Pergamon

0042-6989(95)00325-8

Vision Res., Vol. 36, No. 16, pp. 2579–2586, 1996

Printed in Great Britain
0042-6989/96 $15.00 + 0.00

Research Note

What is Noise for the Motion System?

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Received 3 February 1995; in revised form 14 August 1995; in final form 27 November 1995

Motion coherence thresholds in random-dot patterns have been widely adopted as a measure of performance in visual motion processing. However, there has been diversity in the type of "noise" in which a coherent motion signal has to be detected. Here we compare coherence thresholds for three ways of creating motion noise: dots replotted in random positions in each new frame; dots with a set displacement but following a random walk from frame to frame; or dots moving in random directions which remain constant for a given dot over a sequence of displacements. In each case, the signal dots may either remain the same throughout the display sequence, or the signal dots may be re-selected afresh on each frame ("different").

With our display (3 deg square, 120 msec exposure, velocity = 5 or 10 deg sec^{-1}), all these different noise conditions yielded similar thresholds around 5–8%. There were some small but systematic differences between conditions. Thresholds in random-direction displays were consistently higher than those in random-walk or random-position displays, especially at the lower velocity. However, this effect is much smaller than would be expected from the increased standard error of the noise mean in random direction, perhaps because the motion system integrates information most effectively over a local region of space and/or time. Subjects" performance could not be explained by a strategy of identifying individual signal dots with extended trajectories. The similarity between random-walk and random-position thresholds implies that subjects do not exploit the marked differences in speed distribution between signal and noise dots in the latter case.

The practical message for the design and interpretation of experiments using coherence thresholds is that the results are not much affected by the choice of noise, at least within the range of stimuli tested here. Copyright © 1996 Elsevier Science Ltd.

Motion perception   Random dot displays   Coherence threshold   Visual noise

INTRODUCTION

Studies of the visual motion processing system need a measure which can be used to compare the sensitivity of the system across conditions. One traditional approach to visual motion is to measure the minimum and maximum threshold velocities (or displacements) at which directions can be discriminated. However, these thresholds do not provide very satisfactory general measures, because they characterise the performance of the system only at the bottom and top of the range of velocities that it can process, rather than over the complete range which includes its optimal stimuli.

With the advent of random-dot motion stimuli, the opportunity arose to measure motion performance in terms of a threshold signal/noise ratio (e.g. van Doorn & Koenderink, 1982) which can be determined for any velocity or displacement. van Doorn and Koenderink made such measurements using dense patterns of square pixels which could each randomly take a low or a high luminance value. A pattern in which all the dots moved uniformly (signal) was summed with one consisting of a sequence of random uncorrelated frames (noise). The r.m.s. contrast of the combined pattern was kept constant but the balance of contrast between the two components could be varied, so that the signal/noise ratio for which directional judgements were just possible could be measured. Many other experimenters have used similar measures, except that the patterns have most often consisted of sparse arrays of small dots (e.g. Williams & Sekuler, 1984; Newsome & Paré, 1988; Snowden & Braddick, 1989; Downing & Movshon, 1989; Blake & Hiris, 1993; Watamaniuk *et al.*, 1989). In such patterns some fraction of the dots (signal dots) move coherently in a common direction, while the remaining (noise) dots move in a random or incoherent way. For this version of the task it has become common to express performance in terms of a *coherence threshold* expressed as a percentage,

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e.g. 20% coherence means that 20% of the dots are moving in a common direction, and 80% randomly (corresponding to a signal/noise ratio of 0.25). Usually the threshold is determined for the subject's discrimination between two opposite directions of motion (although it is also possible, for example, to require discrimination between a display containing some coherent motion and one which has 0% coherence). The best coherence thresholds show individual variation but are typically around 5%, both for human observers and trained macaques (Britten *et al.*, 1992).

However, there are a variety of ways in which "noise" can be created in these displays. In many studies, noise dots have been plotted in new locations, randomly selected within the display area, on each successive frame of the sequence. Pairings of noise dots in successive frames are therefore random; they should show a statistically isotropic distribution of directions and a wide range of speeds. In this paper we refer to this as "*random-position*" noise. An alternative approach has been taken by Sekuler and his colleagues (e.g. Williams & Sekuler, 1984). Their starting point was the perception of motion in displays where individual dots moved in a wide distribution of directions, but typically all dots were displaced through an equal distance on successive frames. The extreme case is where the direction distribution is uniform across 360 deg. We refer to this as "*random-walk*" noise. Random-walk and random-position noise appear subjectively very different. In the first, noise dots have a flickery "snowstorm" appearance, familiar as the noise on a TV receiver that is not tuned to any signal. In the second they appear to jitter around in haphazard but well defined paths, like ants around a nest or Brownian motion of small particles.

