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COHERENT GLOBAL MOTION PERCEPTS FROM STOCHASTIC LOCAL MOTIONS

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Abstract—A percept of global, coherent motion results when many different localized motion vectors are combined. We studied the percept with dynamic random dot kinematograms whose elements took independent, random walks of constant step size; their directions of displacement were drawn from a uniform distribution. The tendency to see global, coherent flow along the mean of the uniform distribution varied with the range of the distribution. Psychometric functions were obtained with kinematograms having various step sizes and element densities. The changes in the psychometric function with step size and density are consistent with Ullman's "minimal map theory" of motion correspondence.

INTRODUCTION

The combination of several different motion vectors can produce a percept of coherent motion in a single direction. For example, if two sinsusoidal gratings of similar spatial frequencies move in different directions, they may appear to cohere into a single moving checkerboard-like pattern (Adelson and Movshon, 1982). Also, if contrast is near threshold, two spatially interspersed random dot patterns moving in orthogonal directions can generate a percept of motion along the mean of the two directions (Levinson *et al.*, 1982).

Ullman (1979) has demonstrated that many motion percepts, including the result of combining several different motion vectors, can be explained in terms of purely local interactions. The spatial frequency selectivity of coherent unindirectional motion for moving sinusoidal grating persuaded Adelson and Movshon (1980) that mechanisms which generate the percept of coherent motion operate on the responses of spatial frequency channels. Models of spatial vision that are formulated in terms of spatially localized, spatial frequency channels at each point in visual space have met with considerable success (e.g. Wilson and Bergen, 1979). We were therefore interested in how a coherent global percept could result from the combination of localized motion vectors.

To explore the role of spatially localized processing in the perception of global, coherent motion, we used moving random dot kinematograms. Such kinematograms can be generated according to diverse rules, resulting in as many different types of stimuli. In one common type, large subsets of the dots move in one direction. But such stimuli would not be appropriate for our purposes: the contribution of the local motion of individual dots to the global percept is obscured by the redundancy of multiple motion vectors in the same direction. Instead, we developed a kinematogram in which the direction of motion of each dot is independently defined. The stimuli were constructed in the following manner. Initially, dots were distributed randomly over our cathode ray display. Each dot then took an independent 2-dimensional random walk. Though all dots travelled the same *distance* from frame to frame, the *direction* in which any dot moved was independent of the directions in which the other dots moved. Further, the direction a given dot moved from one frame to the next was independent of the direction of its previous displacements; the possible directions in which all dots moved were chosen from the same uniform probability distribution.

If the range of the distribution of directions extended over all 360 deg, only local, random movement of the individual dots was evident. However if the range of the distribution was less than 360 degrees, the pattern could appear to flow *en masse* in the direction of the mean of the distribution, even though the individual perturbations of the dots were still evident.

We parametrized the probability of seeing a global, coherent percept of unidirectional flow from local motion vectors. To do this, we varied the range of the distribution of vectors and measured the probability of seeing unidirectional flow in a direction along the distribution's mean. We then investigated the properties of local mechanisms of motion by examining how perceived coherence of motion changed with various local parameters. These parameters included spatial factors, the step size in the random walk and the density of dots across the display, as well as a temporal factor, the duration of the movement.

METHODS

The patterns were generated by a PDP 11/34 computer that passed values through a digital-to-analog converter for display on a Hewlett Packard

Table 1. Duration of interframe interval required to generate apparent continuous motion for a given step size

Step size (deg)	Interframe interval (msec)
0.1	35
0.3	50
0.5	70
0.8 or greater	90

1321A $X-Y$ display with a P31 phosphor. The displayed stimulus was confined to a square region with sides measuring 18.5 deg. A "wrap around" scheme caused dots to "disappear" when displaced beyond the boundary of the square and then "reappear" at the opposite side of the square. The pattern was viewed through a cardboard mask with a circular opening with diameter subtending 16 deg of visual angle. Subjects fixated the center of the screen; viewing was monocular with the other eye occluded by a translucent eye patch.

