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ENTRAINED PATH DEFLECTION IN APPARENT MOTION

Stuart Anstis[1] and V. S. Ramachandran[2]

[1]Department of Psychology, York University, 4700 Keele St., Downsview, Ontario, Canada M3J 1P3 and
[2]Department of Psychology, University of California at San Diego, La Jolla, CA 92093, U.S.A.

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Abstract—A dot jumping back and forth between two positions would normally appear to jump along a straight line. But when surrounded by dots which jumped through three positions arranged in a V, it also appeared to jump along a V-shaped trajectory.

Apparent motion   Movement perception   Motion contrast

INTRODUCTION

In this article we describe an illusory bending or deflection of the path of apparent (stroboscopic) motion. A dot jumping back and forth between two positions normally appears to jump along a straight line, but in this case its perceived path was deflected to mimic the V-shaped trajectory of other dots which surrounded it.

Ramachandran (1984) described an illusion of apparent motion (AM) which he called "entrained motion". A random array of 8 dots was flashed up on a T.V. screen, then switched off and replaced by the same pattern shifted horizontally by 1°. The pattern alternated continuously between these two positions, giving an impression of back and forth AM. One of the dots in the second frame (chosen randomly) was then masked off with a small piece of opaque white tape or cardboard so that the corresponding dot in frame 1 had no partner to pair with. The dots in the surround continued to oscillate as expected, but the single unpaired spot also appeared to oscillate, seemingly disappearing behind the occluder on frame 2 and reappearing on frame 1. Thus the observer saw AM toward a nonexistent dot. This "entrained motion" of the single dot was strongest when the occluding piece of tape was clearly visible. When it was removed from the T.V. screen, and the occluded spot was electronically deleted, the entrained motion was much weaker, falling from a mean subjective rating of 10 with the occluder to a rating of 3.2 when the occluder was removed.

We now report a variety of entrainment phenomena in which the path of AM was deflected and no occluder is necessary. The array of entraining dots now jumped between not two but three positions which were arranged in a V [Fig. 1(a)]. The dots were flashed on in frame 1, then jumped down and to the right (toward 4 o'clock) for frame 2, then up and to the right (toward 2 o'clock) for frame 3. As expected, they showed apparent motion along a V-shaped path. The central dot in the array was then electronically delected on frame 2. Thus it was flashed on in frame 1, remained dark in frame 2, and was flashed on in a horizontally shifted position in frame 3. Seen on its own, it simply appeared to jump to the right and back again. But when surrounded by the entraining dots, this back and forth AM could be seen only by prolonged careful scrutiny. During spontaneous or pre-attentive viewing, its apparent motion became entrained or deflected and appeared to follow the same V-shaped path as the other dots.

EXPERIMENT 1: MEASURING THE PATH DEFLECTION

Five dots were displayed on a computer-controlled T.V. screen, arranged like the five spots on a die [Fig. 1(a)]. The four entraining dots lay at the four corners of an imaginary square of side 4°, with the entrained dot at the centre of the square. The five dots were flashed on in three successive positions, like a movie which was three frames long. Each of the three frames lasted for 275 msec. On frame 1 all five dots were flashed on; they were then switched off and replaced in frame 2 by the same dots shifted down and to the right. However, only the four outer dots were visible in frame 2; the centre dot was erased. On frame 3 all five dots were visible again, flashed on in a third position which was shifted up and further to the right of