This dichotomy does not exhaust the alternative possible types of visual noise. In sequences of more than two frames, variations of dot velocity can occur across time as well as space. For noise to be properly described as random-walk, a particular noise dot should have its direction selected afresh from the random distribution on each new frame. Alternatively, each noise dot may have a randomly selected initial direction of displacement, but then continue to move in the same direction on successive frames for the duration of the display. We shall refer to this possibility as "*random-direction*" noise. Watamaniuk *et al.* (1989) have shown that when directions are selected from a limited range, random-walk and random-direction displays yield equivalent judgements of the global direction of flow; but this does not guarantee that they are equivalent in terms of coherence thresholds.

Finally, in multi-frame sequences, a dot that has been initially designated as a signal dot may remain a signal dot on successive frames, and so continue to move in the direction of coherent motion for the duration of the display. Alternatively, there may always be a certain proportion of the dots (say 20%) that are signal dots displaced in the coherent direction, but this 20% may be randomly selected afresh on each new frame. In this case a particular dot may change between being part of the signal and part of the noise one or more times in the course of its trajectory. Following Snowden and Braddick (1989), we shall designate these as "*same*" and "*different*" rules, respectively. [Williams and Sekuler (1984) used the terms "combined" and "separate" to make the same distinction.] Either rule may be applied to any of the three noise types distinguished above. In the case of random-position noise, the display produced by the *different* rule is often described as "limited lifetime".* Figure 1 illustrates schematically the six types of noise that can be generated by these combinations.

Despite the marked subjective differences between them, the various types of noise have been used in experiments without much explicit justification for their selection. Table 1 summarises the variety of methods for generating noise to be found in a selection of published studies. It is important to know whether the type of noise has any strong effect on measured coherence or signal/noise thresholds. If it does, then care will be needed in comparing the results of different experiments, and in selecting how noise is to be generated for a planned experiment. Any difference may also be theoretically illuminating; for example, if thresholds were found to be much higher with random-walk than random-position noise, a possible explanation would be that the concentration of noise in the same band of speeds as the signal impeded its detection, suggesting that speed (across different directions of motion) was an important organising variable for the visual motion system.

In the present experiments, we compared performance for directional judgements with random-position, random-walk, and random-direction noise, using both *same* and *different* rules in each case. Variations in dot speed and density were also explored.

METHODS

Stimuli and apparatus

Stimulus sequences were produced by a computer-controlled vector point plotter (D300, Cambridge Research Systems) driving a Tektronix 606 x–y display with a P31 green phosphor. The vector plotter had 16-bit x- and y-resolution.

The stimulus was a random-dot kinematogram presented in a 3 deg square window. Each presentation consisted of a nine-frame sequence (i.e. eight displacements) at a rate of 75 Hz, so the total stimulus duration was 120 msec. The display was viewed in a dimly illuminated room giving a background luminance of about 2 cd m^{-2}, and the luminance of the dots was set to

*Changing the % coherence with the different rule affects the distribution of signal dot lifetimes; at coherence values close to threshold, few signal dots will have lifetimes more than two frames long (i.e. trajectories extending beyond a single displacement). Alternatively, some studies (e.g. Baker *et al.*, 1991) manipulate directly the lifetime of the signal dots; whenever a signal dot ends its life, it must be randomly replotted elsewhere and the resulting "noise" should be taken into account in quantifying the % coherence of the display.

TABLE 1. Methods of generating noise for motion coherence or signal/noise thresholds

Noise type	"Same" rule	"Different" rule
Random position	van Doorn & Koenderink (1982) van de Grind *et al.* (1983) Baker *et al.* (1991) (*dot noise*)	Newsome & Paré (1988) Downing & Movshon (1989) Snowden & Braddick (1990) Silverman *et al.* (1990) Baker *et al.* (1991) (*Movshon noise*) Britten *et al.* (1992) Raymond 1993)
Random walk	Williams & Sekuler (1984) (*separate*) Watamaniuk *et al.* (1989) (*random path*)	Williams & Sekuler (1984) (*combined*) Blake & Hiris (1993)
Random direction	Watamaniuk *et al.* (1989) (*fixed path*) Bullimore *et al.* (1993) Braddick *et al.* (1994)	

This table is not intended to be complete: in most cases there are other published studies from the same laboratories which use the same methods.

be *c.* 2 log units above their detection threshold. Individual dots subtended about 3 min arc. The display was viewed binocularly at a distance of 80 cm.

Subjects

There were three young adult subjects with normal visual acuity wearing an appropriate spectacle correction where necessary. All were experienced as observers in psychophysical experiments. One of the subjects was the co-author MS; the others were unaware of the purpose of the experiments or the details of the stimulus construction.

