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RESEARCH NOTE

DISPLACEMENT THRESHOLDS FOR COHERENT APPARENT MOTION IN RANDOM DOT-PATTERNS

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Abstract—Two correlated random-dot patterns (A and B) were generated on a CRT screen and presented in rapid alternation; (B) was shifted horizontally by varying amounts in relation to (A) so that coherent apparent motion was seen. We found that larger shifts were tolerated if (i) the stimulus onset asynchrony (SOA) was longer; (ii) if the patterns were optically blurred; and (iii) if there were fewer dots on the screen. Hence apparent motion in random-dot patterns may involve a global pattern matching operation as in stereopsis. Two uncorrelated random-dot patterns were alternated to produce incoherent dynamic "noise". A low spatial frequency sine wave grating was then projected on this "noise" and moved in step with the alternating random-dot patterns. This resulted in "motion-capture"—i.e. all the dots now seemed to move synchronously with the moving grating. The effect could not be obtained with high spatial frequency gratings or with stationary dots. As a tentative solution to the "correspondence problem" it is suggested that low spatial frequencies are matched first and these matches impose constraints on subsequent high frequency matches—thus allowing the system to home in on a unique solution.

Motion correspondence   Apparent motion   Random-dot patterns   Correspondence problem

INTRODUCTION

If two spatially separated spots are presented to the retina in rapid succession the spot will appear to move from the first spot to the second as commonly seen in traffic lights and neon advertisement signs (Korte, 1915; Kolers, 1972; Anstis 1970, 1978, 1980).

Instead of a single spot one can use a whole two-dimensional array of spots distributed randomly on the screen. If the entire array (frame A) is switched off and replaced by an identical (correlated) array (frame B) shifted horizontally one perceives a whole sheet of dots moving to and fro. We shall refer to this as *coherent* motion. The effect is similar to that studied by Anstis (1970), Julesz (1971), Lappin and Bell (1972), Braddick (1973), Ramachandran (1981), and Baker and Braddick (1982), except that the whole array is shifted instead of a small subset of elements.

To achieve coherent motion in correlated patterns the brain has to solve what is often called the "correspondence problem" (Anstis, 1970; Ullman, 1979; Marr, 1982). Any given element in pattern (A) can in principle be matched with any one of a multitude of elements in pattern (B) which happen, by chance, to be similar. How does the brain avoid making all these false matches and how does it choose the appropriate partner for each element? This question is not merely of academic interest. To one of our arboreal ancestors trying to avoid a leopard darting behind a dense screen of fluttering goliage, the task of correlating successive views of the predator is at least as "ecologically valid" as seeing perspective transformations!

This paper is concerned with the limits of the correspondence process in random dot patterns. Some preliminary observations suggested that if pattern (B) is shifted by too large a distance in relation to (A), then coherent motion breaks down. The point where this occurs will be referred to as the *displacement threshold* for apparent motion.

Our first experiment explores the relationship between displacement threshold and speed of alternation (the reciprocal of the stimulus onset asynchrony or SOA). In the case of classical apparent motion between two isolated spots of light, it is known that as the spatial separation between them is increased the SOA has to be made longer for motion to be seen—a relationship that is known as Korte's Third Law (Korte, 1915). Korte's Law makes sense intuitively in that an object in the real world moving at constant velocity will take more time to make longer excursions. Does Korte's Law also hold for the more complex task of achieving correspondence between random dot patterns?

We also examined the effect of dot-density on displacement thresholds for coherent motion. One might expect that increasing the number of dots in each pattern would reduce the maximum tolerated displacement, since it would also make the task more difficult by increasing the number of false-matches.

One way of avoiding false matches in random-dot patterns would be to extract or utilize features—e.g. clusters of dots—from each image before matching these with identical features in the succeeding image. This would be a straightforward way of resolving ambiguities since the probability of two clusters of dots being fortuitously similar in the two patterns is vastly smaller than the probability of two small pixels being similar. To test this possibility we looked at the effects of optical blur on displacement thresholds (Experiment 3). Since blurring will tend to smear clusters of dots into "features" we expected to see an increase in maximum tolerated displacement.

METHODS

Stimulus

The stimulus (Fig. 1) in its static form was a square field of sparse randomly scattered dots or pixels, with each pixel subtending 2 arc min at the viewing distance used (0.5 m). This was switched off and followed immediately afterwards by an identical (correlated) array of dots shifted horizontally by a variable amount *d*. The total display subtended 12° by 12° but it was always viewed through a cardboard window subtending 10° wide by 8° high so as to exclude possible cues from the outer borders of the random-dot arrays.

