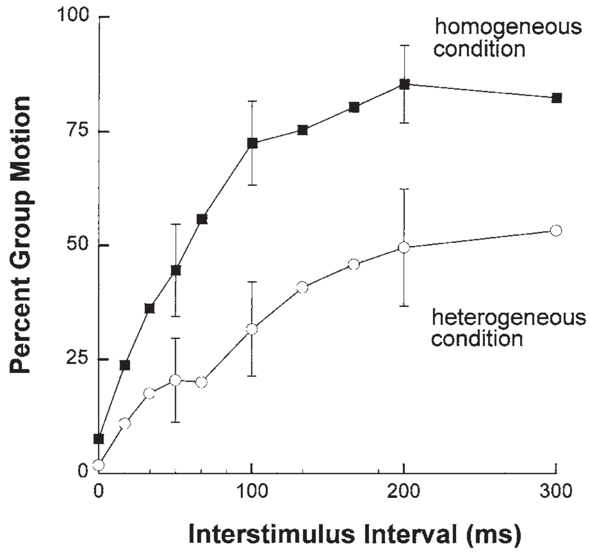

Figure 5. Results of Experiment 1. The two psychometric functions correspond to the two conditions illustrated in Figure 4. Typical error bars are shown. They represent ±1 standard error.

Results and Discussion

The results of Experiment 1 are shown in Figure 5. The probability of group-motion percepts are plotted as a function of ISI for the homogeneous and heterogeneous groups, respectively. The error bars extend to ±1 standard error of the mean. The probability of group motion reports was greater in the homogeneous than in the heterogeneous conditions for a wide range of intermediate ISIs.

To quantitatively compare the homogeneity conditions, we computed the overall probability of observing group motion for each condition collapsed across ISI. The mean percent group-motion responses was 47.3% in the homogeneous condition and 25.1% in the heterogeneous condition. We performed a repeated measures analysis of variance (ANOVA) with one between-subjects grouping variable: square group versus circle group. The grouping factor did not reach significance [$F(1,8) = 0.811$, $p > .3$]. The 22.2% difference between the homogeneous and heterogeneous condition did reach significance [$F(1,8) = 13.740$, $p \leq .01$]. The interaction did not reach significance [$F(1,8) = 1.784$, $p > .2$].

Kolers (1972) and Petersik (1984) failed to find an effect of similarity on the perception of the Ternus display. We have argued that the experimental designs they used may not have been optimal to observe such effects. The displays used in Experiment 1 provided a better assessment of the effect of similarity on apparent-motion perception. The results show that the effect of similarity found in other apparent-motion paradigms generalizes to the Ternus display as well.

EXPERIMENT 2

Experiment 1 was concerned with the effect of grouping by similarity within the Ternus display. Experiment 2 focuses on the effect of perceptual grouping with contextual elements in the Ternus display. Here observers viewed displays in which the apparent-motion elements were presented with contextual elements that perceptually grouped with them via the Gestalt law of grouping by proximity (Koffka, 1935; Wertheimer, 1923). Our aim was to assess the influence of the context on the perception of apparent motion in the Ternus display.

In what follows, we will refer to the apparent-motion elements that participate in the Ternus effect and about which observers made judgments as the "central elements" or "Ternus elements" and the remaining elements as "context elements."

On each trial of our experiment, we presented Ternus displays with or without a context (Figure 6). There were six central elements in each frame of the display. Figure 6A depicts the orthogonal grouping condition, in which the central elements were perceived as being strongly grouped with the stationary context columns. The grouping in this condition was orthogonal to the direction of motion in the Ternus display. In the parallel grouping condition (Figure 6B), the context was present, but the central elements grouped much less strongly with the context than in the orthogonal grouping condition. The grouping in this condition was parallel to the direction of motion in the Ternus display. Figures 6C and 6D show the two no-context conditions, called the no-context: wide and no-context: narrow conditions; they exhibit the same horizontal interelement distance as in the orthogonal and parallel-grouping conditions, respectively.

If spatial grouping (in this case, grouping by proximity) plays a causal role in apparent-motion perception, then the orthogonal-grouping condition should reduce the probability of perceiving group motion relative to the parallel-grouping condition, because the central elements in the Ternus display will tend to be "anchored" in place by virtue of their being grouped with the stationary context. If no context effect is observed, then we must conclude that grouping by proximity does not influence apparent-motion perception.