Procedure

On each trial subjects initially fixated a mark in the centre of the display and following the brief presentation of the motion stimulus, pressed a button to report a forced-choice decision on whether the direction of motion was leftward or rightward. No feedback was given. Each trial in a given experimental run was drawn

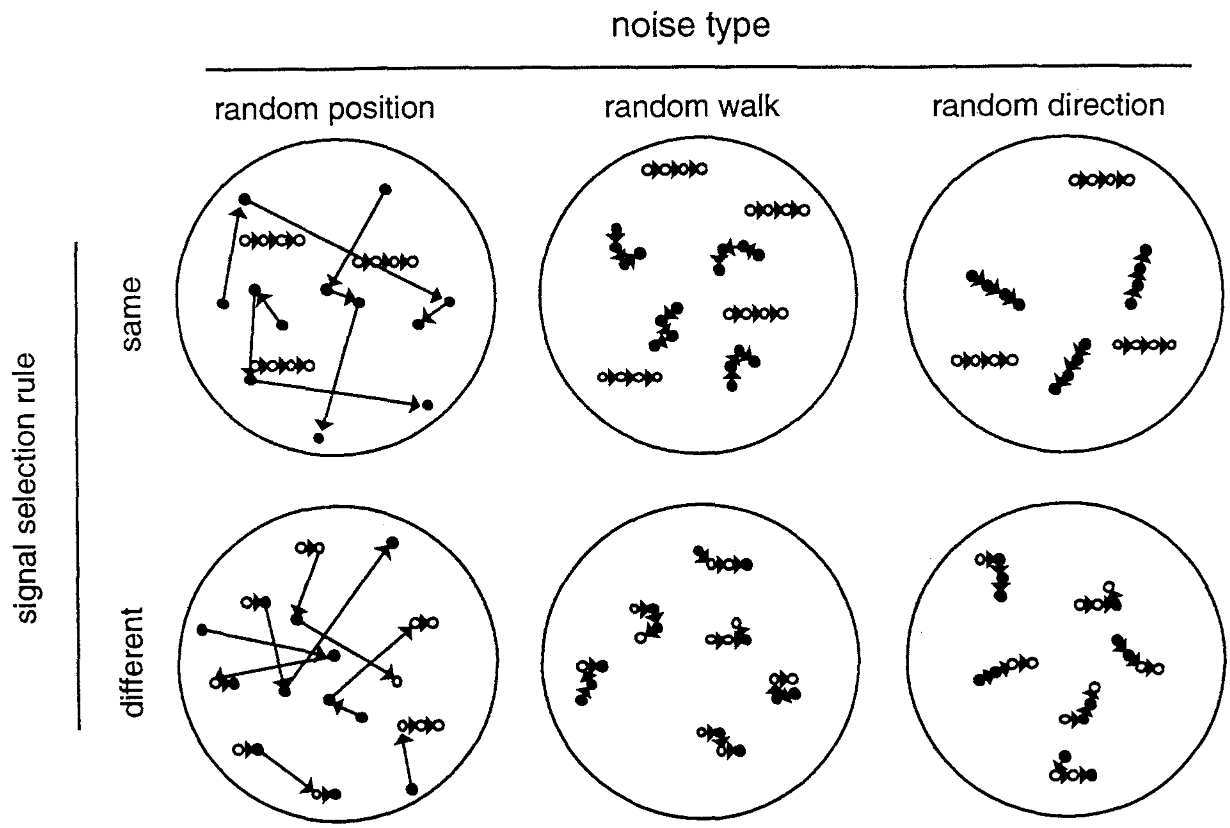

FIGURE 1. Schematic illustration of the six types of signal/noise display generated by the rules described in the text. The figure shows examples with 50% coherence and rightward signal motion in each case. Dots designated as signal dots for the following displacement are shown as open circles, those designated as noise dots are solid circles. In the random-position case, the displacement vectors shown join each noise dot to its new position selected by the plotting algorithm; for the visual system, these are not necessarily the most effective pairings for generating motion signals (see Discussion).