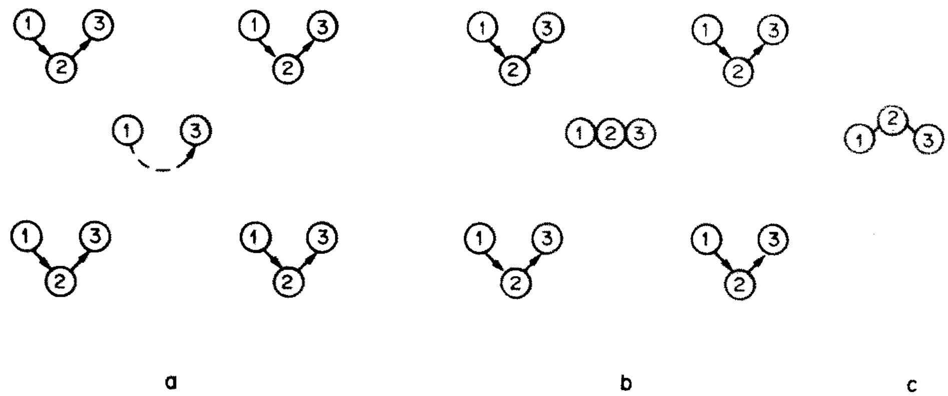

Fig. 1. (a) Path deflection illusion. A square matrix of five spots was presented in frame 1, followed by the same pattern shifted down and to the right in frame 2, and then shifted up and to the right in frame 3. The central spot was deleted from frame 2 so that it appeared only in frames 1 and 3. Numbers in spots show order of presentation. Drawing is not to scale: actual dots were tiny (4 min arc) points of light, not disks. The four spots in the surround were correctly seen as jumping along V-shaped trajectories. The central unpaired spot also appeared to follow a V-shaped trajectory (dashed arrow), even though it had no partner to pair with in frame 2. If the four surround dots were removed (not shown), the central spot was correctly seen as oscillating horizontally instead of describing a V. (b) Motion contrast illusion. Display was the same as *a* except that the central dot was visible in frames 1, 2 and 3, jumping along a straight line. Result: the central dot appeared to move along a slight upward V, as shown diagrammatically in (c).

frame 2. The frames were presented in a continuous sequence 1-2-3-2-1-2-3-2... The outer four dots were seen as jumping back and forth along a V-shaped path, as one would expect. The centre dot was always erased in frame 2, so that it was displayed only in the two extreme positions. However, its perceived motion was deflected or entrained so that it appeared to jump along the same V-shaped path as the other four dots. This illusory deflection was measured by a matching procedure. A sixth dot positioned 9.2° below the centre spot (and thus well removed from the main display) moved in parallel with the entraining dots on frames 1 and 3. However, its vertical position on frame 2 could be adjusted up and down by means of a hand-held joystick controlled by the subject, who could set its trajectory continuously from a steep or shallow upward V through a straight line to a shallow or steep downward V. He was instructed to set the trajectory of this matching spot to look like that of the central entrained spot. Opaque screens were arranged to ensure that he could see either the five-spot display or else the matching spot at any given time, but not both at once, so his comparison judgments had to be made successively, not simultaneously.

The horizontal component of the two jumps (frames 1–2 and frames 2–3) was always set to 24 min arc each. However, the entraining spots jumped along a V-shaped path, so they jumped leftwards down to frame 2, then leftwards up to frame 3 (or up then down for an inverted V). This vertical component of the jumps was randomly pre-set on each trial to a value between 28 min arc upwards and 28 min arc downwards. It was this vertical component that the subject matched. The dots, which were each 4 min arc in diameter, were luminous on a black ground, and the display screen was viewed binocularly in a dimly lit room from a distance of 57 cm.

Results are shown in Fig. 2(a). Each datum point is the mean of 30 readings (3 subjects × 10 settings), and the vertical bars show the standard error for the 30 pooled readings. Figure 2(a) shows that the vertical deflection entrained into the test spot was approximately half the actual vertical displacement of the entraining spots.

EXPERIMENT 2: MOTION CONTRAST

A small but crucial change was now made in the display, which completely altered the results. On frame 2 the central dot was now not erased, but was made visible at a position along a straight line midway between its position in frames 1 and 3. Whereas the surrounding dots moved along a V, the central dot now moved along a straight line (Fig. 1(b)]. Result: the central dot showed an apparent vertical excursion *opposite* to that of the entraining dots. When the entraining dots moved in an upward V the central dot appeared to move in a slight