Each dot measured 0.1 deg in diameter. Through frame duration was always 5 msec, the interframe interval required to generate apparent continuous motion varied with step size; Table 1 lists those intervals for each of the step sizes used. Perception of coherent unindirectional flow varied with the stimulus duration (i.e. the number of frames presented). Therefore, except when we measured perception as a function of the number of frames presented, the stimulus duration was maintained at one second. The reason for choosing this value will be made clear in a later section, dealing with temporal properties of the stimulus.

The $X-Y$ display provided the only luminance in the room and subjects adapted to these luminance conditions for 5 min before starting an experimental session. The luminance of each dot of the patterns was maintained at twice threshold dot luminance. At the beginning of each session the threshold luminance was reestablished using a von Bekesy tracking procedure (Tynan and Sekuler, 1977). Preliminary experiments indicate that a coherent motion percept could be generated over a wide range of dot luminance. However since the temporal conditions for producing coherent motion varied with luminance, we decided to confine the formal study to a single luminance condition.

In preliminary experiments, a 2-alternative forced choice procedure determined the probability of seeing unidirectional flow along the mean of the uniform distribution of directions. These probabilities were measured as a function of the range of the distribution. Steps covered 0.1 deg and the dot density was 1.6 dots per square degree. The results were the same for different directions of the mean (e.g. left, right, oblique, etc.). Therefore, with no sacrifice of generalizability we subsequently concentrated only on the case in which the mean direction was upward with respect to the subject. Data reported in the paper were gathered using a simple yes-no paradigm, in which the observer indicated whether or not a coherent unidirectional flow was evident.

Four subjects were tested, three of whom were naive as to the purpose of the study. The fourth subject was one of the authors.

RESULTS AND DISCUSSION

Experiment 1: step size

For various step sizes, we first measured the probability of seeing coherent flow in the mean direction (upward) as a function of the range of a uniform distribution of directions. Four subjects participated in the study, under conditions already described.

Figure 1 shows the data from subject S.D.T. for 4 different step sizes: 0.1, 0.9, 1.1 and 1.4 deg. The percentage of trials on which the subject reported coherent unidirectional flow "upward" is plotted as a function of the range of the distribution. Note that "upward" is the mean direction of the distribution of directions. Results fall into two categories, depending on whether the step size is larger or smaller than 1.0 deg. If the step size was greater than 1.0 deg, unidirectional flow was reported only when the range of directions was kept close to the mean; directions of motion had to be within approximately 45 deg of the mean for these step sizes. For step sizes smaller than 1.0 deg, a considerably larger range of distribution of directions could generate a percept of coherent flow. In particular, when the total range of 180 deg was used with small steps coherent motion was reported almost 100% of the time. Similar results were obtained for all four subjects participating in the

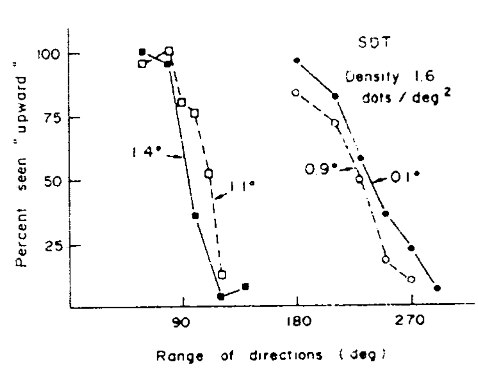

Fig. 1. The percentage reports of unidirectional, coherent flow in the upward direction as a function of the range of a uniform distribution of directions. The mean of the distribution was in the upward direction; the range is given in degrees. Data were obtained for 4 different step sizes 0.1, 0.9, 1.1 and 1.4 deg. The dot density in each case was 1.6 dots/deg^2. The results fall into 2 categories, depending on whether or not the step size is larger or smaller than 1.0 deg (data for subject S.D.T.)