The dot patterns were generated on a P4 phosphor CRT using an Apple-II microcomputer. The number of dots on the screen as well as the magnitude of shift between successive frames could be varied by the experimenter before each session. The rate of alternation could be varied continuously by the subject using a hand held potentiometer.

No interstimulus interval (ISI) was imposed between the offset of the first stimulus and the onset of the second stimulus (other than the unavoidable refresh rate of the 60 HZ t.v. system). The stimulus onset asynchrony (SOA) or duration between onset of first stimulus to the onset of the second was varied by changing the stimulus duration alone. This was done because it is known that SOA influences apparent motion much more the ISI does (Kolers, 1972).

Procedure

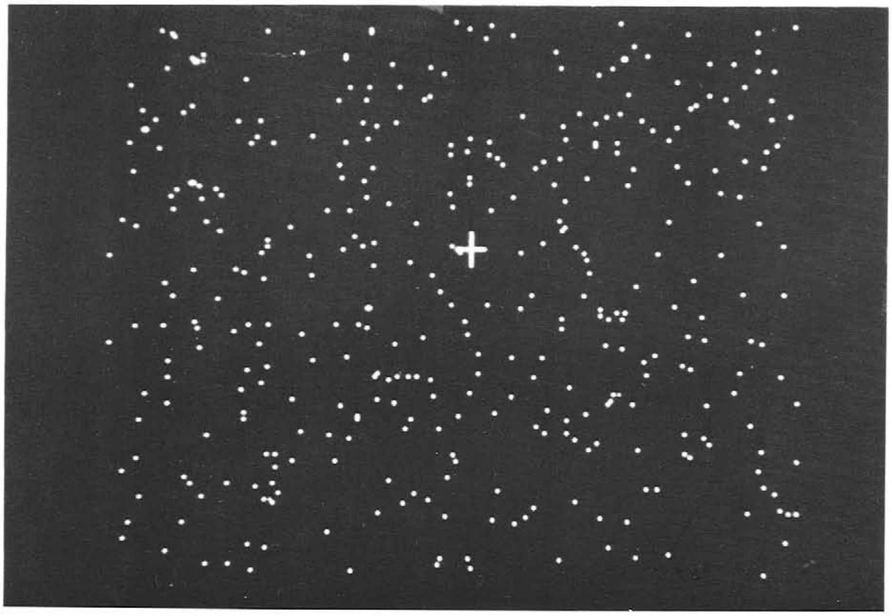
The subjects were four undergraduate students who were unaware of the purpose of the experiment. They were first familiarized with apparent motion, first with single spots and then with random-dot patterns. The distinction between coherent and incoherent motion of random-dot patterns was made clear to them. Coherent motion was demonstrated to them using short horizontal displacements and it was pointed out that all the dots moved synchronously in identical directions to form a moving "sheet." For long displacements this was no longer true and one would see incoherent motion or "snowfall" instead. At intermediate displacements the perception of coherent motion depended critically on SOA, which we used as our dependent variable. At SOA's of short duration motion was incoherent and the subject gradually increased the SOA until he began to perceive coherent motion. This procedure gave very reliable settings.

The subject was asked to fixate a small fixation cross in the center of the screen and carefully avoid tracking the dots with eye movements. The experimenter offset the disparity to a random value before each trial and the subject then viewed the dot displays presented in a continuous oscillatory alternation. The SOA was deliberately set at a low value at the beginning of each trial so that motion was incoherent and the subject's task was to increase the SOA gradually by rotating the potentiometer until he began to see unambiguous coherent motion. Although no time limit was specified, the subject was encouraged to respond as quickly as he could. The setting was recorded by the experimenter and the whole procedure was then repeated for a different (random) displacement chosen by the experimenter. Using this procedure the optimal SOA for seeing coherent motion was obtained for each of 6 randomly chosen displacements ranging from 0.6° to 1.15°.

