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Dynamic visual noise and the stereophenomenon: Interocular time delays, depth, and coherent velocities

DAVID S. FALK
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

and

ROBERT WILLIAMS
Brain and Perception Laboratory, Bristol University, Bristol B58 1TD, England

This study concerns the stereophenomenon obtained with binocular viewing of dynamic visual noise with a neutral density filter over one eye. Such a display offers the opportunity to study quantitatively the way in which perceptions are organized when the stimulus provides virtually no organization. Measurements are reported of interocular delay times, apparent depth, and horizontal streaming velocity. The effects of changes in filter density, viewing distance, and dot rate are discussed within the context of various theoretical models that have been proposed. These models attribute the stereophenomenon to temporal disparity, the Pulfrich effect, and random spatial disparity. None is shown to account fully for all aspects of the phenomenon. Finally, the effects of tracking are explained as a property of dynamic visual noise.

Dynamic visual noise, a changing random dot array, changes its appearance strikingly when an interocular delay is introduced. The plane of dots changes its appearance from random motion within the display plane to coherent horizontal motion in depth planes in front of and behind it. A similar effect has been achieved in a variety of ways. Ross (1974) presented separately to the two eyes two computer-generated displays, identical except for a time disparity, t_0. Tyler (1974) viewed a detuned television receiver binocularly with a neutral density filter over one eye to produce the desired interocular delay. The noise pattern can be created by a thermal white noise generator (Mezrich & Rose, 1977) or a dynamic laser speckle pattern (MacDonald, 1977).

What is striking about these results is that the perceived organization in the random display is produced entirely by the organization within the brain, working with the single hint provided by the interocular delay. Subjective coherent motion appears in the absence of real or ordered apparent velocities, and depth, in the absence of classical depth cues. Thus, this phenomenon offers a rare opportunity for quantitative study of subjective order produced from minimal stimulus order.

Rose (1974) attributed this effect to a form of stereopsis resulting from delay between the reception of a display in the two eyes, as would happen if the display really were moving horizontally on a plane different from that of fixation. Tyler's model (1974, 1977) requires parallel processing of monocular apparent motion and stereoscopic fusion of dots with random spatial disparity which, after the interocular delay is imposed, appear to occur simultaneously. In this model, apparent motion in one horizontal direction could only be associated with a definite disparity (crossed or uncrossed, depending on which eye suffers the delay). Mezrich and Rose (1977) suggested that monocularly observed apparent motion, due to random association of neighboring dots in successive frames, generates depth as in the classical Pulfrich phenomenon. The observed coherent motion occurs because only horizontal motion in the dynamic noise is amenable to the Pulfrich effect. What is required is a quantitative check on the validity of the proposed explanations.

EXPERIMENTS

We measured, independently but under identical conditions, the following parameters associated with the phenomenon: (1) the interocular time delay produced by a neutral density filter over one eye, (2) the apparent depth of the planes of dots, and (3) the ap-

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parent velocity of the coherent motion of the planes. Each measurement was made as a function of filter density, viewing distance from the screen, and average rate of dot presentation.

Procedures

For all experiments, a random noise signal was presented on a television monitor using the video-data sampling technique (Williams, 1973). Using a blank field, the apparatus plots .1-μsec pulses, derived from a wide-band noise source, producing 1-mm-diam spots. As the pulses occur randomly in time, they are distributed by the raster process in a spatially random pattern, which is completely changed every 20 msec. The mean rate can be varied (0-3 MHz), and a digital counter monitors the 1-sec time average. The 380 × 300 mm monitor screen was masked to provide a 230 × 170 mm viewing region. Viewing distance ranged from 380 to 1,040 mm (corresponding screen sizes, 35 × 26 deg to 13 × 9 deg). A 200-mm half-silvered mirror, angled at 45 deg, allowed the subject to view, optically superimposed, the monitor screen and the comparison test display (different for each experiment). Two filter holders defined the viewing distance, acting as viewing peep holes for the subject. The monitor background and mean luminances, at preset spot rates, were checked before each session with a photopically calibrated diode. Absolute average luminances were obtained using an S.E.I. direct vision photometer. Ambient light was provided by two ceiling fluorescent fixtures, since the phenomenon was more easily seen in an illuminated room.