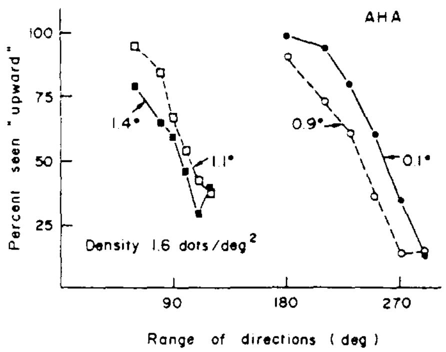

Fig. 2. Same as Fig. 1, except data for subject A.H.A.

study. Those for subject A.H.A. are shown in Fig. 2. A striking feature of both figures is that a small, two tenths of a degree change in step size, from 0.9 to 1.1, produces a large lateral shift in the psychometric function, while other changes by as much as eight tenths of a degree, from 0.1 to 0.9, result in little or no shift.

There is a conceptual impediment to a straightforward interpretation of these results. One can not assume that the perceived path a dot travels is the one which was determined by the random walk prescribed for that dot. It may be that for a given dot, its perceived path is a combination of its own random walk with those for intruding neighbors. This perceptual ambiguity is commonly referred to as the "correspondence problem" (Braddick, 1982; Marr, 1982). If such confusions did occur, spurious directions of movement could be perceived that were inconsistent with the predefined distribution of possible directions. The probability of confusion will depend on such factors as the step size, spacing or density of dots, and the interstimulus interval

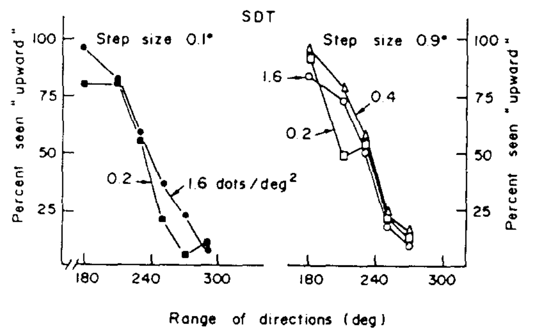

Fig. 3. The percentage reports of unidirectional, coherent flow in the upward direction as a function of the range of a uniform distribution of directions. The mean of the distribution was in the upward direction; the range is given in degrees. Data were obtained for 2 different step sizes 0.1 and 0.9 deg. For both step sizes the measurements were obtained at two dot densities 0.2 and 1.6 dots/deg². For step size 0.9 deg, measurements were also obtained at dot density 0.4 dots/deg². The psychometric function for each step size remains essentially unchanged with a change in dot density (data for subject S.D.T.).

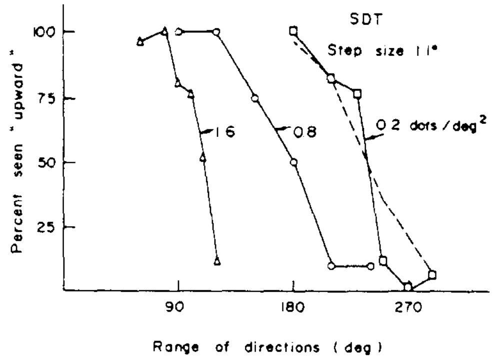

Fig. 4. The percentage reports of unidirectional, coherent flow in the upward direction as a function of the range of a uniform distribution of directions. The mean of the distribution was in the upward direction; the range is given in degrees. Data were obtained for step size 1.1 deg at three different dot densities 0.2, 0.8 and 1.6 dots/deg². For this step size, perceptibility does change with dot density. With a decrease in dot density, unidirectional coherent flow was perceived over a wider range of distribution of directions. For a density of 0.2 dots/deg² the data for a step size of 1.1 deg is almost congruent with those for step size 0.1 degree and density 1.6 dots/deg² (taken from Fig. 1) represented by the dashed line in the figure (data for subject S.D.T.).

(Ullman, 1979). If the spacing among dots is increased while other factors remain constant, it seems reasonable to expect that the probability of confusion among paths should be reduced.