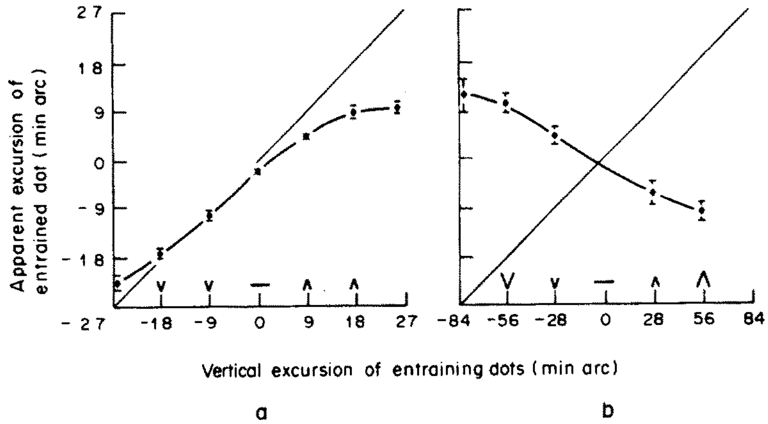

Fig. 2. (a) Path deflection in of the central dot in Experiment 1 [Fig. 1(a)] as a function of the amplitude of the V-shaped trajectories of the four spots in the surround. Each datum point is the mean of 30 readings (3 subjects × 10 readings). Vertical bars show standard errors of the 30 pooled readings. Apparent deflections entrained into the central dot were about half the actual vertical deflections of the surround dots. (b) Motion contrast induced into the central dot in Experiment 2 [Fig. 1(b)]. Each datum point is the mean of 6 readings (2 subjects × 3 readings). Apparent deflection of central dot was now *opposite* to the actual vertical deflection of surround dots. Slope of best fitting line was −0.177. Note that (a) and (b) have different abscissae.

downward V. When the entraining dots moved in a downward V the central dot appeared to move in a slight upward V. Results are shown in Fig. 2(b). Each of the five datum points is the mean of 6 readings (2 subjects × 3 trials). The least-squares fitted line has a slope of −0.177, which implies that when the entraining dots moved up through 1 deg the central dot appeared to move down through 0.177 deg. Note that the vertical component of the entraining dot motion was varied within a broader range than in Experiment 1.

Thus when the central dot was erased in frame 2 (Experiment 1) its vertical apparent excursion was in the same direction as the surrounding dots (motion assimilation). But when it was made visible in frame 2, midway between its positions in frame 1 and frame 3 (Experiment 2), its vertical apparent excursion was in the opposite direction to the surrounding dots (motion contrast). Motion contrast was approximately a third of motion assimilation.

We shall now leave motion contrast and return to entrained motion.

DEMONSTRATION 3: SPATIAL AND TEMPORAL CHARACTERISTICS OF PATH DEFLECTION

Demonstration 3 shows that path deflection has a finite range both in time and in space, and is not caused by eye movements. The stimulus used is shown in Fig. 3.

(*a*) *Temporal localisation: four dot positions instead of three*

In Fig. 1 the entraining dots jumped along a V-shaped trajectory defined by three positions.

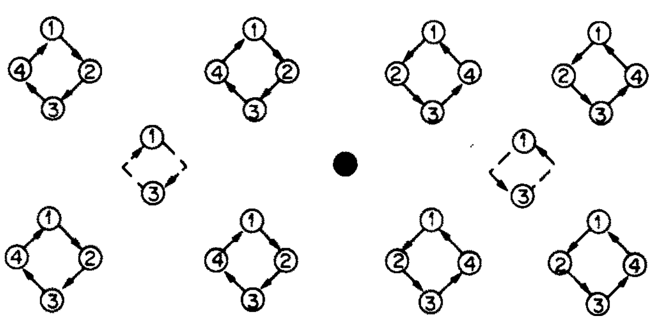

Fig. 3. Stimulus for Demonstration 3. Central fixation spot is shown in black. Left-hand quartet of entraining dots jumped clockwise through four successive positions arranged in a diamond, whilst right-hand quartet was a mirror-image array which jumped counterclockwise. Both the left and right entrained dots, centred within each quartet, actually jumped up and down vertically. However, they were deflected by their immediately surrounding dots along opposite apparent rotary paths (dashed arrows); clockwise for the left dot, counterclockwise for the right dot. See text.

But in Fig. 3. they jumped along circular or diamond-shaped trajectories defined by four dot positions. The motion of the dot pattern was not rotary, but translatory, according to a translatory vector which was uniformly changing its orientation. This circular motion was clockwise in the left half of the field, and counterclockwise in the right half. For simplicity we shall describe what happens in the left half only. The entrained central dot was visible in frames 1 and 3 but was deleted in frames 2 and 4. On its own it would be seen as jumping back and forth vertically between positions 1 and 3. However, the entraining dots deflected its perceived path so that it appeared to follow the same clockwise rotary path (dashed arrows in Fig. 3) as the entraining dots. Thus the path deflection was localised in time, being apparently leftwards on the up stroke between frames 3 and 1, and rightwards on the down stroke between frames 1 and 3. Hence no long integrating time or buildup time is involved in path deflection.

(b) Spatial localisation: opposite deflections in different spatial regions

The rotary entraining motion was made clockwise in the left half of the field, but counterclockwise in the right half of the field. The left and right entrained dots were both made to jump back and forth along parallel vertical trajectories, both being visible only on frames 1 and 3. However, the two entrained dots appeared to move along opposite rotary paths, clockwise for the left entrained dot and counterclockwise for the right entrained dot. Each dot appeared to adopt the trajectory of the dots which immediately surrounded it. This shows that different path deflections could be entrained locally in different spatial regions.

