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FIGURE-GROUND SEGREGATION MODULATES APPARENT MOTION

V. S. RAMACHANDRAN
Department of Psychology, University of California at San Diego, La Jolla, CA 92093, U.S.A.

and

STUART ANSTIS
Department of Psychology, York University, 4700 Keele St., Downsview, Ontario, Canada M3J 1P3

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Abstract—We explored the relationship between figure-ground segmentation and apparent motion. Results suggest that: (a) static elements in the surround can eliminate apparent motion of a cluster of dots in the centre, but only if the cluster and surround have similar "grain" or texture; (b) outlines that define occluding surfaces are taken into account by the motion mechanism; (c) the brain uses a hierarchy of precedence rules in attributing motion to different segments of the visual scene. Being designated as "figure" confers a high rank in this scheme of priorities.

Apparent motion Figure-ground Texture Occlusion

INTRODUCTION

This article is concerned with the manner in which figure/ground segmentation can influence the perception of apparent motion. To anticipate, we find that apparent motion signals are attributed far more often to figural regions that to regions of ground.

EXPERIMENT 1: EFFECT OF STATIC BACKGROUND

We now report that the presence of static elements in the surround can have a dramatic effect upon the perception of apparent movement. We presented two pictures or frames in temporal alternation [Fig. 1(a)]. In the first frame an outline square and a square-shaped matrix of dots were represented simultaneously, side by side. The square and the dots were made to exchange places in the second frame, and the two frames were made to alternate continuously with a stimulus onset asychrony (SOA) of 350 msec (frame duration was 350 msec and ISI was zero). This display was then compared with Fig. 1(b), which was produced simply by embedding Fig. 1(a) in a texture or matrix of static dots in the surround.

All our stimuli were generated on a P4 phosphor CRT screen using an Apple IIc microcomputer. The dots and lines were luminous, not black as in the figures. Each dot subtended 2 min arc, and in this experiment the square and the matrix of dots each subtended about 1.5° × 1.5°, and were separated by 1.75° between centres. The dot density was 9 dots/deg^2.

Four experienced subjects and 12 naive subjects were asked to view either Fig. 1(a) first (eight subjects) or Fig. 1(b) first (eight subjects) and to report what they saw. For the naive subjects, but not the experienced subjects, an unrelated distractor experiment lasting about five minutes was inserted between the two sessions, in order to minimize any persisting response bias from the preceding session. All 16 subjects reported the same results. In Fig. 1(a) they reported seeing a moving square which simply exchanged places with a dot-matrix that jumped in the opposite direction. We shall call this the "exchange" percept. In Fig. 1(b), on the other hand, they always saw an opaque moving square that occluded static dots in the background. We shall call this the "occlusion" percept. Even with considerable effort they could not see the dots as moving in the opposite direction. These results show that the presence of a surrounding context of static dots can dramatically alter the perception of moving stimuli (Inada and Ramachandran, 1985). They also suggest a general hypothesis, which is tested in the experiments which follow. The hypothesis is that the visual system attributes any ambiguous motion signals only to that which it regards

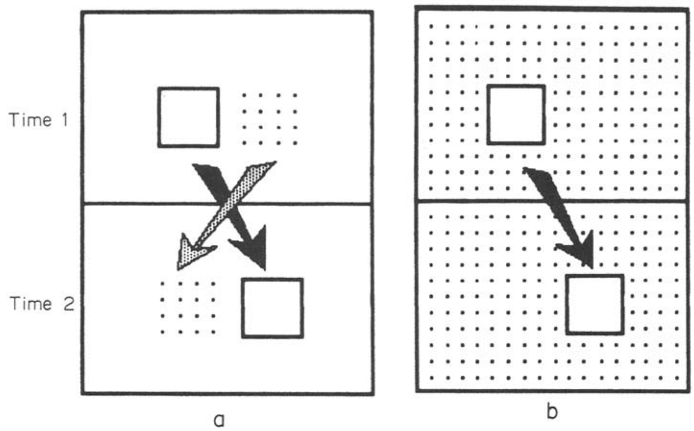

Fig. 1. (a) A square cluster of dots was presented beside an outline square in frame 1. The dots and the square exchanged locations in frame 2. In all the illustrations the two frames are shown one below the other for clarity, but in practice they were visually superimposed and presented in alteration. In Experiment 1 the SOA was 350 sec (alternation rate = 1.42 Hz). Result: the cluster and square appeared to exchange positions, with the square apparently jumping to the right (dark arrow) and the dot cluster to the left (light arrow). (b) The dots were now embedded in a matrix of static spots of the same texture and spacing. The square cluster was now assimilated into the background texture and was no longer seen to move.

as "figure" and ignores motion signals derived from what it considers to be "ground".