To ensure that any observed effects of context in our experiments would be due to perceptual grouping and not to other factors, several precautions were taken. First, we ensured that the vertical and horizontal spacing of the elements in the orthogonal-grouping and parallel-grouping conditions were balanced. Spacing had to be controlled because it might influence the duration of visible persistence (Breitmeyer, 1984; Coltheart, 1980; Hagenzieker & van der Heijden, 1990; Hagenzieker, van der Heijden, & Hagenaar, 1990; van der Heijden, 1992), which in turn could influence the probability of element- and group-motion percepts in the Ternus display (Breitmeyer & Ritter, 1986a, 1986b). The horizontal interelement distance in the orthogonal-grouping condition was identical to the vertical interelement distance in the parallel-grouping condition, and the vertical interelement distance in the orthogonal-grouping condition was identical to the horizontal interelement distance in the parallel-grouping condition (Figures 6A and 6B). This constraint ensured

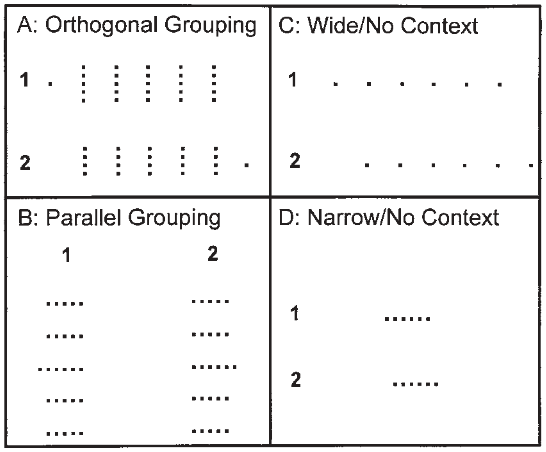

Figure 6. Displays used in Experiment 2. Elements labeled "1" are presented in the first frame, and elements labeled "2" are presented in the second frame. Except for the outermost element on the left in Frame 1, and the outermost element on the right in Frame 2, all elements in successive frames spatially overlap.

that the magnitudes of possible lateral interactions were balanced in these two conditions.

Second, we ensured that the grouping of elements would affect spatial frequency channels with similar bandwidths. The groups consisted of either five columns of five elements or five rows of five elements. The distance between elements within groups and the distance between groups were both held constant. Since spatial frequency affects apparent contrast (Cornsweet, 1970) and visible persistence (Bowling, Lovegrove, & Mapperson, 1979; Breitmeyer, 1984; Coltheart, 1980; Meyer & Maguire, 1977), it could indirectly influence the percept of apparent motion (Petersik & Grassmuck, 1981; but see Breitmeyer, May, & Williams, 1988, and Casco, 1990). Assuming that horizontal and vertical spatial frequency channels with similar bandwidths have comparable visible persistences, the possible differences in visible persistence between conditions due to differences in spatial frequency were controlled in the present experiment.[3]

Third, to address the possibility that horizontal and vertical lateral interactions might not be comparable, and that horizontal and vertical spatial frequency channels might have different visible persistences, we conducted a control experiment in which the entire display was rotated by 90º so that the Ternus display was vertically oriented. If orientation differences between conditions somehow biased apparent-motion percepts, then rotating the display by 90º should reveal this bias.

Finally, the primary manipulation in the experiment involved varying the interelement distances in different conditions. However, as mentioned earlier, Pantle and Petersik (1980) found that decreases in horizontal interelement distance led to increases in the probability of perceiving group motion. Because of the spacing constraints required to equalize lateral interactions (as discussed earlier), it was necessary to compare the performance in the two context conditions with that in the two no-context conditions. We expected the difference in horizontal interelement distance to affect performance in both the no-context and the grouping conditions; any additional influence observed in the grouping conditions might be attributed to the effect of perceptual grouping on motion perception.

Method

Subjects. Fifteen subjects took part in two 1-h sessions on 2 separate days in return for a $10 payment. Thirty-eight additional subjects served in the 90º rotated control experiment. For 8 of these additional subjects, data were collected in two 1-h sessions on 2 separate days in return for a $12 payment. The other 30 additional subjects served in only one 1-h session in return for a $6 payment. All subjects were undergraduates at the Johns Hopkins University, were naive as to the purpose of the experiment, and had normal or corrected-to-normal visual acuity. Four subjects were excluded from the analysis because they did not show an effect of ISI on group- versus element-motion judgments, suggesting that they did not understand the instructions. The data of 1 subject were lost due to computer malfunction.