(c) Path deflection is not caused by eye movements

In viewing Fig. 3, subjects were instructed to fixate the stationary central disc. Even if they did not obey this instruction, it is clear that since the eyes obviously cannot roll clockwise and counterclockwise at the same time, eye movements can be ruled out as the primary cause of the two opposite path deflections which were simultaneously visible in Fig. 3.

In Experiment 1 and Demonstration 3, the apparent deflections of the AM in the entrained spot were roughly at 45° to the spot's physical displacement as it jumped from frame 1 to frame 3. So they cannot be simply a form of visual interpolation, applied locally to the entrained spot on its own. Any such interpolation would presumably lie along a straight line joining the two positions at which the entrained spot was visible (Morgan, 1979; Burr and Ross, 1979). The fact that the AM appeared to deviate from this straight line, and to deflect along trajectories which were parallel to the V-shaped or diamond-shaped paths of the surrounding spots, shows that these other spots were influencing and entraining the selected spot. The effect depends upon long-range spatial interactions rather than on local interpolations between successive positions of the central test dot.

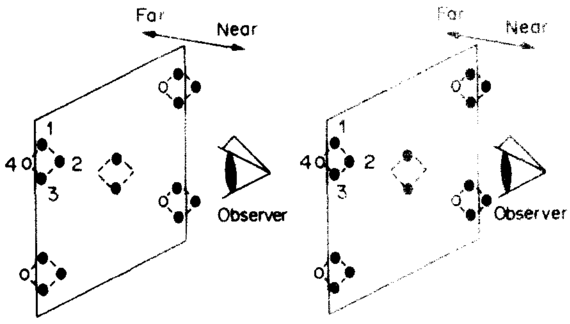

Fig. 4. Deflection of apparent motion in the third dimension. If the reader free-fuses this stereoscopic diagram by diverging his eyes he will see what the stimulus was for Demonstration 4. The four spots in the surround described rotary trajectories in stereoscopic depth. They lay in the fixation plane in frame 1, then jumped downwards and forwards (nearer to the observer) in frame 2, then jumped downwards and backwards (into the fixation plane again) in frame 3, then up and behind the fixation plane in frame 4. The central test spot was seen to perform a similar motion in depth although it was visible only in frames 1 and 3, when it actually lay in the plane of fixation.

DEMONSTRATION 4: DEFLECTION OF STEREOSCOPIC MOTION

The entrained dot was now centred among the four entraining dots, as in Experiment 1. However, the display was presented stereoscopically so that the four dots moved in depth (Fig. 4). They were presented on frame 1, then down and forward in depth on frame 2 so that they lay in front of the fixation plane. On frame 3 they jumped down but backwards in depth, into the fixation plane again. On frame 4 they jumped up and backwards in depth, lying directly behind their positions in frame 2. Then they jumped back to their original positions in the fixation plane in frame 1. This cycle repeated continuously.

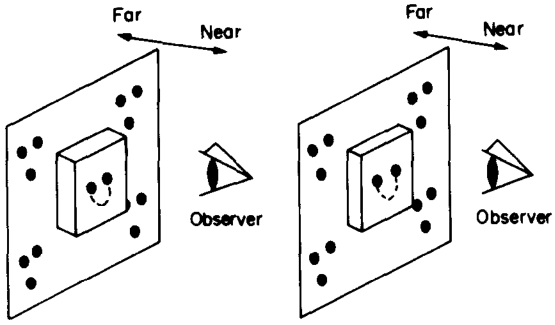

Fig. 5. Disparity-specific motion entrainment. If the reader free-fuses this stereoscopic diagram by diverging his eyes he will see what the stimulus was for Demonstration 5. All the dots moved in frontoparallel planes but the central dot lay in a different depth plane in front of the four entraining dots. Motion entrainment was weaker but still visible.

The entrained dot was presented, as usual, only on frames 1 and 3, oscillating back and forth vertically between two positions but never leaving the plane of fixation. However, its path was strongly deflected in depth, so that it appeared to follow the same rotary path in depth as the entraining dots. It appeared to move forwards with them in frame 2, and back with them behind the plane of fixation on frame 4.