Experiment 1: Interocular delay. To measure the extra latency (t_0) resulting from a neutral density filter, two methods were utilized:

(1) A classical Pulfrich arrangement with an oscilloscope screen, displaying a spot oscillating 77 mm horizontally (6.4 deg at 690 mm) at about 1 Hz, superimposed by the half-silvered mirror upon the noise display. A filter over one eye gave the illusion that the spot (whose actual motion was on the monitor screen) was moving in a horizontal ellipse extending toward and away from the subject. The subject set an optical track marker at the maximum forward apparent excursion of the Pulfrich spot. The interocular delay time was calculated from this value. Lower spot velocities were also used to ensure that Panum's limits were not exceeded, but the results were independent of velocity.

(2) A direct interocular delay technique, injecting two separate green LED sources into the fields of view of the two eyes by arranging further half-silvered mirrors at 45 deg immediately behind the filter holders. The subject viewed the unfused monocular images of the LEDs superimposed on the noise field. These images were of about the same luminance as the spots in the noise field and were pulsed at about 1 Hz. An apparent interocular delay was produced by a neutral density filter in front of one eye. This delay was offset by the subject varying the LED phasing to produce phenomenal simultaneity. The actual time delay between the pulses to the LEDs was then measured. To reduce asymmetry effects, the filter was alternated between eyes and the results averaged.

Experiment 2: Depth measurements. An optical bench track with a moveable point light source was placed parallel to the screen, in front of it and to one side. This light was superimposed on the monitor screen and binocularly viewed. The subject adjusted the stereoscopic depth of the image of this point source to the apparent depth of the dots by turning the rack and pinion mechanism of the optical bench. The source's position was then measured. The point source (a pinhole illuminated by a 10-W quartz iodide lamp) was red-filtered and was 1.5 log units brighter than the mean screen luminance.

This experiment measured b, the apparent distance that the back plane of dots lies behind the TV screen (the positions of the dots in the absence of the filter). We used only observers for whom the depth was well defined, although after a long, tiring session the display would appear to break down into several depth planes. The back plane was used because it was the most easily discriminated by our subjects.

Experiment 3: Velocity matching. An oscilloscope was positioned at right angles and adjacent to the monitor screen so that its display was superimposed on the screen. A variable waveform, low-frequency oscillator replaced the time base. The oscilloscope trace was swept at constant speed horizontally, with amplitude 63 mm and with its frequency set by the subject to obtain a match with the apparent coherent velocity of the noise display. To minimize tracing, the subject fixated on a spot attached to the screen at about 2½ deg below the path of the oscilloscope trace (Murphy, Kowler, & Steinman, 1975). To minimize adaptation effects, the filter was alternated between eyes, and measurements were repeated at different times within a session. This experiment measured V_m, the velocity matched to the apparent velocity of the coherent motion of the planes.

SOME COMMENTS ON PROPOSED EXPLANATIONS

We first discuss some proposed explanations in order to be able to present our results in a theoretical framework.

Temporal Disparity Model

Ross' (1974, 1976) suggestion that a temporal disparity between the two eyes may be interpreted as stereoscopic depth, "as if it had been generated by eye movements," implies a definite relation between the observed velocity and the angle, from a point on the actual display plane, subtended by the two eyes. That is, an object located at point P on the display plane (Figure 1) is seen by one eye at time t and by the other (delayed) eye at the time $t + t_0$. If this delay is to be interpreted as motion in depth, then the object must appear to have moved through an angle ϕ during the time t_0 with, consequently, angular velocity ϕ/t_0. Here ϕ is the angle from P subtended by the two eyes and is equal to $(180/\pi)S/D$(degrees), where S is the interocular spacing and D is the viewing distance. (Note that ϕ is independent of the fixation point, which need not be P, and is therefore not necessarily the vergence angle.) Hence, a temporal disparity interpreted as motion in depth will result in an apparent angular velocity of the motion, of value $V_{td} = (180/\pi)(S/t_0D)$. Mathematically, this formula is senseless for vanishingly small t_0. (Ross, 1974, observed the coherent streaming of the dots only for $t_0 > 50\text{-}70$ msec.)