Apparatus and Stimulus Materials. The apparatus was the same as that used in Experiment 1. The stimuli were white squares 0.45º of visual angle in height with a luminance of 73.0 cd/m^2 on a black background of 1.5 cd/m^2, and were presented under the same low ambient room illumination as in Experiment 1. A chinrest was used to ensure a viewing distance of 60 cm.

The horizontal interelement distances were 2.0º of visual angle (measured center to center) in the orthogonal-grouping and no-context: wide conditions (Figures 6A and 6C) and 0.5º in the parallel-grouping and no-context: narrow conditions (Figures 6B and 6D). The vertical interelement distances were 0.5º in the orthogonal-grouping condition and 2.0º in the parallel-grouping condition. The horizonal interelement distance in the orthogonal-grouping condition was therefore equal to the vertical interelement distance in the parallel-grouping condition, and the vertical interelement distance in the orthogonal-grouping condition was equal to the horizontal interelement distance in the parallel-grouping condition. This was to ensure that lateral interactions were approximately equated in these two conditions, as discussed earlier.

The elements that were not displaced from frame to frame were grouped in either five columns of five elements (orthogonal-grouping condition) or five rows of five elements (parallel-grouping condition). This was to ensure that, in both conditions, the grouping of elements would affect similar spatial frequency channels. In the control experiment, the display was rotated 90º, the columns were now rows and the rows columns.

Design. We completely crossed context condition (orthogonal grouping, parallel grouping, no context: wide, and no context: narrow) with ISI (0, 17, 33, 50, 67, 100, 133, 167, 200, and 300 msec), yielding a 4×10 design. Within each block, each of the 40 different conditions occurred four times in a random order. Subjects participated in one or two sessions with three blocks of 160 trials per session. Thus, for each combination of ISI and context condition, we obtained 24 observations from each subject who participated in two sessions and 12 observations from each subject who participated in one session.

Procedure. In each trial, the subjects were shown Frame 1 for 200 msec, followed by the appropriate ISI, Frame 2 for 200 msec, and another blank ISI. This sequence was repeated for four cycles. During the ISI, the screen was entirely black (no context elements were presented). The intertrial interval was 1 sec. The subjects were asked to keep their eyes on the center of the screen but to pay attention to the entire display.

Before the presentation of the experimental trials, each subject was shown a sequence of example trials. First they were shown trials with an ISI of 0 msec and then trials with an ISI of 300 msec.

The stimuli shown in Figures 6C and 6D were used for this purpose. After each example trial, the subjects were asked, without prompting, to report what they had seen. The presentation of examples continued until the subjects had described their percepts in a way consistent with element motion in the presentations with the ISI of 0 msec and with group motion in the presentations with the ISI of 300 msec. These descriptions occurred spontaneously in all subjects after just one or two exposures to the example trials. After the subjects had described their percepts in this way, without prompting, they were told that we would label the perceived motion in the former case *element motion* and the perceived *motion* in the latter case *group motion*.

Responses were unspeeded. The subjects responded by pressing one of two keys on a custom response box: they pressed the left key to indicate that they had perceived element motion and the right key to indicate that they had perceived group motion.

Results

Figure 7 shows a psychometric function for each of the four experimental conditions, with percent group-motion responses plotted as a function of ISI. Figure 8 shows the psychometric functions for the 90º control experiment. The error bars extend to ±1 standard error of the mean.

Four effects can be seen in Figures 7 and 8. First, for all experimental conditions, the probability of group motion increased monotonically with ISI, from near zero at ISI = 0 msec to a maximum at ISI = 300 msec. This is the standard and robust effect of ISI seen in many previous studies using the Ternus display. Second, the probability of perceiving group motion was greater overall for the conditions without context than for the conditions with context. Third, narrow spacing resulted in a larger percentage of group-motion responses overall than did wide spacing (the narrow: no-context and the parallel-grouping conditions vs. the wide: no-context and the orthogonal-grouping conditions, respectively). Finally, an interaction between context and spacing is evident: The difference in group-motion percepts is greater for the two context conditions than for the two no-context conditions.