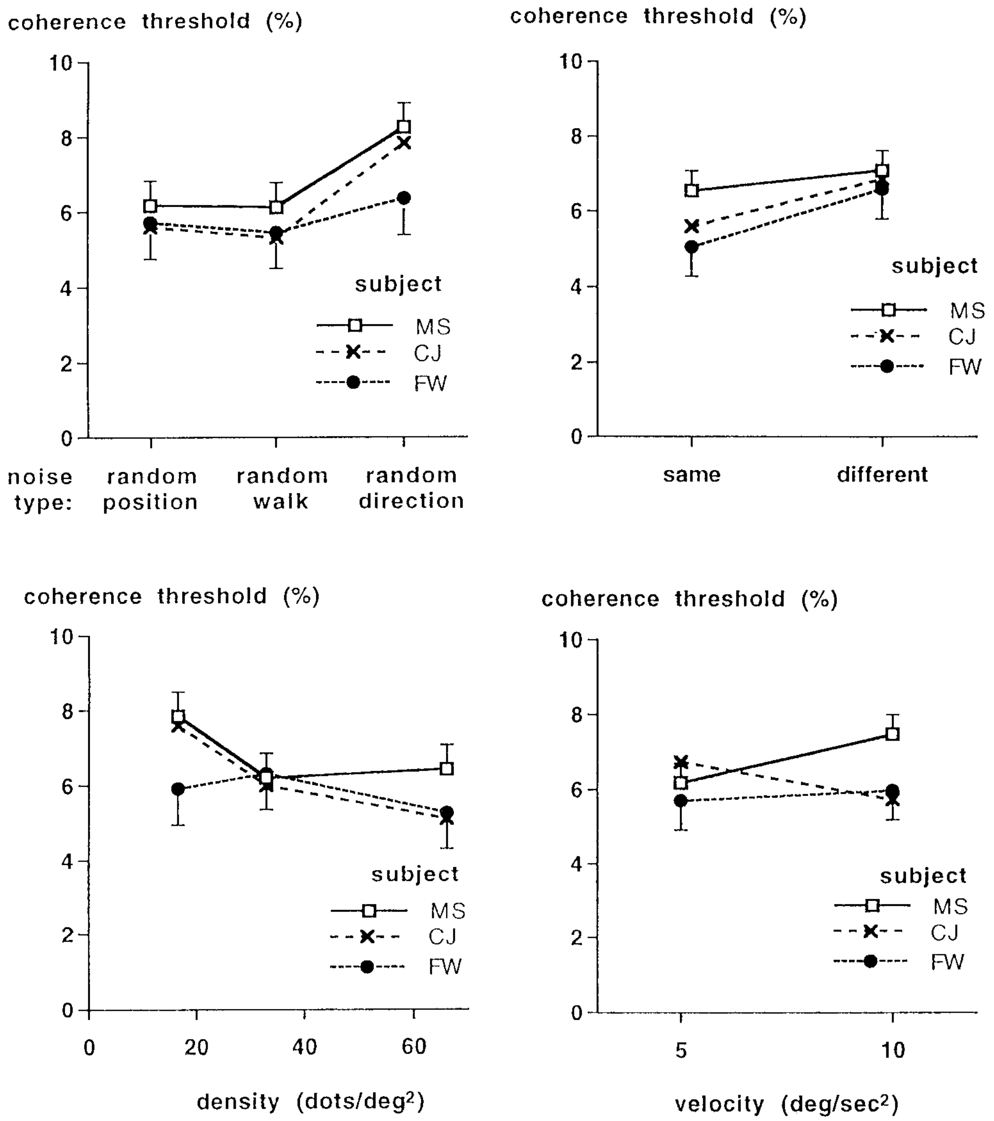

FIGURE 2. Mean coherence thresholds as a function of noise type, signal selection rule, density and velocity. In each case, the thresholds are averaged across the other variations in display conditions. Data for each of the three subjects are plotted. Error bars are S.E. of the mean across staircases within each subject, derived from the error term in individual analyses of variance; for clarity, error bars for subject CJ are omitted, but were slightly smaller than those for MS.

randomly from one of six staircases. These differed in the type of noise (random position, random direction, or random walk) and in the direction of motion (left or right) of the signal dots. Within each staircase the percentage of signal dots was varied according to the "two-up, one-down" rule which converges on the 71% correct level. Each run continued until ten reversals had been completed in each staircase. Only the last eight reversals were used in data analysis.

Between experimental runs, the following parameters were varied: signal selection rule (*same* vs *different*), dot density (16.5, 33 or 66 dots deg^{-2}), and signal speed (5 or 10 deg sec^{-1}, manipulated by varying the dot displacement at a constant frame rate). Two of the subjects completed two experimental runs with each combination of conditions, so that each estimate of threshold is based on 16 staircase reversals; for the third subject each estimate is based on eight reversals in a single staircase. Each experimental sessions lasted no more than 45 min and data were collected in a number of sessions over several days with a counterbalanced design.

RESULTS

Since no left–right anisotropies were apparent in the data from any subject, data from staircases with leftward and rightward signal motion have been combined to yield a single estimate of threshold (i.e. from four or two staircases per condition).