EXPERIMENT 2: DENSITY OF DOT CLUSTER

The regular arrays of dots used in Fig 1(a,b) were replaced by textures of sparse random dots (Figs 2 and 3). The stimulus onset asynchrony (SOA) was 400 msec, and no interstimulus interval (ISI) was interposed between frames. A cluster of dots (without a textured background) will readily exchange places with a square outline shape [Fig. 2(a)], even though the dots constituting the cluster are not correlated between frames. But if the cluster is embedded in a static random-dot texture [Fig. 2(b)] only the square is observed to move. However, if the surrounding random-dot texture is sparser than the dot cluster (so that the cluster can be perceptually segregated from the surround even in a single frame) then the "exchange" percept can still be obtained [Fig. 3(a)].

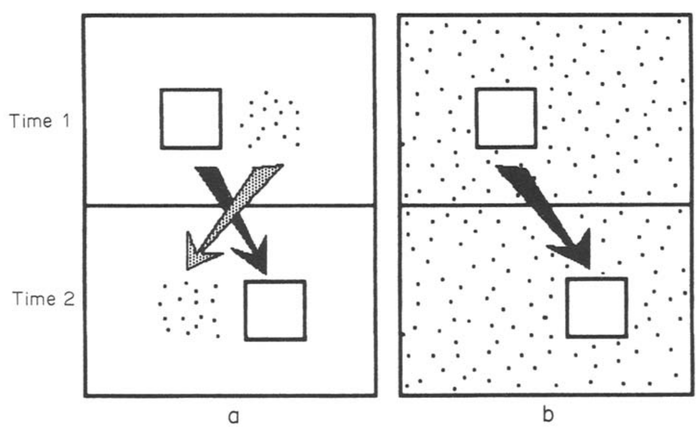

Fig. 2. Same as Fig. 1(a) except that random dot clusters were used instead of regular arrays of dots. The random-dot backgrounds were the same, but the dot clusters were uncorrelated, in the two frames. SOA was 400 msec. The cluster and square appeared to change places, as in Fig. 1(a). (b) Same as Fig. 1(b) except that the dots were randomly distributed instead of being in a regular array. This stimulus was produced by embedding Fig. 3 in a matrix of static random dots in the surround which were correlated in the two frames. Since there was no ISI the dots in the surround were static and continuously visible; so now, as in Fig. 1(b), they were perceptually assimilated into the background and no longer moved.

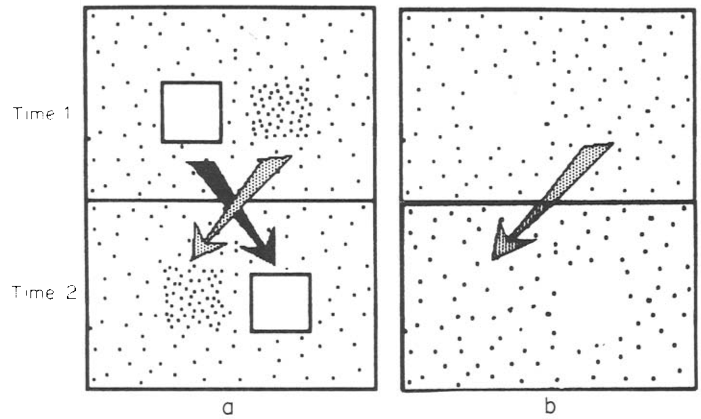

Fig. 3. (a) Same as Fig. 2(a) except that the dots which were disoccluded by the jumping square were now denser than the surround. Result: they now appeared to exchange places with the square (arrows). This result was more like that from Fig. 2(a) than from Fig. 2(b). (b) Same as Fig. 2(b) except that the outline square was removed. Result: the hole (where the square had been) did *not* appear to move. Instead, the cluster of dots which was "disoccluded" by the jumping hole, was seen as moving (light arrow), jumping back and forth between two perceptually stationary holes. This result differs from Fig. 2(b).