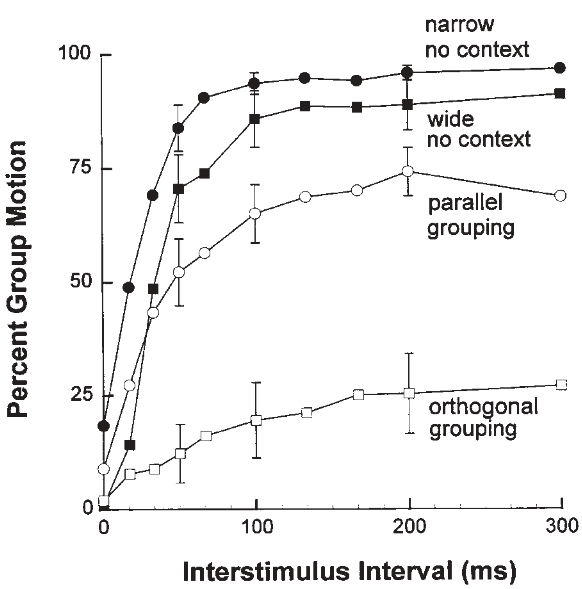

Figure 7. Results of Experiment 2. The four psychometric functions correspond to the four conditions illustrated in Figure 6. The filled symbols represent the no-context conditions; the open symbols represent the grouping conditions. Typical error bars are shown. They represent ±1 standard error.

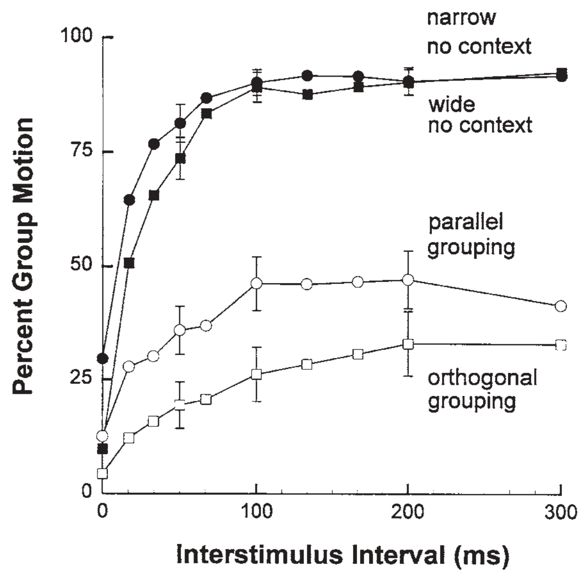

Figure 8. Results of the 90º rotated control of Experiment 2. The four psychometric functions correspond to the four conditions obtained after rotating the display illustrated in Figure 6 over 90º. Typical error bars are shown. They represent ±1 standard error.

It is necessary to consider the effect of vertical versus horizontal grouping separately from the possible effects of horizontal interelement distance per se. As can be seen in the two no-context conditions, the probability of group motion is greater for the narrow: no-context condition than for the wide: no-context condition. This replicates earlier findings by Pantle and Petersik (1980), who also found that decreasing interelement distance increased the probability of group-motion perception. Recall that the within-row spacing for the parallel-grouping condition was, by design, identical to the narrow: no-context condition, and similarly the spacing for the orthogonal-grouping condition was identical to the wide: no-context condition. Therefore, we needed to determine whether the effect of orthogonal versus parallel grouping was even greater than that produced by narrow versus wide spacing itself. In order to quantitatively compare the positions of the psychometric functions, we computed the overall probability of observing group motion for each condition collapsed across ISI.

The mean percent group-motion responses were 78.6% in the narrow: no-context condition and 65.1% in the wide: no-context condition. A within-subjects planned comparison revealed that the 13.5% difference was significant [$F(1,14) = 18.91$, $p \leq .001$], which replicates the interelement distance effect of Pantle and Petersik (1980).

The mean percent group-motion responses was 16.5% in the orthogonal-grouping condition and 53.4% in the parallel-grouping condition. A within-subjects planned comparison showed that the 36.9% difference was significant [$F(1,14) = 34.30$, $p < .001$]. More importantly, this 36.9% difference was significantly greater than the 13.5% difference between the two no-context conditions [$F(1,14) = 15.20$, $p \leq .002$].

For the 90º control experiment (see Figure 8), the mean percent group-motion responses were 79.5% in the narrow: no-context condition and 73.2% in the wide: no-context condition. A within-subjects planned comparison revealed that the 6.3% difference was significant [$F(1,32) = 9.78$, $p < .005$], which replicates our previous finding and the interelement distance effect of Pantle and Petersik (1980).