Figure 2 shows, for each subject, the mean coherence thresholds for the three noise types, the "same" and "different" rules, the three density values, and the two velocities. The data have been analysed by an analysis of variance across subjects. Of the main effects shown in

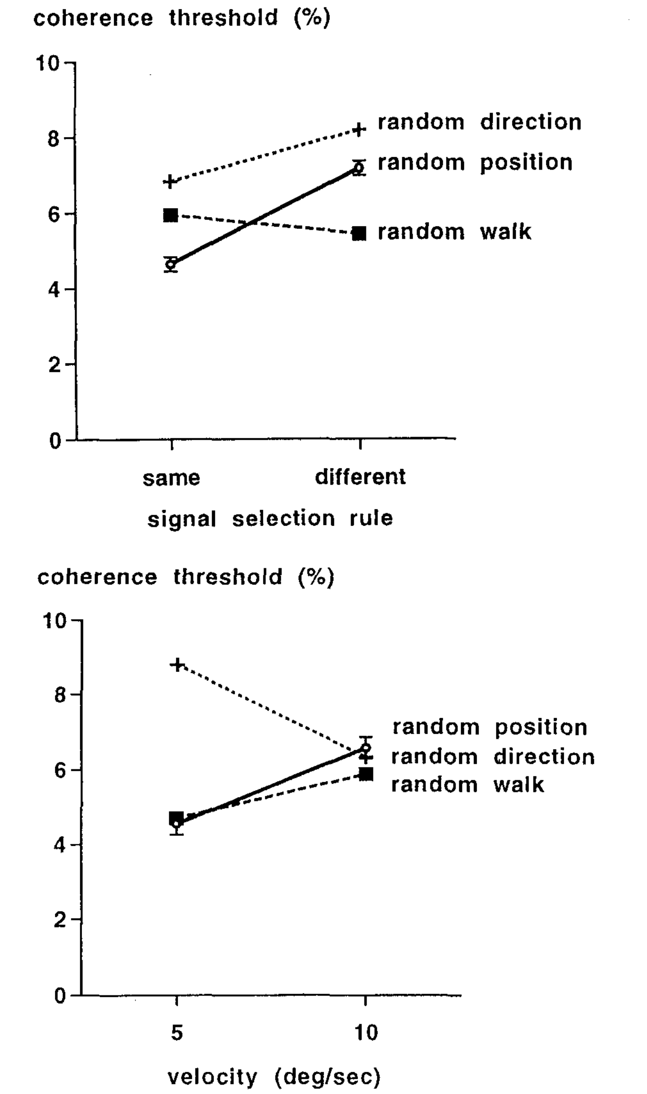

FIGURE 3. Plots of coherence thresholds (averaged across the three subjects) illustrating the two interactions found to be significant by analysis of variance. Above: interaction of noise type with same/different rule. Below: interaction of noise type with velocity. Error bars are S.E. of the mean across subjects, all derived from the error term in the analysis of variance (hence those omitted would be equal to those shown in the same graph).

Fig. 2, the variation between noise types reached statistical significance [$F(2,4) = 12.40$, $P < 0.02$]; clearly this is due to a slightly but consistently higher threshold for the random-direction condition. The main effect of same–different rule just failed to reach the 5% level of significance [$F(1,2) = 15.50$, $P = 0.059$]. Among the possible interactions between noise type, same/different rule, density, and velocity, the two interactions illustrated in Fig. 3 were significant: (i) noise type and same-different rule interact [$F(2,4) = 31.15$, $P < 0.005$], with the random walk case not showing the increase in threshold for the different rule that is apparent for the other noise types; and (ii) noise type and velocity interact [$F(2,4) = 21.34$, $P < 0.01$] with the effect of noise type appearing largely at the lower velocity. However, in all these cases, the mean thresholds fall into a quite narrow range of *c.* 5–8%.

DISCUSSION

The most important feature of these results is that, for the various types of noise that we used, all gave values of coherence threshold in a quite narrow range. We have not explored the full range of parameters such as velocity. However, on the present evidence there does not seem to be any great need for concern with the precise details of the algorithm used to generate "noise", when evaluating coherence threshold measures of motion sensitivity in the research literature.

Performance variations and "ideal observers"

There were, however, some effects which, although not very great in magnitude, were statistically reliable. To consider what any effects, or the absence of effect, may signify it is useful to consider how performance might be affected by the variations in the statistical information present in the display. For the related task of discriminating the overall direction of a random-walk display, Watamaniuk (1993) analysed an "ideal observer" model. Each presentation contains a number of dot-displacements distributed both in space and time. Watamaniuk's ideal observer treats each displacement as a separate observation from the population and computes the mean direction of the sample provided by a particular presentation. Its ability to discriminate two motions depends on the standard deviation of this sample mean.