Pulfrich Model

We recall some basic properties of the Pulfrich phenomenon (for details, see Levick, Cleland, & Coombs, 1972). An object perceived at a depth b behind the screen must be due to a stimulus undergoing a (real or apparent) displacement d during the interocular delay time t_0, where $d = Sb(D + b)^{-1}$ (see Figure 2). Equivalently, the motion of the stimulus during t_0 subtends, from the subject, an angle

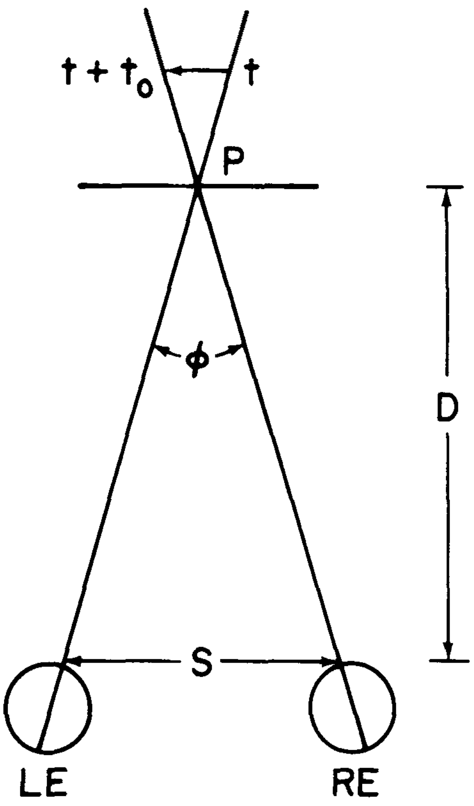


Figure 1. Left and right eyes, with interocular spacing S, view screen from distance D. Object on screen at point P is seen by left eye at time t and by right eye at time $t + t_0$. From P, the two eyes subtend an angle ϕ.

$\theta = (180/\pi)(d/D)$ (degrees). Measurements of the depth, b, may then be expressed in terms of the angle $\theta = (180/\pi)[Sb/D(D + b)]$.

The advantage of expressing the data in terms of θ is threefold. First, the angle θ is approximately equal to the binocular disparity. Second, θ/t_0 is the angular velocity in degrees/second of the motion across the screen, and so may be compared with V_m, the velocity obtained by matching with a moving spot. We call $\theta/t_0 = V_i$ the velocity inferred from the depth measurements. Third, in the classical Pulfrich phenomenon, with a definite *linear* velocity across the display plane, the observed angular velocity would vary inversely with D, and so would V_i (and thus θ). If, however, there is a spectrum of velocities across the display plane (as for apparent motion in dynamic visual noise[1]), and if we assume (as do Mezrich and Rose reasonably) that the eye favors a given *angular* velocity from this spectrum in the production of the depth phenomenon, then V_i would be that angular velocity. In this presumably more relevant case, we should expect both V_i and θ to be roughly independent of D. (A weak dependence might ensue because changing the viewing distance has the effect of modifying the velocity spectrum present in the display. Changing the dot rate would have a similar effect.) In either case, we would expect V_i to be independent of t_0.