DEMONSTRATION 5: PATH DEFLECTION SPECIFIC TO DEPTH PLANE

The entrained dot was centred among the four entraining dots, as in the previous demonstration. However, the display was presented stereoscopically so that all dots moved in the frontoparallel plane, but the entrained dot lay in a different depth plane in front of the four entraining dots (Fig. 5). Note how this differed from the previous demonstration: in Demonstration 4 all visible dots lay in the same depth plane at any given time, but the entraining dots moved in depth as well as downwards, whereas in Demonstration 5 the entrained and entraining dots lay in different depth planes, but the entraining dots moved sideways, not in depth. The horizontal and vertical jumps were held constant at 24 min arc, and the disparity of the central dot relative to the others was varied between 12 min arc crossed and 12 min arc uncrossed disparity. It was observed that the path deflection was most marked when the entrained dot lay in the same depth plane as the entraining dots, and grew progressively weaker when the entrained dot lay in front of or behind the entraining dots.

DEMONSTRATION 6: DICHOPTIC PATH DEFLECTION

The usual five-dot display was now presented dichoptically in such a way that all four entraining dots were presented to the left eye only, on frames 1, 2 and 3, whereas the test dot was presented to the right eye only, on frames 1 and 2. Result: the path deflection was still visible but less compelling. This suggests that the path deflection may have a central component.

DEMONSTRATION 7: ENTRAINMENT CAN PULL BUT NOT PUSH

In Fig. 1(a) the central dot appears to deflect downwards in a V. Its perceived path is *pulled* downwards by the dots below it, and *pushed* downwards by the dots above it. We showed that pulling is far more effective than pushing, by selectively deleting the upper or the lower dots. The perceived path of the central dot was successfully pulled downwards by the lower dots [Fig. 6(a)] or by flanking dots in a straight line [Fig. 6(c)] but was not pushed down by the

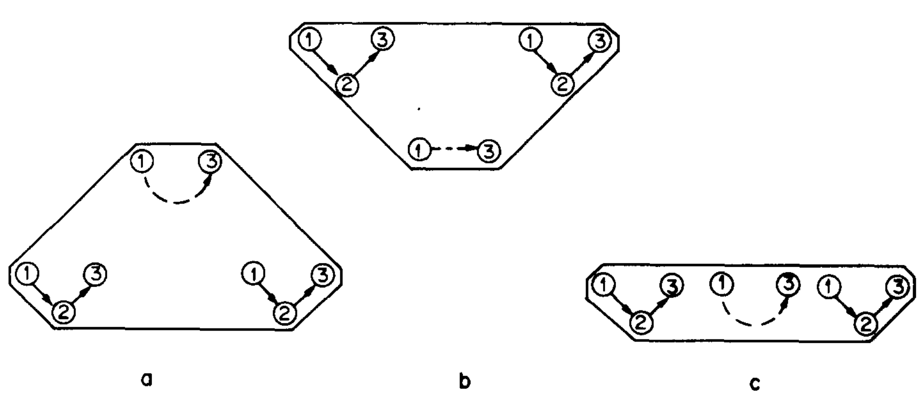

Fig. 6. Entraining dots can pull (a, c) but not push (b) a deflection into a dot's path. Dashed arrows show apparent path of the central dot, which shows entrainment in a and c but not in b. Thin line around dots is the convex envelope outside which, we conjecture, motion cannot be entrained.

upper dots [Fig. 6(b)]. Conversely, when the trajectory of the surround dots was inverted, so that they moved up then down in an inverted V, it was now the upper but not the lower dots that produced path deflection; this is equivalent to looking at Fig. 6 upside down.

Possibly, motion can be entrained only within a convex *envelope* defined by snapping an imaginary rubber band around the position of all the visible dots. Pulling downward would keep the deflected path of the central dot within the permitted envelope of motion. Attempts to push the path outside this envelope failed.

DEMONSTRATION 8: ENTRAINMENT IS REDUCED AT EQUILUMINANCE

Motion perception is mediated almost entirely by the luminance pathways and receives only a weak input from the opponent colour pathways (Ramachandran and Gregory, 1978; Anstis *et al.*, in press). Thus the perception of an oscillating square in a random-dot kinematogram is reduced considerably if the black and white dots are replaced by red and green dots at equiluminance. This shows that colour provides only a weak cue to apparent motion and that the motion-dependent segregation of the central square of random dots is especially dependent on luminance contrast. However, if single isolated spots are used instead of random-dot patterns apparent motion can be seen quite clearly (Ramachandran and Gregory, 1978). This raises the question whether spatial contextual illusions such as entrained path deflection also require a luminance input. We presented a square matrix of five spots as shown in Fig. 1, except that instead of white spots on a black background we used red spots on a green background. The display was presented on a colour monitor controlled by a microcomputer. By looking through a variable-colour filter combined with a polarizer we were able to vary the luminance ratio of the two colours continuously over a wide range. At equiluminance we found an almost complete loss of entrainment; the central spot was seen to move horizontally instead of following the V-shaped trajectory of the surrounding spots.