Four naive subjects were first familiarized with the percepts of "exchange" and "occlusion" using Fig. 2(a,b). Starting with a stimulus similar to Fig. 2(b) we added extra randomly positioned dots into the region corresponding to the cluster. This gave the stimulus shown in Fig. 3(a). One could also obtain Fig. 3(a) by adding a background of random dots to Fig. 2(a)]. The density of dots in this region, and hence the salience of texture discrimination, was varied randomly from trial to trial while the dot density of the background was always held constant. The subject's task was to rate the strength of the exchange versus occlusion percept on a scale of 1–10, in which 10 stood for optimum exchange without any occlusion, whilst zero stood for occlusion only. No time limit was imposed but the subjects were encouraged to respond as quickly as possible.

The square and the dot cluster each subtended 1.5° and were separated by 1.5° between centres. The density of the dots in the surround was held constant at 3 dots/deg^2. The actual dot density of the cluster could be set at one of the following eleven different values: 3, 10, 20, 30, 40, 50, 60, 70, 80, 90 or 100 dots/deg^2. The random-dot surround subtended 4° × 4°.

Results are shown in Fig. 4. Each datum point is the mean of 128 readings (4 subjects × 32 trials each). Note that each increase in the dot density of the cluster made the cluster more salient and made it more likely to be seen as moving, so the subject's tendency to report "exchange" increased monotonically. When the cluster had the same dot density as the surround it had zero salience and was never seen as moving; the subject reported seeing only occlusion.

EXPERIMENT 3: NO OUTLINE

This was similar to Experiment 1, except that the outline square was omitted. This left a square black dot-free patch, which now looked like a black hole instead of like a square [Fig. 3(b)]. We now asked subjects to report whether they saw a moving "hole" or a moving set of

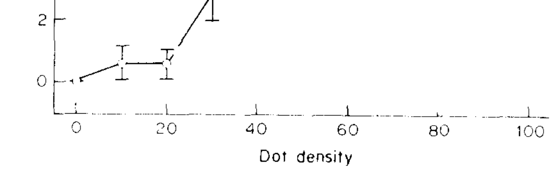

Fig. 4. Results of Experiment 2. Increasing the density of the dot cluster in Fig. 3(a) increased its salience and also the strength of its subjective movement. A rating of zero meant that the square appeared to move but the dot cluster did not, whilst a rating of 10 meant that the dot cluster seemed to move [light arrow in Fig. 3(a)] just as strongly as the square (dark arrow) as they exchanged positions.

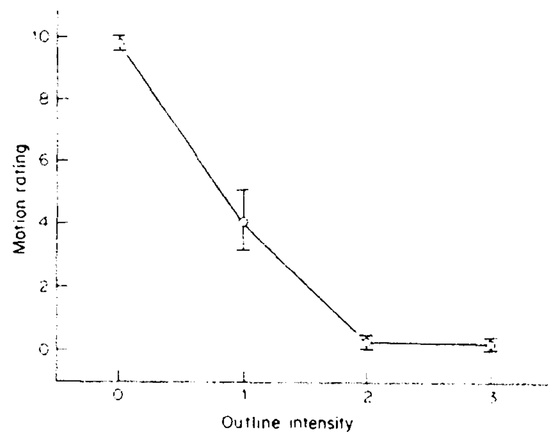

Fig. 5. Results of Experiment 4. Increasing the luminance of an outline square, from zero [as in Fig 3(b)] through different luminance levels [as in Fig. 2(b)] increased the subjective motion of the square. A rating of zero meant that only the square appeared to move [dark arrow in Fig. 2(b)] whilst a rating of 10 meant that only the dots appeared to move [light arrow in Fig. 3(b)]. Intermediate ratings meant that the dots and the square were perceived as changing places. The different luminance values of the outline were $0 = 5\ cd/m^2$, $1 = 25\ cd/m^2$, $2 = 45\ cd/m^2$, $3 = 110\ cd/m^2$. Background luminance was held constant at $5\ cd/m^2$.

