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EXTRAPOLATION OF MOTION PATH IN HUMAN VISUAL PERCEPTION

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According to Newton's First Law of Motion, a physical object moving at uniform velocity in one direction will persevere in its state of uniform motion unless acted upon by an external force to change that state (Newton, 1687).

Since the visual system has evolved to process information from the physical world, one might expect to find a similar principle of "inertia" in the visual perception of moving objects. Using dot displays (Fig. 1) we have found that any object which moves in one direction at uniform velocity will tend to be perceived as continuing its motion in that direction (Ramachandran and Anstis, 1981). This might be regarded as a perceptual equivalent of Newton's first law.

If two spatially separated spots of light (Fig. 1a) are presented to the retina in rapid succession the spot will appear to move from the first point to the second, as commonly seen in neon advertisement signs (Korte, 1915; Kolers, 1972; Anstis, 1970, 1978; Julesz, 1971; Burt and Sperling, 1981). If a single spot is followed by two flanking spots (Fig. 1b) which appear on either side of it simultaneously, it is almost always seen to "split" and to move simultaneously in opposite directions (Ullman, 1980). This predilection for splitting can be overcome by placing one of the flanking spots nearer to the first spot, in which case it will always attract the apparent motion. We shall call this the "proximity" rule.

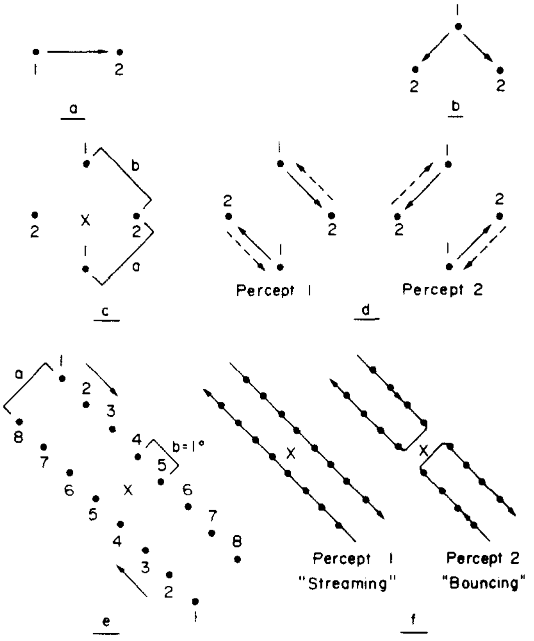

Fig. 1. (a) Apparent motion between two dots flashed sequentially. Small numerals indicate order of presentation and arrows indicate direction of perceived motion. Our computerized display system is described in Cavanagh and Anstis (1980). (b) A single dot followed by two simultaneous flanking dots gives split motion. (c) Square matrix of four dots, with the north and south pair alternating in presentation with the east and west pair. Central dot was fixation point. The distance *a* and *b* could be varied independently. When *a* and *b* were equal the percepts No. 1 and No. 2, shown in (d), were seen with roughly equal probability. (e) Same square matrix embedded in two long parallel rows consisting of dots flashed sequentially in the order shown by the numerals. Note that only two dots were illuminated at a time. Spacing (*b*) between dots within a row was fixed at 1°, but the subject could increase the spacing (*a*) between rows to favor "streaming" [Percept 1 in (f)] or decrease it to favor "bouncing" [percept 2 in (f)].