Our experiment differed from Watamaniuk's both in the nature of the distributions and in the exact task required of the observer. Without detailed analysis, it is uncertain how an "ideal observer" for our task should best be constructed. It could, like Watamaniuk's, compute the mean of each sample of directions, and determine whether it had a net leftward or rightward component. Alternatively, it might count the displacements falling in two narrow ranges of directions around left and right, or it could divide the displacements into a set of bins distributed around 360 deg and determine which is most numerous. However, in all cases the performance will be determined by the noisy nature of the stimulus and will be subject to some similar statistical limitations.

There are several plausible ways in which a human subject might deviate from the performance of any such model. First, subjects may not be able to integrate information from the whole area and duration of the display, and so they may base their decisions on a sample that is limited in space and/or time. Secondly, the decision is presumably based on signals from motion detectors, each having a certain receptive field size and temporal integration function. Information from multiple displacements stimulating the same detector (e.g. successive displacements of the same dot) would be expected to be integrated according to a different rule from the way the subject combines the outputs of different detectors (and perhaps nearby and distant detectors are combined differently). Thirdly, individual detectors will respond only when the displacements are within a certain spatial and temporal range (Mikami *et* *al.*, 1986), and the system as a whole will have a maximum displacement ("d_{max}") and time interval for motion detection, at least for any particular stimulus configuration (Braddick, 1974; Baker & Braddick, 1985a,b; Morgan & Fahle, 1992). Thus displacements over large space and/or time intervals, which are no less available than small ones for an abstract ideal detector, will be relatively ineffective in the real visual system. Fourthly, although an ideal observer with knowledge of the signal characteristics could restrict the information used to motions having the directions and speed possible for signal dots, a wider range of the motions in the display may influence the decisions of real observers.

Effects of noise type: Random direction noise

The significant main effect of noise type we found was primarily due to relatively high thresholds for random-direction noise compared to the other two types (Fig. 2). Qualitatively, this is not a surprising result, if the statistical nature of the task is considered. The subject must extract from the display (or from some sampled part of it) some global measure of direction, whether it is "average leftward component in the displacements" or 'percent of displacements in "leftward" bin minus percent in "rightward" bin'. Whatever measure the ideal observer computes, the contribution from the noise dots will vary randomly from trial to trial, because of the statistical nature of the stimulus. Over an infinite number of noise displacements, the noise contribution would be exactly balanced, since the noise population mean has no net direction. The smaller the standard error of the summed noise contribution, the more reliably the global measure of direction will be determined by the contribution of a few signal dots, and so the lower the coherence threshold should be.

Now in *random-walk* noise, each dot has a displacement on each new frame which is randomly sampled afresh from the 360 deg distribution of directions. With each displacement, therefore, each dot contributes a new independent direction sample. In *random-direction* noise, however, it continues to move in the same direction as the initial random sample for that dot, so the successive samples are completely non-independent. This lack of independence will increase the variability contributed by the noise dots to any global motion measure, and hence would be expected to reduce random-direction relative to random-walk performance. Note that this is an argument about the statistical non-independence of the displacements, not about the way they are combined by the observer.

Specifically, comparing the random-walk case where an independent sample is derived from each of eight displacements, with the random-direction case of eight identical displacements, the standard error of the mean direction in the latter should be greater by a factor of $\sqrt{8}$. If the decision were based upon the sample mean, the number of signal dots required, i.e. the coherence threshold, might be expected to increase by the same amount. (A similar increase would be expected if the decision depended on the number of displacements falling into particular bins.) However, the actual increase is much smaller than this, presumably reflecting some deviation from the principles of an ideal observer's computation. For example, in random-direction, compared to random-walk, successive identical displacements are more likely to activate a single motion detector, and so the system may combine these signals differently from those in separate detectors. The size and direction of such an effect would depend on the detailed assumptions about the combination rule.

There is another potential reason why performance in the random-direction case might be worse than for the other two types of noise. In the random-position and random-walk conditions, any dot which undergoes a number of successive displacements in the same direction is almost certainly a signal dot. So detecting a single dot that moves in this way would give a very strong indication of the signal. As can be seen from Fig. 1, this strategy should be most useful for displays generated by the "same" rule, and ineffective for the random-direction display where both signal and noise dots have extended trajectories. The rather small advantage of random-walk and random-position conditions over random-direction, and the fact that the interaction of noise type with same–different rule does not go in the predicted direction, suggests that this purely local strategy does not make any great contribution to subjects' performance which must, therefore, depend on integrating information globally over an extended spatial region.*

Figure 3 shows that the overall small disadvantage of random-direction performance comes entirely from the 5 deg sec^{-1} velocity. The reason for this interaction is not clear.