DISCUSSION

Context effects in apparent motion are scarcely new. In his classic paper, Wertheimer (1912) showed that apparent motion can be experienced, with a *temporal* context of repeated double exposures, when only a single stimulus is shown. He presented a vertical line followed by a horizontal line at a rate which gave good motion, several times in succession, with pauses of 1–5 sec between presentations. During one of the intervals, the vertical line was turned off. "The next two or three exposures, presenting only one of the objects, produced a smaller motion.... In the first of such exposures this rotation was of about 45°, in the second it was a small arc, until, only the third or fourth exposure brought complete rest. This phenomenon can hardly represent a mere error of judgment: it appeared in both the naive and the sophisticated procedures, regularly and clearly observable" (p. 1052). Thus, from the very beginning of experimental research in the field, it was clear that stroboscopic motion is influenced by various factors apart from the local stimulus conditions.

Ramachandran and Anstis (1983a, b) demonstrated a spatial context effect in ambiguous apparent motion. Two dots at the top left and bottom right corners of an imaginary square were flashed on, then replaced by dots at the other two corners. This ambiguous stimulus gave either horizontal apparent motion along the top and bottom sides of the square, or vertical motion along the sides. In a spatial display of a dozen of these dot quartets flashing on and off together it was found that all the motions were in the same direction; if one quartet appeared to move horizontally (or vertically) they all did. From time to time the direction of apparent motion changed from horizontal to vertical or vice versa, but when it did so all the quartets changed at the same instant. Ramachandran and Anstis (1983b, d) found a temporal context effect which they called "visual momentum". A single ambiguous dot quartet was embedded in two horizontal rows of dots which were flashed in sequence to give horizontal apparent motion. This led to horizontal apparent motion in the dot quartet.

Perception often requires the resolving of ambiguities in the visual input. Fortunately, ambiguity in natural conditions of observation is much smaller than it may at first appear (Gibson, 1979) since we do not live in a chaotic and amorphous world. Objects have obvious physical properties which can be incorporated as constraints on early visual processing (Marr, 1982; Ramachandran and Anstis, 1983). A moving object, for instance, usually has surface rigidity. Consequently all features of the object will tend to move in the same direction with nearly identical velocities. The entrained motion illusion may be a perceptual manifestation of surface rigidity, such that in ambiguous situations the brain may adopt constraints that result in a preference for uniform motion over incoherent motion.

Although it is plausible to expect this illusion, given the statistical properties of the real world, the mechanisms underlying it need further study. We discuss four points of view: (1) object conservation, (2) occlusion/disocclusion, (3) attention failure, and (4) cooperative parallel algorithms. These possibilities need not be mutually exclusive.

(1) Object conservation

It is well known that when we view a single spot exposed in two successive positions, we perceive a single motion rather than two successive but unrelated events. The reason has been well put by Shepard and Zare (1983):

"This phenomenon [of apparent motion] provides evidence for the internalization of principles of object conservation and least action. The brain evidently prefers the interpretation that a persisting object moved over the most direct path consistent with the available evidence rather than an interpretation that the object moved over some longer path or, worse, that one object went out of existence and a second object simultaneously materalised at another location".

Thus when a spot disappears at one position and another nearby spot promptly appears, the brain treats this as not just a coincidence but as a pair of connected events. In the same way, when five spots disappear simultaneously (after frame 1) and reappear simultaneously (in frame 3), this is also treated as not just a coincidence. Although the centre dot behaves differently from the others on frame 2 it is perceived as moving with the other dots. In our opinion, path deflection arises from the same principle of least action that causes us to see apparent motion of a single dot in the first place. When a central spot jumping from position 1 to position 3 is surrounded by a quartet of dots with each jump from 1′ to 2′ to 3′, the brain adopts the economical hypothesis that all the spots move together like a rigid surface, rather than that four dots move along one trajectory while the central spot coincidentally happens to move along a different, linear trajectory. We might say that the brain abhors a coincidence and loves a common cause.