dots, or both. A moving hole would be the equivalent of the occlusion percept in Experiment 1; seeing both move would be the equivalent of the equivalent of the exchange percept; and seeing only the dots move would be a new percept. We found that this new percept now predominated. When our 12 subjects viewed the display without the outline square [Fig. 3(b)] they always reported seeing the cluster of dots moving, and not the hole moving. (As in the previous experiment the dots constituting the central cluster were uncorrelated in successive frames but the dots in the surround were correlated and did not change location.) The occlusion percept, so vivid in Figs 1(b) and 2(b), could no longer be seen in this display. Instead, a cluster of dots, invisible within each static frame, was immediately seen when motion commenced, and appeared to jump back and forth between two apparently stationary holes, alternately filling each hole and leaving it vacant. This is one of our most surprising results. It suggests that the outline is necessary to delineate the occluding surface which in Experiment 2 was seen to move back and forth over a static background texture. The hole on its own, without its outline, is not treated as an "object". What is surprising is that the cluster of dots which fills in the hole is seen to move rather than the hole itself; although the dot cluster is completely embedded in static dot texture and connot be discerned at all in either of the two frames of Fig. 3(b). On the other hand, the hole can readily be seen without scrutiny in each frame, yet it fails to generate the apparent motion; an observation that is somewhat inconsistent with our own conjecture that low spatial frequencies dominate apparent motion (Ramachandran *et al.*, 1983).

EXPERIMENT 4: VARYING THE LUMINANCE OF THE OUTLINE

Next we varied the salience of the outline in Fig. 2(b) by changing its luminance. Four different luminance levels (including zero luminance, that is, no outline) were presented in random order to each of four subjects. They were asked to use the same subjective scale as in Experiment 2 to rate the apparent strength of the dot motion. For instance, a rating of 10 would correspond to movement of the dots only with no movement of the dark square, whilst movement of the square only would earn a rating of zero.

Figure 5 shows the results. Each datum point is the mean of 8 readings (4 subjects × 2 readings each). As the contrast of the outline was raised there was an increasing tendency to see a moving occluder rather than moving dots.

EXPERIMENT 5: ILLUSORY CONTOURS AS OCCLUDERS

In this experiment the real contour which outlined the square in Fig. 2(b) was replaced by a subjective contour (Kanisza, 1979). See Fig. 6. We found that this was just as effective at defining the square and in attracting the signals of apparent motion (Ramachandran, 1985).

Subjects viewing Fig. 6(a) always saw a moving square occluding stationary elements in the background, whereas in the control stimulus [Fig. 6(b)] they always reported seeing a central cluster of dots jumping back and forth. The physical differences between Fig. 6(a) and (b) are very small but the perceptual change was dramatic. In Fig. 6(a) the small quadrants cut out of the disks stimulate the visual system to perceive a subjective square which jumps back and forth. The completed disks in Fig. 6(b) generated not a subjective square but merely a vacant dot-free hole, which, as in Fig. 3(b), was not sufficiently figural to pre-empt the apparent

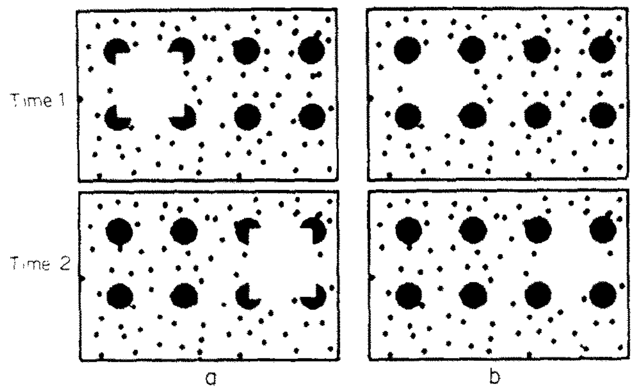

Fig. 6. (a) Compare this to Fig. 2(b), except that the jumping square was defined not by a real outline but subjective contours produced by the "Pacman" pie-wedges at the corners (Ramachandran, 1985). Result: this subjective square was seen at jumping (dark arrow), as in Fig. 2(b). (b) The pie wedges were changed into solid black disks which no longer defined a subjective square. Result: instead of apparent motion of the dot-free hole, the cluster of dots which was previously disoccluded by the subjective square was now seen as moving (light arrow).

motion. So by default a cluster of dots was seen jumping between two perceptually stationary empty holes.