Random Spatial Disparity Model and the Reverse Stereophenomenon

Tyler (1977) argues against the Pulfrich, or apparent movement, model, laying heavy emphasis on the existence of the reverse stereophenomenon. Here the two eyes are shown complementary random-dot patterns. The pattern shown one eye is bright where the other is dark. When these patterns are viewed with a neutral density filter over one eye, Tyler reports the observation of coherent streaming and depth of the dot pattern, as in the usual stereophenomenon but somewhat weaker. The streaming appears, however, in the opposite direction to that observed when both eyes observe the same pattern. Tyler argues that this reverse stereophenomenon precludes the Pulfrich explanation and thus strengthens the random spatial disparity explanation.

The reverse stereophenomenon, however, is not inconsistent with a Pulfrich model. Because any bright spot will have dark spots on both sides of it, the complementary pattern has two patches of light, one to each side of the location of each light patch

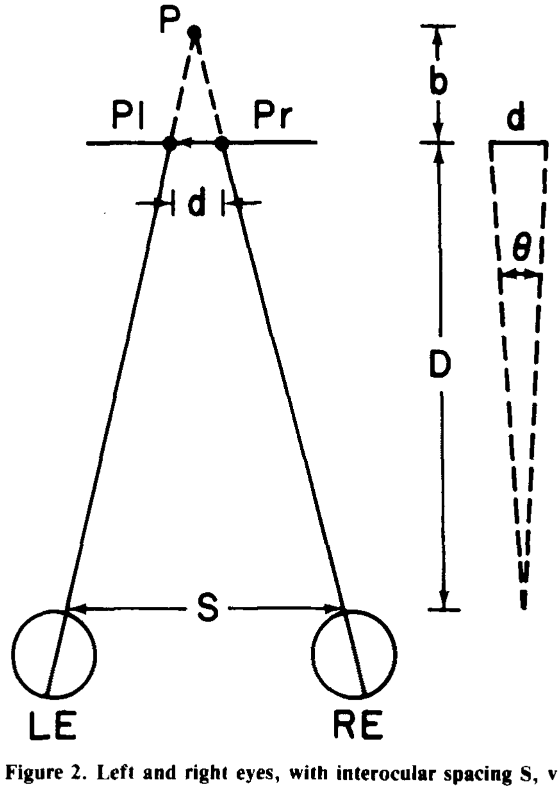
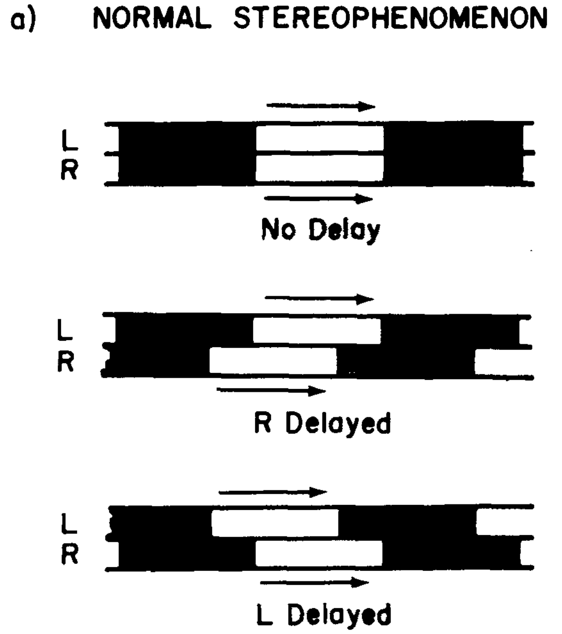


Figure 2. Left and right eyes, with interocular spacing S, view screen from distance D. Motion in display plane from P_r to P_l is perceived as occurring at P, a distance b behind display plane, if, due to interocular delay, the left eye observes the motion at P_l while the right eye is still observing it at P_r. The distance d, separating P_r and P_l, subtends an angle θ.

in the original pattern. These two light patches will apparently move in the same direction, one preceding and one trailing, as any apparent motion of the light patch in the original pattern. The two eyes will correlate the light patches which are spatially closest to each other and this will result in a reverse stereophenomenon by the usual Pulfrich argument, if the interocular delay is not excessive. The phenomenon will be weaker since the correlated patches will be similar but not identical.