The rectilinear path of the central spot should be considered not as a local interpolation but simply as the default trajectory in the absence of more information. Shepard and Zare (1983) added a curved gray path, briefly flashed between two alternately displayed black dots. This induced the illusion of a single dot moving back and forth over that path. In our experiment, on the other hand, the extra information came from the V-shaped trajectories of the *surrounding* dots some distance away. This offered contextual evidence that the central dot's path was longer than a direct straight line, and the invisible central spot at position 2 provided no direct evidence against this; so the observer perceived all five spots as following parallel V-shaped paths.

(2) Occlusion/disocclusion

An entrained dot (Ramachandran, 1984) disappears behind an occluder, but the central dot in our display seems to move even when no occluder is present. Sigman and Rock (1974) also explored the role of occlusion in apparent motion. They propose that the perception of apparent motion can be the outcome of an intelligent problem-solving process. They exposed two spots a and b in alternation, by moving an opaque rectangle back and forth, alternately covering and uncovering two stationary spots a and b, in the right places and tempo that ought to give good apparent motion. As far as other theories of apparent motion are concerned, there is no reason why these conditions should not produce an impression of a and b moving. But from the standpoint of problem-solving theory, the moving rectangle provided an explicable basis for the appearance and disappearance of a and b, namely that they are there all the time but are undergoing covering and uncovering. This is what the subjects reported; they rarely reported apparent motion. However, if the rectangles were drawn so as to look transparent they did not look capable of covering anything, so it was no longer a fitting or intelligent solution to perceive a and b as two permanently present dots that were simply undergoing covering and uncovering. In this condition, subjects again reported apparent motion (Rock, 1983).

Clearly occlusion/disocclusion is an attractive explanation for simple entrained motion (Ramachandran, 1984). The entrained dot, which flashes on and off next to an opaque piece of card, is perceived as jumping back and forth, going behind the card then emerging again. This phenomenon is the converse of the effect described by Sigman and Rock (1974), who moved a card back and forth and found that dots which would otherwise have been seen as moving were now seen as stationary. Ramachandran kept the occluder stationary and provided a context of jumping dots, and found that a flashing dot which would otherwise have been seen as stationary was now seen as moving. In Rock and Sigman's experiment the motion of the occluder vetoes the motion signal from the spots. In Ramachandran's experiment the static occluder allows a motion signal to be seen; a signal that would otherwise be rejected by the brain.

We regard path deflection as a form of entrained motion. However, it is a stronger illusion, and in particular it needs no occluder. We believe the reason is that in entrained motion the brain must extrapolate from one seen position of the entrained dot to a second, unseen position, whereas in path deflection it has merely to interpolate between two seen positions to a third, unseen intermediate position. Perhaps disembodied motion signals are not accepted unless the motion can be attributed to a visible object or feature. Ramachandran (1984) reported that without the occluder, no second dot existed to carry the motion, but with the occluder present the observer could assume that the dot had now hidden behind it, so the illusion was considerably enhanced. In deflected motion, the unpaired spot reappeared in the third frame so the visual system could confidently attribute the motion signal to this reappearing spot.

On the other hand, when the central spot is visible at three positions in line (Experiment 2) it does provide direct evidence countermanding the hypothesis of entrainment, which is consequently rejected. Now a different phenomenon came into play: The rectilinear path of the central spot now appeared bent in the opposite direction from the surround because of motion contrast, a process akin to induced movement. Motion contrast has been reviewed by Anstis (1986). Whereas occlusion may be involved in motion assimilation or entrainment, it plays no part in motion contrast since the central dot remained visible and unoccluded at all times.

(3) Attention failure

Treisman and Schmidt (1982) have suggested that in perceiving objects we may integrate separable features, such as colour and shape, by directing attention serially to each item. In accord with this feature-integration theory, they found that when attention was diverted or overloaded, features were sometimes wrongly recombined, giving rise to "illusory conjunctions". For instance, when a card exhibiting a pink X and a green T was flashed up briefly, observers often clearly saw a pink T. It is arguable that object movement might be such a separable feature, so that in the visual processing of motion there may be a partial separation between object identity and object motion. Thus the question of which object moved may not be synonymous with where in the visual field the motion occurred. The "where" question may be answered by a global motion detector that sees motion averaged over the whole of the dot cluster. The motion signal thus derived is then attributed to all the finer image features as well—including the single unpaired dot. Ramachandran and Inada (1985) have called this effect "motion capture".