Random position vs random walk

The case of random-position noise raises questions about the application of ideal observer models. A common assumption of such models is "signal known exactly"; in our task, an observer could look for signal dots having one of two specified vector velocities (left and right). The probability that any particular dot will be randomly replotted close to either the leftward or the rightward signal displacement will be very small. In random-walk noise the probability must be higher since the scalar displacement is constrained to equal that of the signal. This difference might be expected to yield much better performance in the random-position case than the random-walk display, but no such effect appears in the results.

In considering random-position noise, however, it is likely to be misleading to consider the notional displacement due to a particular dot being replotted at a new location on the screen. Many of these random replottings

*The "ideal observers" discussed here consider each displacement independently and so would not take advantage of this temporal structure. Such behaviour is not strictly ideal, in the sense that it does not use all the possible information in the stimulus that could help to detect the direction of coherent motion.

would yield displacements exceeding d_{max}.* The activation of motion detectors by such dots will be that due to the transient appearance of single dots, and to chance pairings of dots that fall within d_{max}. Each transient dot will activate motion detectors only weakly, but the motion energy it provides will be uniformly distributed among all directions. This weak contribution of each noise dot to all directions must be compared with the random-direction case, where each noise dot contributes more motion energy in one direction, and across the population of dots this energy is uniformly distributed in direction. The relative contribution of noise in the two cases will depend on detailed assumptions about the way signals summate within and between detectors.

Whatever assumptions are made, however, the motion energy in the random-position noise must be distributed across a wide range of speeds, since neither transient dots nor chance pairings will preferentially activate detectors corresponding to any particular speed or displacement. The motion energy of random-walk noise is concentrated at a speed equal to the signal. Qualitatively it is worth pointing out that the appearance of the two kinds of display is very different; there is no question of the effective distributions of velocities being indistinguishable. Nonetheless, they have similar coherence thresholds. This suggests that observers, although they can recognise the variation of speeds in the random-position display, still base their leftward/rightward decision on detectors responding to a wide range of speeds, not just speeds around the signal value (for example, the decision might be based on "percent of dots with any leftward component in their motion"). It is possible that the neglect of differential speed information defining the signal is associated with the specific requirement to judge direction; it would be of interest to investigate the role of directional variation in a task where subjects had to make a judgment purely of speed.

Effects of density

As dot density decreases, the probability decreases that random pairings of dots in successive frames will have displacements less than d_{max}. Thus random-position noise would be expected to become less effective at activating motion detectors, and coherence thresholds might be expected to fall relative to the random-walk case. However, there is no suggestion in the data of any significant interaction between density and noise type; even at our lowest density plenty of chance pairings within plausible values of d_{max} would still be expected, and so much lower densities may be needed to produce any such effect.

An ideal observer approach would also predict a main effect of density, since a doubling of density doubles the total number of dots, increasing the signal by a factor of 2 but the effect of noise by only $\sqrt{2}$ (based on a similar argument to that above for the number of independent samples in different types of noise). This effect is not apparent in the data either, perhaps because in all conditions observers base their decisions on a small subset of the information in the display. [Watamaniuk (1993) also found that density effects of performance were weak in his task.] An effect which might act to oppose such an increase is discussed in a later section.

"Same" vs "different" rule

For the ideal observer, the same information is provided whether the signal dots are assigned by the "same" or the "different" rule; only the way the information is distributed across space and time is changed. For real observers, this distribution is likely to be important. If successive signal displacements form the trajectory of an individual dot, they are likely to be integrated either by a single motion detector or by closely coupled detectors (Snowden & Braddick, 1989); this is likely to be a more efficient process than combining information from successive displacements that are scattered across the display. However, it is unrealistic to suppose that successive displacements can be combined in this way only if they are applied to the same dot, since plausible receptive field sizes would cover a number of dots. In fact, Williams and Sekuler (1984) and Snowden and Braddick (1989) both found closely similar performance with the two rules and concluded that summation of successive displacements occurred over areas that were not restricted to a single dot trajectory. In the present data, each subject showed a small advantage for the "same" over the "different" rule, but the difference did not attain overall significance (perhaps because it did not occur at all for the random-walk condition—Fig. 3). Any advantage of the "same" rule might be expected most for low densities, where neighbouring dots are less likely to fall in a single receptive field; but there was no sign of an interaction between same/different rule and density.

Effects of velocity

The motion system certainly works only over a restricted range of velocities, and its efficiency would be expected to vary within that range; indeed, investigating this variation has been one of the reasons for using coherence thresholds. In this experiment, there was no reliable difference between performance at 5 and 10 deg sec^{-1}. This is in fact consistent with other findings; for example the data of van de Grind *et al.* (1983), in the condition closest to ours, show a broad plateau of optimum performance between about 1 and 10 deg sec^{-1}.