The mean percent group-motion responses were 37.0% in the parallel-grouping condition and 22.3% in the orthogonal-grouping condition. A within-subjects planned comparison showed that the 14.7% difference was significant [$F(1,32) = 16.44$, $p < .001$]. More importantly, this 14.7% difference was significantly greater than the 6.3% difference between the two no-context conditions [$F(1,32) = 4.72$, $p < .04$].

Discussion

The data in Figures 7 and 8 suggest that the apparent-motion percepts produced by the Ternus display were significantly influenced by the context in which they appeared. There are two sources of evidence for this claim. First is the interaction between spacing and context: Narrow spacing produced more group-motion percepts than wide spacing did; above and beyond this effect, orthogonal grouping produced more element-motion percepts than parallel grouping did. This suggests that the orthogonal context tended to anchor the middle elements in place, which led to more element motion. There is a potential difficulty in interpreting this interaction, however. It is possible that ceiling effects may have suppressed a true difference between the no-context conditions relative to the grouping conditions. Inspection of Figure 7 reveals that the probability of group-motion responses approached unity in the no-context conditions for ISIs of 100 msec or more. The presence of possible ceiling effects makes the interaction, by itself, an inconclusive source of evidence for grouping in Experiment 2.

A second source of evidence for grouping is the main effect of context (i.e., the increased probability of element motion for the two context conditions relative to the two no-context conditions). This effect has two possible sources. One source of the context effect is perceptual grouping. To the extent that the critical elements perceptually group with the context, we would expect a greater incidence of element-motion percepts, even in the parallel-grouping condition. Another possible source, however, is that the presence of contextual elements produces lateral inhibition of the critical elements, thus decreasing the brightness of these elements. This, in turn, would be expected to increase the duration of their visible persistence (Coltheart, 1980), which would tend to support element-motion percepts.

Of course, there may be contributions from both sources, but there is reason to believe that grouping is the more important and potent source of this effect. A pair of experiments reported by Kramer and Rudd (1995) provides evidence for this claim. In both experiments, a Ternus display was used in which two vertical lines served as the elements appearing in two of three possible locations. In the control condition, the lines were of equal length, and a standard psychometric function relating group-motion response probability to ISI was obtained. In the experimental condition, the line in the middle location was increased in length (Figure 9).

Consistent with the finding for the orthogonal-grouping condition of the present experiment, Kramer and Rudd found significantly more element motion in the experimental condition than in the control condition. This outcome is consistent with a grouping interpretation and not with a persistence-based interpretation: increasing the size of the middle line decreases its persistence duration (Breitmeyer & Ritter, 1986a, 1986b), which would be expected to increase the percent group-motion percepts. The observed increase in element-motion percepts suggests, instead, that the two short lines grouped by similarity in opposition to whatever effects might have been exerted by changes in persistence duration. Hence, we conclude that possible persistence effects produced by context elements in the present experiment are also likely to be minor compared with grouping effects.

To summarize, there are two sources of evidence for grouping effects in the present experiment. First, there is an interaction between the spacing and context factors, which supports a grouping interpretation; second, the main effect of context is consistent with a grouping interpretation. Although it is possible that the main effects and interactions in Figures 7 and 8 are due in part to other causes, we conclude that the entire constellation of results is most parsimoniously explained by perceptual group-

Figure 9. The display used by Kramer and Rudd (1995). Elements labeled "1" were presented in the first frame, and those labeled "2," in the second frame.

ing of the central elements with their context, which caused them to be "anchored" in place, thereby influencing apparent-motion judgments.

EXPERIMENT 3

In Experiment 2, the context was always stationary. When it was grouped with the elements in the Ternus display, it caused those elements to appear to be "anchored" in place, leading to an increase in element-motion perception. In Experiment 3, we investigated the possible effects of displacing the context elements. The organization of the context elements induced strong vertical grouping (Figure 10). Panel A of Figure 10 shows the stationary-context condition, and panel B shows the displaced-context condition. The motion of the context in the displaced condition was bistable rather than unambiguous. In this respect, they differ from typical motion-capture stimuli. These stimuli differed from those of Petersik and Rosner (1990; see Figure 6) in three respects: (1) We included a larger number of context elements; (2) we increased horizontal interelement distances within the display; and (3) we included two dim red arrows to indicate the row about which the group- and element-motion judgments were to be made. The first two of these modifications were designed to increase the strength of perceptual grouping within the display.