Experiment 2: density of dots

In the previous experiment the density of dots was constant, 1.6 dots/deg² for all step sizes. We repeated the experiment at three additional densities 0.8, 0.4 and 0.2 dot/deg², and several step sizes. Four subjects participated in this experiment. Figure 3 shows the results for step sizes of 0.1 and 0.9 deg obtained from subject S.D.T. For clarity of presentation the data for each step size have been plotted against a separate abscissa.

No significant change in perceptibility occurs when dot density changes by a factor of eight, from 1.6 to 0.2 dots/deg², for either step size. This constancy is not evident for step sizes larger than 1.0 deg. As shown for subject S.D.T. in Figs 4 and 5, for step sizes of either 1.1 and 1.4 deg, decreasing the density of dots increases the tendency to perceive unidirectional flow, permitting unidirectional flow to be seen over a wider range of directions. The dashed line in each figure represents the psychometric function for step size 0.1 deg and density 1.6 dots/deg² taken from Fig. 1. For a density of 0.2 dot/deg² the data for both step sizes, 1.1 and 1.4 deg, are almost congruent with this dashed line. Thus for sufficiently small density of dots, perceptibility for step sizes greater than 1.0 deg is nearly equivalent to that for step sizes less than 1.0 deg.

Two important points follow from the results. First, the fact that spacing of dots can alter

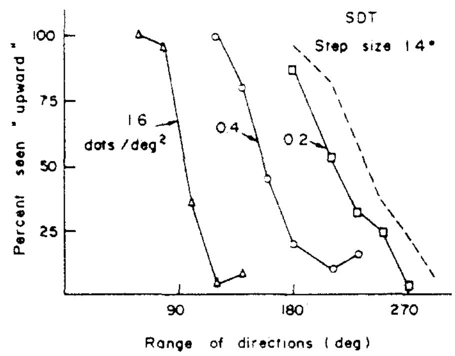

Fig. 5. The percentage reports of unidirectional, coherent flow in the upward direction as a function of the range of a uniform distribution of directions. The mean of the distribution was in the upward direction; the range is given in degrees. Data were obtained for step size 1.4 deg at three different dot densities 0.2, 0.4 and 1.6 dots/deg². For this step size, perceptibility does change with dot density. With a decrease in dot density, unidirectional coherent flow was perceived over a wider range of distribution of directions. For a density of 0.2 dots/deg² the data for a step size of 1.4 deg is almost congruent with those for step size 0.1 degree and density 1.6 dots/deg² (taken from Fig. 1) represented by the dashed line in the figure (data for subject S.D.T.).

perception has important implications for the spatial properties of any hypothesized local mechanisms of motion detection and the "correspondence problem". These implications are described below, in the General Discussion. A second implication is more germane to the formulation of the remaining experiments and will be discussed here. For step sizes less than 1.0 deg, the constancy of results over a large range of dot densities suggests that spurious directions of displacement do not significantly contribute to the percept. Thus for small step sizes, the perceived random walks more faithfully reflect the prescribed distribution of directions. Because we wish to draw conclusions based on the assumed perceived distribution of directions, the remaining experiments were conducted under conditions for which the perceived distribution of directions would be most consistent with the distribution of directions which define the random walks.

Experiment 3: stimulus duration

Detectability of unidirectional flow was measured as a function of stimulus duration (i.e. the number of frames presented). For two subjects, the effect of stimulus duration was determined for a step size of 0.9 deg with a dot density of 1.6 dots/deg². Stimulus durations (number of frames presented) used were 2 frames, and all odd numbers of frames ranging from 3 to 13. For a third subject measurements were made for a step size of 0.1 deg at a dot density of 1.6 dots/deg². The stimulus durations considered in this case were 6, 12 and 25 frames. The relationship proved to be nonlinear: up to 11 frames the probability of seeing unidirectional flow increased with the number of frames presented; presentation of additional frames beyond 11 did not further augment perceptibility. Figure 6 shows the data for two durations, two frames and 11 frames, with step size of 0.9 deg and density 1.6 dots/deg². It should be noted that the previous experiments discussed and those in the remainder of the paper were conducted using a stimulus duration for which perceptibility is in the asymptotic region.