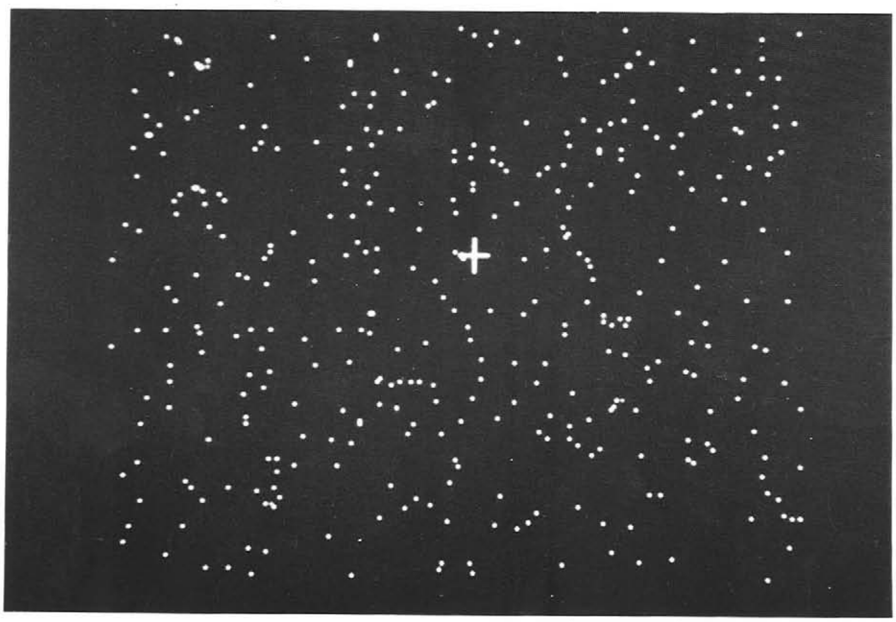
Results

The solid line (A) in Fig. 2 shows the results of our first experiment using a dot density of 9 dots deg^{-2}. Each datum point (solid circles) on the graph is the mean for 1 observation × 4 subjects. Note that the maximum tolerated displacement for seeing coherent motion increases systematically with SOA—showing that Korte's Law is also valid for the relatively complicated task of achieving correspondence between random dot-patterns (or successive views of a leopard!) Also note that the slope is roughly linear.

In our second experiment [Fig. 2(B)] we reduced the dot density to 4.5 dots deg^{-2}. Again, each datum point (solid triangles) represents the mean for 1 observation × 4 subjects. Note that the slope is significantly less than (A). This shows that for most values of SOA one can bridge a wider distance when there are fewer dots—presumably because there are fewer potential false matches. At first sight these results seem somewhat at odds with the recent observation of Baker and Braddick (1982). These authors found that varying dot-density and SOA had very little effect on displacement thresholds for coherent motion in random-dot patterns. One reason for this apparent discrepancy might be that Baker and Braddick used "segregation" of a central square-shaped region of correlated dots as their criterion for coherent motion whereas in our experiments the perception of coherence itself was directly used as the criterion. A second reason might be that they were using much smaller displacements. Braddick (1973) has suggested



(A)



(B)

Fig. 1. Random-dot patterns of the kind used in our experiment. The two patterns (A and B) are shown one below the other for clarity but were in fact optically superimposed. They were shifted horizontally in relation to each other by varying amounts and presented in rapid alternation.

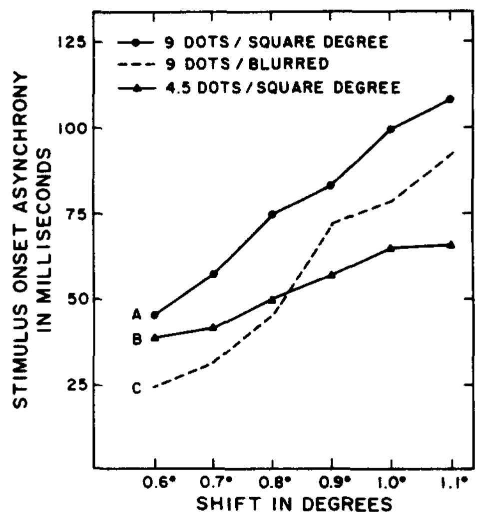


Fig. 2. Displacement thresholds for coherent apparent motion (see text).

that there may be a "short-range" process in apparent motion that has an absolute spatial limit of about 0.25°; and obviously one would not expect such a process to be influenced by dot-density. The smallest displacement we used (0.6°) was in fact bigger than the largest one used by Baker and Braddick (0.5°). Also, notice that the two lines (A) and (B) in Fig. 2 meet at about 0.45° when extrapolated. Perhaps below this limit SOA would be unaffected by dot-density but we have not specifically investigated this. In fact it may turn out that the point of intersection of (A) and (B) corresponds roughly to the "Braddick limit" for our displays.