DISCUSSION

Many experiments suggest that visual stimuli are analysed into several dimensions or attributes such as colour, form, depth and motion. There are even hints that such analysis proceeds at least partly in parallel in various extra-striate visual areas (Baker *et al.*, 1981; Zeki, 1978; van Essen, 1979). This raises a feature assignment problem: how does the visual system know which features belong together to define a single object (Crick, 1984; Treisman, 1977; Koch and Ullman, 1984)?

Here we are concerned with a special case of the feature assignment problem, namely the selective attribution of motion signals to different parts of the visual scene (Ramachandran, 1985). The visual system senses motion and also senses various objects and has to determine what is moving (Duncker, 1929). We find that in most instances motion signals are attributed to a set of elements when they are seen as figures in the foreground but not when they are seen as part of the background texture.

A direct demonstration of the effect of figure-ground reversal on apparent motion is depicted in Fig. 7. Here were present two sets of vertical stripes in alteration (SOA = 400 msec). The width of the black stripes in frame 2 is twice the width of the corresponding stripes in Frame 1, and the two frames are optically superimposed so that the centers of the stripes are in exact registration. When the black bars are perceived as "figure", they are seen to perform to-and-fro 3-D rotation against a white back-

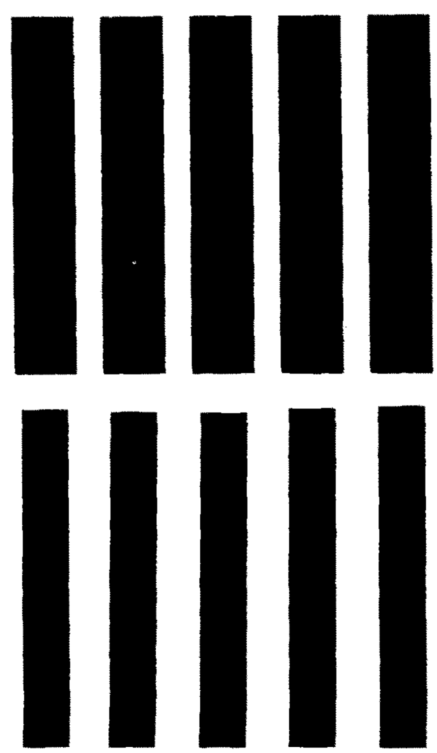

Fig. 7. Depicts the effect of voluntary figure-ground reversals on the perception of 3-D apparent motion. The narrow vertical black stripes in Frame 1 (above) are presented in alternation with the broad black stripes in Frame 2 (below) and the centers of the stripes are in exact registration. One can either perceive black vanes rotating on a white background or white vanes rotating on a black background. If the black–white stripes are replaced by red–green stripes at isoluminance the depth effect is reduced considerably.

ground (as in "Venetian Blinds"). By producing a voluntary figure ground reversal, however, one can switch to seeing the white bars as vanes rotating against a black background. The bars which are perceived as "figure" are always seen to rotate in 3-D and one rarely sees a two-dimensional expansion and contraction. We have recently observed that this 3-D rotation is obtained only if the bars are defined by brightness contrast. If the black–white stripes are replaced by red–green stripes at isoluminance the kinetic depth effect is reduced considerably (Ramachandran and Anstis, 1986); an observation that is consistent with earlier claims that motion perception is reduced at isoluminance (Ramachandran and Gregory, 1978; Cavanagh *et al.*, 1985).

The results of Experiment 2 suggest that a if target that is embedded in a surround of similar texture it becomes assimilated into the background and cannot participate in apparent motion. The visual system appears to use a hierarchy of precedence rules in attributing motion signals to different segments of the visual scene. Being designated as "figure" seems to confer a very high rank in this scheme of priorities. However, this does not explain why motion of the dot cluster [Fig. 3(b)] is seen quite clearly in Experiment 3 even though the dot cluster is not segregated from the background. Although the hole is more perceptually salient than the dots it is the dots that are seen to move. Thus, perceptual salience alone does not necessarily predict whether a set of elements will participate in apparent motion. It looks as though the presence or absence of occluding surfaces is also taken into account by the visual system in interpreting motion signals. Since a hole is not a surface, it cannot occlude anything.