In analyzing temporal summation for our display, it is important to note that its local motion vectors are distributed in the visual field and this distribution varies with time. We therefore wondered whether the perception of coherent motion depended only on the set of directions present from frame to frame or if it also depended on the particular path each dot took over time. For example, would consecutive steps by the same dot in the same direction over a number of frames be more significant to perception than if these individual steps were spatially separated over successive frames?

Experiment 4: temporal summation

To examine if spatial factors contribute to temporal summation, we compared perceptibility of coherent motion under two conditions. The first condition used stimulus patterns consisting of two sets of spatially interspersed random dots. For one set of dots (denoted as "noise") the distribution of directions was uniform over all possible 360 deg of directions; for the other set (denoted as "signal"), dots moved only in a single direction: upward on the display. The set assignments of the dots remained the same over all frames presented, so that some dots moved upward frame after frame while other dots

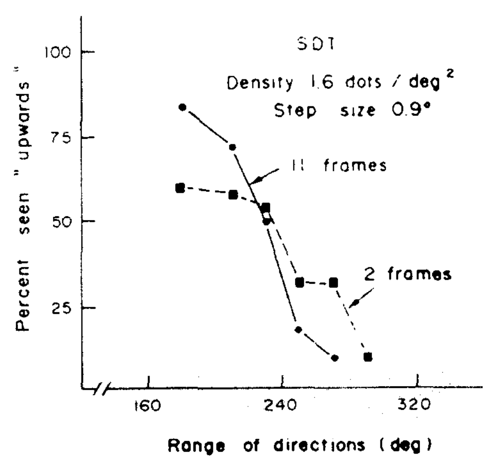

Fig. 6 The percentage reports of unidirectional, coherent flow in the upward direction as a function of the range of a uniform distribution of directions. The mean of the distribution was in the upward direction; the range is given in degrees. Data are shown for two different stimulus durations; 2 frames and 11 frames. The step size was 0.9 deg and the dot density was 1.6 dots/deg². Perceptibility increases with the number of frames presented (data for subject S.D.T.)

moved randomly frame after fame. We'll call this condition the "Separate" case.

The second condition was identical to the first except in one aspect: in each frame, the particular dots constituting the signal set and those constituting the noise set were chosen independently of the dot assignments to the two sets in previous frames. Although the proportion of dots constituting the signal remained constant over all frames in this condition, there were *not* two disjoint sets of dots, one signal and one noise, as in the first condition. We'll refer to this condition as the "Combined" case.

In both conditions, for a given proportion of dots which made up the signal, the distribution of possible directions from one frame to the next is the same. For the Separate case, the probability that any dot made N consecute steps in the "upward" direction is equal to the proportion of dots which are signal; for the Combined case the probability that any dot makes N consecutive steps in the upward direction is the proportion of dots in the signal raised to the power N.

The probability of seeing unidirectional coherent flow upward for both conditions was measured as a function of the proportion of the total number of dots which were in the signal. The step size was 0.9 deg and density was 1.6 dots/deg^2. Two subjects participated in the study.

As shown in Fig. 7, there is no significant difference in the perception of coherent unidirection flow upward between the separate and combined cases. The results indicate that temporal summation over frames is critically dependent only on the distribution of directions of motion present from frame to frame. We can conclude that temporal summation does not depend on the spatial relationship between local motion vectors over time.