To show that the perceptual organization of the context elements was the key determinant of a context effect, and not vertical interelement distance per se, the vertical interelement distance was set at 1.5º of visual angle, which was the same vertical distance Petersik and Rosner (1990) used.

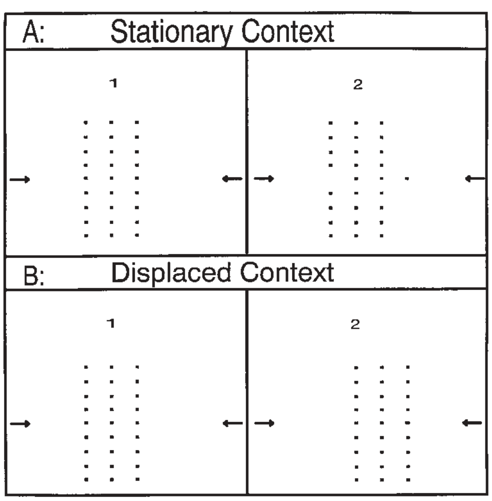

Figure 10. Displays used in Experiment 3. Panel A shows the two frames (labeled "1" and "2") used in the stationary-context condition. Panel B shows the displaced-context condition. In panel A, Frames 1 and 2 entirely overlap except for the outermost element on the left in the middle row in Frame 1, and the outermost element on the right in Frame 2. In panel B, Frames 1 and 2 entirely overlap except for the outermost column of elements on the left in Frame 1 and the outermost column of elements on the right in Frame 2.

If perceptual grouping exerts an important influence on apparent-motion perception, we should observe more group-motion responses when context is displaced compared to when it is not, even in the absence of connecting lines.

Method

Subjects. Nine undergraduates and one graduate student at the Johns Hopkins University served as subjects in return for a $5 payment. All subjects had normal or corrected-to-normal visual acuity. The subjects took part in one 1-h session, and were naive as to the purpose of the experiment.

Apparatus and Stimulus Materials. The same apparatus was used as in the previous experiments. The stimuli consisted of elements that were similar to the ones used in Experiment 2. The horizontal interelement distance was 3.0º of visual angle. The vertical interelement distance was 1.5º of visual angle. Elements were organized in three columns of nine elements in order to induce strong vertical grouping. Two thin, dim red arrows (8.0 cd/m^2) on either side of the middle row, 6º from the outer most elements, indicated the row about which the element- versus group-motion judgment was required. The other rows provided context. The arrangement of the elements in each condition is shown in Figure 10.

Procedure. The procedure was similar to the one used in Experiment 2, except that only two context conditions were used (shown in Figure 10).

Results and Discussion

Figure 11 shows the probability of group motion as a function of ISI for the displaced-context and stationary-context conditions in Experiment 3. All but 1 subject reported group motion more often in the displaced-context condition than in the stationary-context condition.[4] The mean percent group-motion responses averaged over all ISIs (with the deviating subject excluded) was 75.4% in the displaced-context condition and 15.6% in stationary-context condition. A paired samples *t* test showed that the 59.8% difference was significant [$t(8) = 8.57, p < .001$]. With the deviating subject included, the difference was 44.2% and still significant [$t(9) = 2.64, p < .03$].

These results suggest that context can influence apparent-motion perception even with a vertical interelement distance as large as 1.5º. Why did we observe an effect of context without connecting lines when Petersik and Rosner (1990) did not? We suggest that the unconnected context in Petersik and Rosner's displays grouped only weakly, if at all, with the elements in the row under investigation. For example, the horizontal (within-row) interelement distance was 0.75º; the vertical interelement distance was 1.5. These relative distances probably induced horizontal grouping and suppressed vertical grouping with the context elements. Furthermore, Petersik and Rosner's displays contained only a single context row, which also contributed to weak grouping. Only by adding connecting line segments—a strong cue to grouping (e.g., Palmer & Rock, 1994)—did context influence apparent-motion perception.