In our last experiment [Fig. 2(C)] we examined the effects of optical blur on displacement thresholds. Blurring was obtained by fitting the subjects with −4 D lens eye-glasses. (Subjects may have partly compensated for the blurring by means of accommodation.) Note that the slope of this line remains roughly the same as (A) but that it has shifted about 0.15° to the right. This implies that at any given SOA longer displacements are tolerated with a blurred image than with sharp images perhaps by creating smeared clusters of dots to be used as tokens for correspondence. Alternatively the presence of high-spatial frequencies might actually *mask* motion between correlated low spatial frequencies and blurring might serve to "unmask" this motion.

DISCUSSION

In summary, we have found that the upper displacement threshold for breakdown of coherent AM between two random-dot patterns was increased, i.e. AM was seen more readily, when (1) SOA was increased; (2) dot density was reduced; (3) the dots were blurred. A similar effect of optical blur was also noticed by Chang and Julesz (1981).

Our observations suggest two tentative conclusions. First, coherent AM breaks down sooner for high than for low spatial frequencies, and the simultaneous presence of high spatial frequencies can actually decrease the upper displacement threshold. This implies that high and low spatial frequencies are not processed independently for motion perception—a suggestion that has already been made in the context of stereopsis (Ramachandran and Nelson, 1976). Second, since long SOA's can raise the upper displacement threshold (increase the spatial range over which AM is seen) in the same manner as optical blur, perhaps the time-constants of mechanisms that use low-spatial frequencies are significantly longer than those that use high-spatial frequency components. It may be, that neural motion detecting units of the kind postulated by Barlow and Levick (1965) are organized in such a way that units with large "disparities" (i.e. picking up wider excursions) also have larger receptive fields and longer time constants.

The link between large displacements and long time-constants is understandable since at any given velocity an object would obviously take a longer time to make a wider excursion. However the link between these two in turn and large receptive fields is harder to account for. Perhaps large receptive fields allow the system to tolerate the irrelevant "jitter" that would inevitably accompany longer excursions. One could also argue that if Barlow units which have small receptive fields also had large disparities there would be directional ambiguity for movement of large objects; whereas for large receptive field units the direction would be unambiguously specified.

A unit with a large receptive field will therefore considerably reduce the range of possible directions—i.e. it will serve to confine the number of legal high-frequency matches to a small angular range of directions. One can then ignore all other high frequency matches as being false and pick appropriate matches from within this angle. Thus the system could "home in" on the correct direction of motion; and this would provide a simple solution for the "correspondence problem". A clearer argument would require quantitative treatment along the lines suggested by Marr and Poggio (1979) for stereopsis.

It is not easy to test a hypothesis of this kind but we have recently made an observation that seems relevant (Ramachandran and Anstis, 1982). If two *uncorrelated* sparse random-dot fields are alternated at a suitable SOA (say 150 to 300 msec), then one typically sees incoherent motion, i.e. dots moving in many different directions. (We used small dots—2 min arc—covering about 5% of the screen and the dot-density was 10 per deg^{-2}.)

We then superimposed a low-contrast low spatial frequency sine wave grating (0.2 c/deg) on the random-dot display and moved it in step with the alternating random-dots fields. Even for large displacements of the grating (e.g. 2°) four naive subjects reported that all the dots in the display were "captured" by the grating and appeared to form a uniform sheet moving synchronously with it. This effect could not be seen if (a) the spatial frequency of the grating was too high (2 or 3 deg^{-1}); (b) if the grating was moved out of step with the alternation of random-dot fields; (c) if the random-dot field was static rather than dynamic. A somewhat related observation was reported by D.M. MacKay (personal communication) though his interpretation is different from our own. MacKay found that if a black wire-loop was moved in front of a detuned television set the dots on the CRT screen appeared to adhere to the loop and move synchronously with it.

These effects, referred to as "motion capture" (Ramachandran and Anstis, 1982) suggest that low spatial frequencies predominate in apparent motion and determine the nature and extent of matches made in high spatial-frequency channels—as suggested for steropsis by Ramachandran and Nelson (1976) and by Marr and Poggio (1979). The nature of this interaction certainly merits further attention.

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