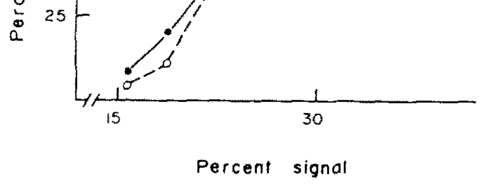

Fig. 7. The percentage reports of unidirection coherent flow in the upward direction as a function of the percentage of dots in the "signal set". Dots in the "signal set" moved only in the upward direction; dots in the "noise set" took their directions from a uniform distribution covering 360 deg. The curve labelled "Separate distribution" denotes a condition in which dot allocation to the "signal set" and "noise set" did not change for all frames presented. The curve labelled "Combined distribution" denotes a condition in which dots are allocated to each set on each frame independently of allocations on previous frames. There is essentially no difference in perception between the two conditions (data for subject S.D.T.).

GENERAL-DISCUSSION

As we noted before, it is not possible to know *a priori* whether the perceived path a dot travels is identical to the random walk prescribed for that dot. Consider two successive frames, N and $N + 1$. For a given dot, A, on frame N we can define its "correspondent dot", B, on frame $N + 1$. B is the dot on the frame $N + 1$ to which A is perceived to move between frame N and $N + 1$. If A's correspondent dot is the one that was determined by the random walk prescribed for A, the correspondent dot is said to constitute a "match"; if A's correspondent dot is not the one defined by A's random walk, the correspondent dot is said to constitute a "mismatch". Such mismatches produce spurious directions of motion that could be inconsistent with the predefined distribution of possible directions.

Mismatches are the result of the perceptual confusion of random walks prescribed for different dots. Decreasing the spatial density of dots should reduce the possibility of such confusions. If spurious directions of motion due to mismatches do affect the occurence of perceived coherent, unidirectional motion then a change in the density of dots alone should alter the psychometric function. Our experiments showed such changes. For step sizes greater than 1.0 deg, decreases in dot density, increases the probability of perceiving coherent flow (see Figs 4 and 5). In these conditions unidirectional flow was perceived over a wider range of distribution of directions at the lower dot densities. This suggests that spurious directions of motion due to mismatches may contribute to the percept of coherent motion.

However our experiments also contained conditions in which the psychometric function was not affected by changes in dot density. For step sizes less than 1.0 deg, a change in dot density by a factor of eight, from 0.2 to 1.6 dots/deg^2 did not alter the detectability of coherence (see Fig. 3). This suggests that for the small step sizes only the directions of local motion determined by the predefined distribution of directions significantly contribute to the perception of the unidirectional, coherent motion. Mismatches appear to be minimized or nonexistent for these small step sizes. It should be noted that at a density of 0.2 dots/deg^2, perception of coherent motion for steps greater than 1.0 deg is equivalent to that for the steps less than 1.0 deg (see Figs 4 and 5).

Since mismatches are minimized for the smaller step sizes at all dot densities and at the lowest dot density for the larger step sizes, it seems reasonable to speculate that the correspondence between dots on successive frames is based on a preference for nearest

Table 2. The probability that the distance from a given dot in a frame to the nearest dot in the next frame is less than the step size

Step size (deg)	Density of dots (dots/deg²) 1.6	0.2
0.1	0.05	0.01
0.9	0.98	0.40
1.1	0.99	0.53
1.4	0.99	0.71

The distribution of dots on each frame is Poisson with parameter, d, the density of dots/deg². The probability that the distance from a given dot on a frame to the nearest neighbor on the next frame is less than the step size, s, is given by

$$1 - \exp(-\pi * d * s * s).$$

neighbors. In this view, the correspondent dot will be the dot on the next frame that is closest. If the correspondent dot constitutes a match, then by definition, the perceived distance moved is the step size. Table 2 lists the probability that the distance from a given dot on one frame to the nearest dot on the next frame is less than the step size. If a dot is always perceived to move to the nearest dot on the next frame, the Table gives the probabilities that the correspondent dot will not be the one prescribed by the random walk. This is the probability of a mismatch occurring. For each of the step sizes 0.1, 0.9, 1.1 and 1.4 deg, this probability is shown for two different dot densities: 1.6 and 0.2 dots/deg².