The results presented here suggest that if strong vertical grouping is employed, context does affect the per-

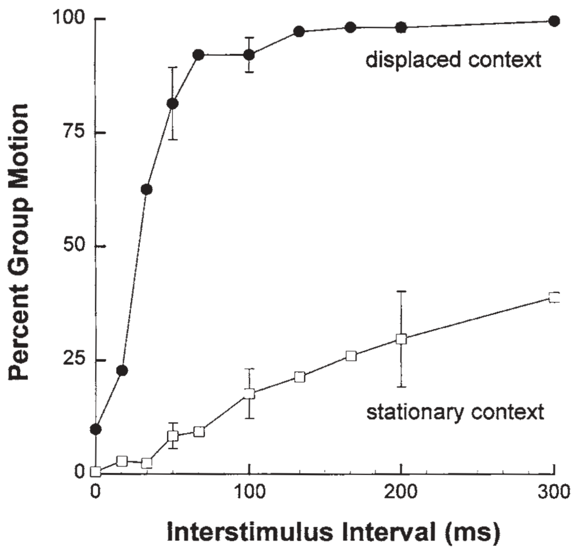

Figure 11. Results of Experiment 3. The two psychometric functions correspond to the two conditions illustrated in Figure 8. Typical error bars are shown. They represent ±1 standard error.

ception of the Ternus display, even without connecting line segments and even when motion in the context is bistable rather than unambiguous.

The present results can be viewed as a manifestation of motion capture (Ramachandran & Cavanagh, 1987). However, typical motion-capture experiments involve the capture of dynamic noise or coherently moving dots by an unambiguously moving context. In the present experiment, the contextual elements exhibited bistable motion; therefore, the experiment was not precisely comparable to the motion-capture phenomenon. It is likely that motion capture will be sensitive to perceptual grouping; for example, it is possible that motion capture could be enhanced with a judicious use of grouping principles. More research is required to clarify this matter.

GENERAL DISCUSSION

More group motion is perceived when elements within the frames of a Ternus display form a coherent group than when the elements are heterogeneous (Experiment 1). Enhanced coherence based on grouping by proximity can also explain the interelement distance effect in which a decrease in interelement distance leads to more group-motion percepts. When the critical elements in a bistable apparent-motion display are strongly grouped with a stationary context, the perception of element motion increases, because the overlapping elements in the Ternus display are more likely to be perceived as “anchored” in place (Experiment 2). Similarly, when the critical elements are grouped with a moving context, subjects are more likely to report group motion, because critical elements are less likely to be anchored in place than they would be in a stationary context (Experiment 3). These results show that the perceptual experience of apparent motion evoked by these displays depends in part on the configurations of elements formed by perceptual grouping.

Kolers (1972) and Petersik (1984) did not find effects of grouping by similarity in the Ternus display. We have argued that the manipulations in these studies were not optimal for obtaining the effect, and, in Experiment 1, we showed that large effects can be obtained.

In Petersik and Rosner (1990), weak grouping by proximity between context elements and a Ternus display rendered no effect of context, but strong grouping by contiguity (via connecting lines) between the context and the Ternus elements had a profound effect. Petersik and Rosner concluded that grouping by contiguity is necessary to observe context effects. Our results suggest, instead, that any manipulation that yields strong perceptual grouping is likely to produce significant context effects. Contiguity is only one of these.

Earlier, we argued that competition between temporal and spatial grouping determines which perceptual experience is most likely to be reported in a bistable apparent-motion display. The experiments reported here provide evidence for this idea. Further experimentation is required to assess the relative weights of spatial and temporal proximity and to provide additional tests of this conjecture.

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NOTES

1. Although commonly known as the "Ternus" display, Ternus himself (1926, footnotes on pp. 86, 132, 133) attribed the invention of the display to Pikler (1917, cited in Ternus, 1926).

2. Dawson and Wright (1994) note that a third percept, simultaneity, can be produced by the Ternus display. However, they found very few reports of simultaneity with frame durations of 100 msec and virtually none with frame durations of 150 msec; we therefore expected few, if any, such percepts in the present experiments with frame durations of 200 msec.

3. The effect of spatial frequencies and lateral interactions may well reflect a common underlying mechanism, however: both affect apparent contrast, and it has been shown that keeping apparent contrast constant eliminates the effect of spatial frequency on apparent motion (Breitmeyer et al., 1988).

4. The subject deviating from the general pattern also did not report element motion at zero ISI in the stationary-context condition, which is extremely unusual. It is possible that this subject misunderstood the task. The pattern of results was not affected by whether this subject's data were included in the analysis or not.

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