Figure 1c shows a matrix of dots (Gengerelli, 1948) forming the four corners of a diamond. This display (as well as subsequent ones described in this paper) was generated on a p4-phosphor CRT using an "Apple 2" microcomputer and viewed from a distace of 1 m. The dots were arranged in a diamond with oblique sides because a square array with vertical sides shows an unwanted preponderance of vertical rather than horizontal apparent motion, possibly because of inter-hemispheric delays across the visual midline. The sides of the square subtended 1° and the dots themselves were about 4 min of arc in diameter. The number by each dot refers to the time at which it is presented. If *a* and *b*, the sides of the square, are of equal length the display will be ambiguous and always seen as clearly bistable. The two possible percepts, which are equally probable and mutually exclusive, are indicated in the diagram as Percept 1 (northwest–southeast) and Percept 2 (northeast–southwest). Figure 1e shows how we attempted to bias the percept towards one of these two states by embedding the same four dots in two long parallel rows consisting of dots which were flashed sequentially, starting from the left hand end of the top row and the right hand end of the bottom row. If the embedded dots now showed Percept 1 then the overall apparent motion was of dots "streaming" along two straight, parallel paths. If the embedded dots shows Percept 2 then the overall apparent motion was of dots "bouncing" along two U-shaped paths (Fig. 1f). If the distance between the dots was arranged so that *a* and *b* were the same length, one might expect that the two percepts would again be equally probable, as they had been in Fig. 1d. However, when we presented this display to eight naive observers, they all reported seeing the "streaming" percept No. 1 and none reported seeing the "bouncing" percept No. 2. As a control condition we now occluded the biassing sequence of dots, and found that streaming and bouncing were now reported equally often. If the occluder was removed, streaming immediately regained its predominance. In our interpretation, if an object has once been seen moving in one direction, there is a strong perceptual tendency to continue seeing motion in that direction, so that straight-line streaming is perceived in preference to the angled path of bouncing. We shall refer to this as "visual momentum," based on a loose analogy with moving physical objects. Admittedly, this resemblance may be superficial. Indeed, visual momentum did not increase with velocity (i.e. presentation rate) as physical momentum would; this is not surprising since it is well known that the perceptual quality of apparent motion is not a linear function of presentation rate, but deteriorates if the presentation rate is too fast or too slow (Korte, 1915). The U-shaped curve (bottom curve in Fig. 2) suggests that the same may be true for visual momentum. Nevertheless, our findings imply that the interactions of a pair of dots seen in sequence are influenced by the history of their *past* interactions with earlier dots. It may be that neurons responding to motion are directionally coupled to allow "feed forward" facilitation in a way that promotes the perception of unidirectional movement

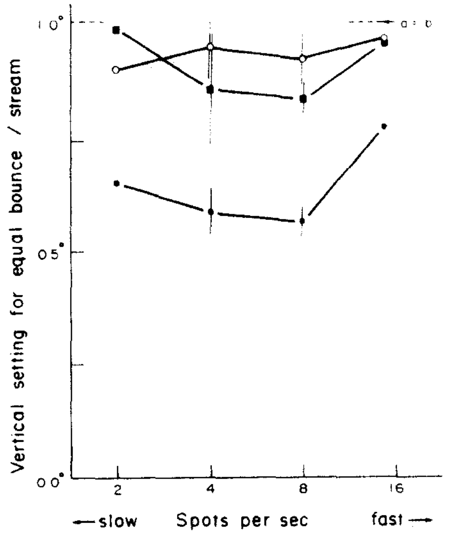

Fig. 2. Subjects adjusted distance (a) between rows until they saw bouncing and streaming with equal probability. When four tests dots were shown without biassing dots, *a* and *b* were set about equal (open circles) as expected. Embedding the test dots in parallel rows of eight sequentially presented dots greatly increased the probability of seeing linear "streaming" motion (solid circles). However, parallel rows of stationary dots had much less effect (solid squares). The vertical lines indicate standard error.

The tendency to see streaming could be pitted against the proximity rule by making *a*, the distance between the two rows, smaller than *b*, the distance between the dots within each row. This distance (b) between the dots was kept constant at 1° and the dots subtended 4 min of arc. We gradually reduced the distance between the rows (keeping presentation rate constant) until subjects reported seeing bouncing and streaming with equal frequency; and this gave us a measure of the magnitude of visual momentum. Subjects were instructed to fixate a stationary dot which was at the center of the display, and to avoid tracking the apparent motion with their eyes. Data were collected with a psychophysical "staircase" method: subjects hit two different computer keys to indicate whether they saw streaming (or bouncing), which automatically moved the two rows of dots slightly closer (or further apart). Ten judgments of reversals were collected, and the mean of the last six judgments was printed out. Figure 2 shows the result of such an experiment on five naive subjects for each of four different presentation rates. None of the five subjects was aware of the purpose of the experiment. Without the biassing dots, *a* and *b* were set very nearly equal (open circles) as expected. But when the biassing dots were in apparent motion (solid circles), there was a strong preference for seeing streaming, even when *a* was smaller than *b*. Thus, visual momentum could actually override the proximity rule. To make bouncing as easy to see as streaming, the separation between the rows had to be reduced to about 60% of the dot spacing within each row.