We tried to determine whether the probability of mismatch could explain the variation in the psychometric function with dot density. For a step of 0.1 deg the probability of a mismatch is extremely small, less than 0.05 at dot densities of both 1.6 and 0.2 dots/deg² (see Table 2). This is consistent with the results shown in Fig. 3 for this step size—a decrease in dot density from 1.6 to 0.2 dots/deg² did not alter the psychometric function. With step sizes of 1.1 and 1.4 deg, the same decrease in dot density reduces the probability of mismatch from 0.99 to 0.53 and 0.71, respectively (see Table 2). With such a large change in the probability of mismatch one would anticipate a significant alteration in the psychometric function. As shown in Figs 4 and 5, for both these step sizes this decrease in dot density produces a large increase in the tendency to see unidirectional coherent motion (Figs 4 and 5). For a step size of 0.9 deg, decreasing the dot density from 1.6 to 0.2 dots/deg² reduces the probability of mismatch by an even larger amount, from 0.98 to 0.40 (see Table 2). As for step sizes 1.1 and 1.4, with such a substantial change in the probability of mismatch, one would expect to find an alteration in the psychometric function with the same change in dot density. However as shown in Fig. 3, with the 0.9 deg step size, the probability of seeing unidirectional coherent motion was unaffected by this change in dot density. We suggested above that a variation in the confusability of various random walks could explain why a change in dot density affected the probability of seeing coherent flow. If this explanation is correct, our results for step sizes 1.1 and 1.4 deg, and particularly those for 0.1 deg are consistent with the hypothesis that confusability—or its inverse, correspondence—is determined by nearest neighbor relationships. However the results for the 0.9 deg step size imply that this can not be the sole determinant. Braddick (1974) and Ullman (1979) arrived at similar conclusions regarding the utility of a nearest neighbor basis for the correspondence process.

It is clear that one mismatch will generate other mismatches. If correspondence is based strictly on a preference for nearest neighbors such cascading of mismatches will force some dots to move long distances. In particular a Monte Carlo simulation for the case with step size 0.9 deg and dot density 1.6 dots/deg² indicates that up to 10% of the dots will be forced to move more than 0.9 deg if a strict nearest neighbor relationship is used. To deal with this inadequacy, Ullman (1979) has proposed a "minimal map theory of motion correspondence" to account for the perceived direction of motion of each element in multi-element motion stimuli. It is within the framework of this global minimization theory that it is possible to account for the changes in the psychometric function with step size and density. Ullman has derived a computational scheme for determining correspondence with in this theory. According to the theory, each element (in our case, each dot) is assigned a "cost function" that determines the probability that a dot will appear to move at a particular velocity. Since the temporal characteristics of all of the elements in our stimuli are the same for step sizes of 0.9 deg or larger, we replace velocity with distance travelled by a dot to simplify the discussion. According to Ullman, the cost function is identical for each element. The distance each element or dot will be perceived to move from one frame to the next will be the distance that minimizes the "total cost" over all elements in the stimuli. Preliminary results suggest that the functional form of the cost function will be sigmoid (Ullman, 1979, p. 118).

Consider a sigmoid cost function that increases with distance travelled and whose sharply rising portion of the sigmoid begins after 0.9 deg. For step size 0.9 deg, the "over all cost" will be minimized by having the dots move from frame to frame the distance perscribed by the predefined random walk. The path each dot is perceived to travel would then be the one defined by the prescribed random walk, since the number of mismatches would be minimized for all the dot densities considered. For step sizes of 1.1 and 1.4 deg, it will be more cost efficient to have the dots move distances less than 0.9 deg from frame to frame where ever possible. At the higher dot densities this would result in a significant number of mismatches. As dot density is decreased, the possibility of having a dot closer than 0.9 deg to the correspondent dot would be reduced, thereby reducing the number of mismatches. At the lowest dot density, each dot would be perceived to travel according to its predefined random walk. It can be seen that by the appropriate choice of cost function, the results of the first two experiments would be consistent with the minimal map theory of motion correspondence proposed by Ullman (1979). The parameters of the cost function will provide constraints for spatially localized mechanisms of motion perception.