These results have two implications for theories of apparent motion:

(1) Static elements in the visual field can strongly influence the perception of apparent motion.

(2) Object surfaces and boundaries must be delineated and figures demarcated from ground, before motion signals are allocated to different segments of the visual scene. Consider a leopard moving in front of a textured background. As the leopard moves it successively covers and uncovers leaves in the background and therefore these elements are seen in reverse sequence by (say) retinal motion detectors. The resulting spurious motion signals might be eliminated if the motion signal from the occluder (i.e. the leopard) were to veto the signals from the background texture elements. Figures 1(b), 2(b) and 6(a) (Experiments 1, 2, and 5) suggest that this is indeed what happens in human vision. An ingenious experiment by Sigman and Rock (1974) supports this idea. They found that if an opaque occluder was moved back and forth in front of two stationary light spots so as to occlude them alternately, then no apparent motion of the light spots was seen since the brain could not "intelligently" interpret the motion signals as arising from the occluder rather than from the spots themselves.

This line of reasoning is consistent with many of our findings but it does not explain why no occlusion is seen in displays 1(a), 2(a) and 3(a). Why is the "exchange" percept preferred here? One possibility is that the occlusion rule is brought to bear on a situation only after "figure" and "ground" labels have already been clearly assigned. In Figs 1(a), 2(a) and 3(a) the dot clusters have distinct figural attributes and so the motion signal arising from them is not suppressed.

We have recently reported two further examples of illusory occlusion (Ramachandran, 1983; Anstis and Ramachandran, 1985). In the first example, which we call "entrained motion", we began with an array of 8 dots scattered randomly on the CRT screen. These were switched off and replaced by an identical set shifted horizontally by 0.5° and the procedure was repeated in a continuous cycle. One of the spots in the second frame alone was then masked off by means of a piece of opaque masking tape. As expected, the dots in the surround continued to oscillate horizontally, but we found that the single unpaired spot also continued to oscillate, apparently jumping behind the piece of tape. The surprising aspect of this illusion was that one was seeing apparent motion towards a non-existent spot of light! If the spot in the second frame was simply deleted (rather than covered by a occluder) then entrained motion was still seen but it was considerably reduced (Ramachandran, 1983). In the second example we began with a small triangle positioned below a large square in frame 1, and followed it by a large square alone in frame 2, to the right of the first large square, and the two frames were then exposed in continuous alternation (Anstis and Ramachandran, 1985). Subjects always reported seeing a triangle moving up to the right and hiding behind a square that appeared to occlude it. The percept was a compelling one and it was often hard to persuade naive subjects that there really was no triangle on the second frame!

Moving objects in nature have at least two physical properties associated with them, rigidity and kinetic occlusion. As a result of surface rigidity, all points on the surface of an object will tend to move in the same direction with identical velocities (even for tumbling 3-D objects this principle is approximately true for small areas and small excursions). "Kinetic occlusion" refers to the fact that moving objects generally occlude and disocclude successive portions of the background (Gibson, 1979). Unlike rigidity, kinetic occlusion is not a primitive attribute but is the product of two other properties of physical objects, namely opacity and existence constancy. It is the opacity of moving objects that momentarily hides the background and it is the assumption of continued existence of objects in the background that causes one to see occlusion rather than (say) simple disappearance and reappearance of background.

Our experiments suggest that the visual system adopts these common properties of moving objects as basic assumptions and uses them in selecting between competing perceptual hypotheses. However, we suspect that these assumptions exists as constraints on early processing (Marr, 1981) rather than as "top-down" effects based on high-level stored knowledge about specific objects. On way to reveal these constraints is to investigate the rules used by the visual system in interpreting ambiguous displays. We conclude that in a surprising number of instances these rules reflect two natural properties of moving objects—surface rigidity and kinetic occlusion.

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