But we doubt that path deflection is caused by attention failure. Attention can fail for two reasons: pre-attentive processing limits in the visual system, or attentional load applied by a difficult task. Neither seems to apply to our experiments. In normal viewing we very rarely misattribute colors or motion; we seldom perceive a green rose with red leaves, and we rarely perceive the wrong part of the scene as moving, except perhaps in difficult viewing conditions such as seeing a leopard moving behind fluttering foliage. (We do sometimes misattribute motion, for instance when the moon seems to sail behind drifting clouds or the river bank seems to swirl upwards after we have gazed at a waterfall. But induced movement and the motion aftereffect probably involve inhibitory interactions between motion sensing channels, and have nothing to do with illusory conjunctions or the overloading of attention.) So in normal viewing conditions color and motion perception are not constrained by pre-attentive processing limits; errors of illusory conjunction arise only when attention is overloaded, for instance by the brief tachistoscopic exposures used by Treisman and Schmidt (1982). But we never used brief exposures or difficult viewing conditions; our observers were free to inspect the display for as long as they wished, yet the path deflection phenomenon was clearly seen. We conclude that there is little evidence that either attentional load or pre-attentive processing limits play a role in path deflection.

(4) Cooperative algorithm

Motion may be analysed by the same types of co-operative parallel algorithms as are used to analyse global stereopsis in random-dot stereograms (Julesz, 1971; Sperling, 1970; Dev, 1975; Nelson, 1975; Marr, 1982). Units tuned to similar directions and velocities may facilitate each other and thereby reduce or eliminate spurious signals of incoherent motion based on potential false matches.

In summary, the four mechanisms postulated to process object identity and object motion separately are consistent with several aspects of both versions of entrained motion.

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REFERENCES

Anstis S. M. (1986) Motion in the frontal plane: sensory aspects. In *Handbook of Perception* (Edited by Kaufman L. and Boff K.). In press.

Anstis S. M., Cavanagh P., Maurer D., Lewis T. and Mather G. (1986) Computer-generated screening test for color blindness. *Color Res. Applic.* In press.

Burr D. C. and Ross J. (1979) Acuity for apparent vernier offset. *Vision Res.* **19,** 523–532.

Dev P. (1975) Perception of depth surfaces in random-dot stereograms: A neural model. *Int. J. Man-Machine Stud.* **7,** 511–528.

Gibson J. J. (1979) *The Ecological Approach to Visual Perception.* Houghton Mifflin, Boston.

Julesz B. (1971) *Foundations of Cyclopean Perception.* Univ. of Chicago Press.

Marr D. (1982) *Vision.* Freeman, San Francisco, Calif.

Morgan M. J. (1979) Analogue models of motion perception. *Phil. Trans. R. Soc. Lond. B* **290,** 117–135.

Nelson J. I. (1975) Globality and stereoscopic fusion in binocular vision. *J. theoret. Biol.* **49,** 1–88.

Ramachandran V. S. (1984) Entrained motion: A new visual illusion. *Invest. Ophthal. visual Sci., Suppl.* **25,** 200 (Abstr.).

Ramachandran V. S. and Anstis S. M. (1983a) Perceptual organization in moving displays. *Nature* **304,** 829–831.

Ramachandran V. S. and Anstis S. M. (1983b) Extrapolation of motion path in human visual perception. *Vision Res.* **23,** 83–85.

Ramachandran V. S. and Gregory R. L. (1978) Does colour provide an input to motion perception? *Nature* **275,** 55–57.

Ramachandran V. S. and Inada V. (1985) Spatial phase and frequency in motion capture of random-dot patterns. *Spatial Vision* **1,** 55–67.

Rock I. (1983) *The Logic of Perception.* MIT Press, Cambridge.

Shepard R. and Zare S. (1983) Path-guided apparent motion. *Science* **220,** 632–634.

Sigman E. and Rock I. (1974) Stroboscopic movement based on perceptual intelligence. *Perception* **3,** 9–28.

Sperling G. (1970) Binocular vision: A physical and neural theory. *Am. J. Psychol.* **83,** 461–534.

Treisman A. and Schmidt H. (1982) Illusory conjunctions in the perception of objects. *Cogn. Psychol.* **14,** 107–141.

Wertheimer M. (1912) Experimentelle Studien uber das Sehen von Bewegung. Translated in part as: Experimental studies on the seeing of motion. In *Classics in Psychology* (Edited by Shipley T.), pp. 1032–1089. Philosophical Library, New York, 1961.