Irrespective of the mechanisms of correspondence between the dots on successive frames, the correspondence process alone is not sufficient to explain the generation of a unidirectional coherent percept of motion from local motion vectors. Our data suggest that step sizes less than 1.0 deg and dot densities of 1.6 dots/deg^2 or less, only the directions of local motion determined by the predefined distribution of directions significantly contribute to the perception of coherent flow. We also found that although temporal summation occurred in a nonlinear manner over frames, it depended only on the set of directions of motion present from frame to frame. Taken together, these two results are consistent with the idea that directions of the individual steps are independently detected and that these responses are then pooled over time and space to generate the perception of coherent motion.

From the results of Experiment 1, we know that for a step size less than 1.0 deg and dot density 1.6 dots/deg^2, a uniform distribution of directions with range 180 deg generates a percept of unidirectional, coherent motion along the mean for nearly 100% of the trials (see Figs 1 and 2). Consider, as usual, the mean of the distribution to be upward with respect to the subject. For this stimulus, on each sucessive frame, each dot will be above or at least level to its position on the previous frame. (The majority of the dots will of course be translated horizontally on sucessive frames as well.) If the directions of the individual steps are independently detected and then the responses pooled, the simple *failure* to perceive a dot below its previous position may be sufficient to generate the percept of coherent, unidirectional flow in the upward direction. We tested the idea. For the distribution of directions with a range of 180 deg, the probability of seeing unidirectional flow along its mean was measured as a function of the range of a uniform distribution of directions that was deleted from the center of the original distribution. For each of the distributions constructed in this manner, every dot will be above or at least level with its position on the previous frame. The step size used was 0.9 deg and the dot density was 1.6 dots/deg^2. Data were obtained for two subjects and the results are shown in Fig. 8.

The percentage of trials on which the subject sees coherent, unidirectional upward flow is plotted as a function of the range of the distribution of directions deleted. As shown in Fig. 8, if the directions of motion within 20 deg of the mean were removed from the initial distribution, the frequency of seeing coherent flow along the mean is reduced to 50%. It should be noted that for this particular distribution, more than 98% of the dots will be above their position on the previous frame, while less than 2% will be level with its previous position. It is clear that the presence of local motion vectors all of which have a component in the direction of the mean is not sufficient to ensure a percept of coherent unidirectional flow. To generate the percept, directions of local motion vectors in the neighborhood of the mean must also be present. This suggests that the percept results from the spatial pooling for responses of direction selective mechanisms that are tuned to the mean direction of the distribution.

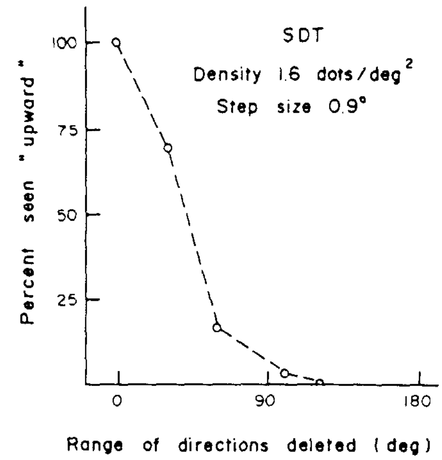

Fig. 8. The percentage of reports of unidirection coherent flow in the upward direction as a function of the range in degrees of a uniform distribution of directions deleted from the center of a uniform distribution. The distribution, before deletion, covered 180 deg (data for subject S.D.T.).

In summary, a global, coherent motion percept can result when many different localized motion vectors are combined. The results suggest that directions of the individual steps are independently detected and that the responses are pooled over both time and space to generate the percept. Finally, the changes in the psychometric function with step size and dot density indicates that motion correspondence is not based strictly on a nearest neighbor preference but is more consistent with Ullman's minimal map theory of motion correspondence.

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