It should be pointed out that in all these experiments we varied the stimulus onset asynchrony (SOA) rather than the inter-stimulus interval (ISI); since the former is known to more critically influence apparent motion than the latter (Kolers, 1972). The ISI was kept constant at zero msec and SOA was varied by changing the stimulus duration alone.

We looked for a stationary analogue of the visual momentum effect by embedding the four oscillating test dots in two rows of dots which were in the same positions as before but were stationary and unchanging, i.e. all present simultaneously, instead of being flashed in sequence. Interestingly, there was still a slight tendency to see the motion of the test dots as aligned with the rows of dots rather than at right angles to them. However, we measured this tendency and found that it was significantly smaller—*a* had to be about 80% of *b* to null the static induction, vs 60% to null visual momentum. So streaming was induced largely by the motion, not by the mere presence, of biassing dots. These results show that the perceptual pairing of dots to give apparent motion is influenced strongly by interactions with earlier dots, and to a lesser extent by their spatial relationships with nearby stationary dots.

One has to consider the possibility that at least part of what we call "visual momentum" might arise from tracking eye movements. This seems unlikely to us. Although our subjects were unaware of the purpose of our experiment they had all had experience with psychophysical tasks involving fixation (e.g. experiments involving stereopsis); and were specifically instructed to maintain careful fixation. A slight tendency to track may have persisted inspite of our instructions but it is hard to see how a *slight* tendency can account for the fact that *a* had to be less than 60% of *b* in order to over-ride momentum. Further, the effect in question can be seen just as clearly if two displays identical to Fig. 1c are presented *orthogonal* to each other (and moving in opposite directions). In this situation, even when *a* is smaller than *b* for both displays—the "streaming" mode is seen for both. This observation suggests that eye movements cannot explain the "momentum" effect.

The critical task for motion perception is to detect correspondence, i.e. to identify specific portions of a changing visual scene as representing a single object in motion. In principle, any small feature in one visual "snapshot" can potentially be matched with any one of a multiplicity of features in the succeeding snapshot which happen by chance to be similar. Fortunately the number of possible false matches is greatly reduced by our living in a non-random world, in which objects have predictable continuities and redundancies (e.g. rigidity, unchanging surface textures and colors, etc.) which impose constraints on the number of legal matches which "make sense." The visual system translates these informational redundancies into specific rules (Marr, 1982). Thus, visual momentum may exemplify a prediction by the visual system that at least for small excursions the motion of a physical object is likely to be unidirectional and along a straight line.

We have described context-dependent effects in apparent motion which cannot be predicted simply from the interactions of two spots. For a further example, consider an equilateral triangle of three dots with A at the apex and B, C at the base corners. Flashing B then C gives horizontal apparent motion from B to C, both to a human observer and to a neural motion detector. Flashing B, then A, then C gives a V-shaped motion path from B up to A and from A down to C. This pre-empts the apparent motion from B to C, which has now disappeared: the motion "link" from B has now been used up by A and is no longer available to link up B with C, even though the time interval between B and C is kept the same. The link between B and C might be inhibited at an early level, or else vetoed later by a higher level decision process.

Certain cells in the mammalian retina (Barlow and Levick, 1965) and cortex (Hubel and Wiesel, 1969; Zeki, 1974; Petersen *et al.*, 1980) seem to be specialized primarily for detecting moving targets. Some of these cells (e.g. in the retina) also respond to apparent motion: at least for small displacements of the stimulus. It would be interesting to present our stimuli to such units to see if these cells display contextual effects based on lateral interaction, without the need to invoke higher psychological processes. Experiments along these lines are now in progress.

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