CONCLUSION

The effects of varying the type and parameters of signal-noise displays are potentially theoretically revealing. It is certainly desirable to make comparisons across stimuli that are as similar as possible. However, in

*For example, if d_{max} is taken as 0.5 deg, a reasonable value for the conditions of this experiment (Baker & Braddick, 1985a), then about 9% of the noise dots (25 dots at the highest density) will be plotted so as to yield a displacement less than d_{max}.

practice, the various diverse ways that signal/noise ratios can be manipulated yield numerically similar results, across the range of conditions that we have explored.

REFERENCES

Baker, C. L. & Braddick, O. J. (1985a). Temporal properties of the short range process in apparent motion. *Perception, 14*, 181–192.

Baker, C. L. & Braddick, O. J. (1985b). Eccentricity-dependent scaling of the limits for short-range apparent motion perception. *Vision Research, 25*, 803–812.

Baker, C. L., Hess, R. F. & Zihl, J. (1991). Residual motion perception in a "motion-blind" patient, assessed with limited-lifetime random dot stimuli. *Journal of Neuroscience, 11*, 454–461.

Blake, R. & Hiris, E. (1993). Another means for measuring the motion aftereffect. *Vision Research, 33*, 1589–1592.

Braddick, O. J. (1974). A short-range process in apparent motion. *Vision Research, 14*, 519–527.

Braddick, O. J., Smith, E. & Scase, M. O. (1994). Spatial incoherence increases visible persistence of moving dots. *Investigative Ophthalmology and Visual Science, 35*, 1389.

Britten, K. H., Shadlen, M. N., Newsome, W. T. & Movshon, J. A. (1992). The analysis of visual motion: A comparison of neuronal and psychophysical performance. *Journal of Neuroscience, 12*, 4745–4765.

Bullimore, M. A., Wood, J. M. & Swenson, K. (1993). Motion perception in glaucoma. *Investigative Ophthalmology and Visual Science, 34*, 3526–3533.

van Doorn, A. J. & Koenderink, J. J. (1982). Temporal properties of the detectability of moving white noise. *Experimental Brain Research, 45*, 179–188.

Downing, C. J. & Movshon, A. J. (1989). Spatial and temporal summation in the detection of motion in stochastic random dot displays. *Investigative Ophthalmology and Visual Science (Suppl.), 30*, 72.

van de Grind, W. A., van Doorn, A. J. & Koenderink, J. J. (1983). Detection of coherent motion in peripherally viewed random-dot patterns. *Journal of the Optical Society of America, 73*, 1674–1683.

Mikami, A., Newsome, W. T. & Wurtz, R. H. (1986). Motion selectivity in macaque visual cortex. II. Spatiotemporal range of directional interactions in MT and V1. *Journal of Neurophysiology, 55*, 1328–1339.

Morgan, M. J. & Fahle, M. (1992). Effects of pattern element density upon displacement limits for motion detection in random binary luminance patterns. *Proceedings of the Royal Society of London B, 248*, 189–198.

Newsome, W. T. & Paré, E. B. (1988). A selective impairment of motion processing following lesions of the middle temporal area (MT). *Journal of Neuroscience, 8*, 2201–2211.

Silverman, S. E., Trick, G. L. & Hart, W. M. (1990). Motion perception is abnormal in primary open-angle glaucoma and ocular hypertension. *Investigative Ophthalmology and Visual Science, 31*, 722–729.

Snowden, R. J. & Braddick, O. J. (1989). Extension of displacement limits in multi-exposure sequences of apparent motion. *Vision Research, 29*, 1777–1787.

Snowden, R. J. & Braddick, O. J. (1990). Differences in the processing of short-range apparent motion at small and large displacements. *Vision Research, 30*, 1211–1222.

Watamaniuk, S. N. J. (1993). Ideal observer for the discrimination of the global direction of random-dot stimuli. *Journal of the Optical Society of America (A), 10*, 16–28.

Watamaniuk, S. N. J., Sekuler, R. & Williams, D. W. (1989). Direction perception in complex dynamic displays—the integration of direction information. *Vision Research, 29*, 47–59.

Williams, D. W. & Sekuler, R. (1984). Coherent global motion percepts from stochastic local motions. *Vision Research, 24*, 55–62.

Acknowledgements—A preliminary account of the work described here has been presented at the 1994 meeting of the Applied Vision Association and appears in abstract form as: Scase, M. O., Braddick, O. J. & Raymond, J. E. (1994). *Ophthalmic and Physiological Optics, 14*, 436–437.

We thank John Wattam-Bell, Scott Watamaniuk, and Johannes Zanker for helpful discussions. This work was supported by grant GR/K33439 from the Engineering and Physical Sciences Research Council (formerly Science and Engineering Research Council) under the Image Interpretation Initiative.