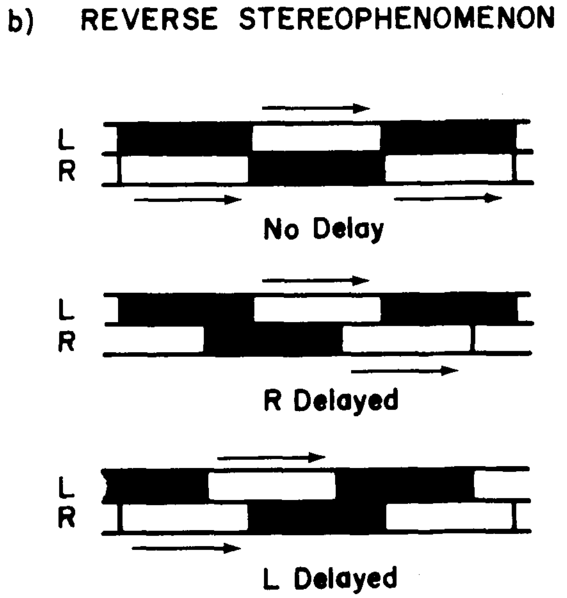


Figure 3. (a) The normal stereophenomenon. Patterns of light and dark patches observed by the left eye (L) and the right eye (R) for apparent motion to the right, as indicated by the arrows adjacent to the light patches. The situations of no interocular delay, the right eye suffering a delay, and the left eye suffering a delay are shown. When one eye suffers a delay, the bright spot seen by it *lags* that with which it is paired in the pattern seen by the other eye. (b) The reverse stereophenomenon. Similar to Figure 3a, except that the two eyes see complementary patterns. Here, when one eye suffers a delay, the bright spot seen by it *leads* that with which it is paired in the pattern seen by the other eye.

To see how the Pulfrich explanation works, consider Figure 3. Figure 3a shows the patterns observed by the left and right eyes in the normal stereophenomenon, with the arrows indicating the direction of the apparent motion. The bright spot observed by the eye suffering the delay *lags* that observed by the undelayed eye. The correlation of these observed spots results, by the usual Pulfrich argument, in the appearance of depth. If the right eye suffers the delay, crossed spatial disparity results when there is apparent motion to the right. Figure 3b shows the same situations when the two eyes are subjected to complementary patterns. Here, because the bright spot seen by one eye corresponds to a dark spot seen by the other, a bright spot seen by the eye suffering the delay *leads* the nearest bright spot observed by the undelayed eye (unless the delays become excessive). For apparent motion to the right, if the right eye suffers the delay, uncrossed spatial disparity results, and there is a reverse stereophenomenon, as observed.[2]

RESULTS

One of the most notable observations was the relative instability of V_m, as compared with t_0 and b. V_m tended to vary considerably for each observer from session to session, by as much as 40%, and larger variations could be produced if the subject attempted to track the coherent flow. The velocity was, however, stable over each session (about an hour), allowing measurements of it with different parameters, and the dependency of V_m on these parameters was reproducible. For this reason, most results for V_m are given as ratios showing the fractional change of V_m as the various parameters are changed.

Interocular Delay

Figure 4 shows measured interocular delay times (Experiment 1) for two subjects, R.W. and J.P.H., as well as results obtained by a stereoscopic null method of Rogers and Anstis (1972), averaged over their two subjects, for relative visual latencies at this luminance. (A dot rate of 14×10^5 dots/sec corresponded to an average luminance of about 3,000 Tr.) The direct results agree reasonably well with the Rogers and Anstis results, as do the Pulfrich results for R. W. However, J.P.H. shows significantly smaller results for t_0 by the Pulfrich method, indicating a weak Pulfrich response.

Temporal Disparity Model

Knowing t_0, it is now possible to calculate the

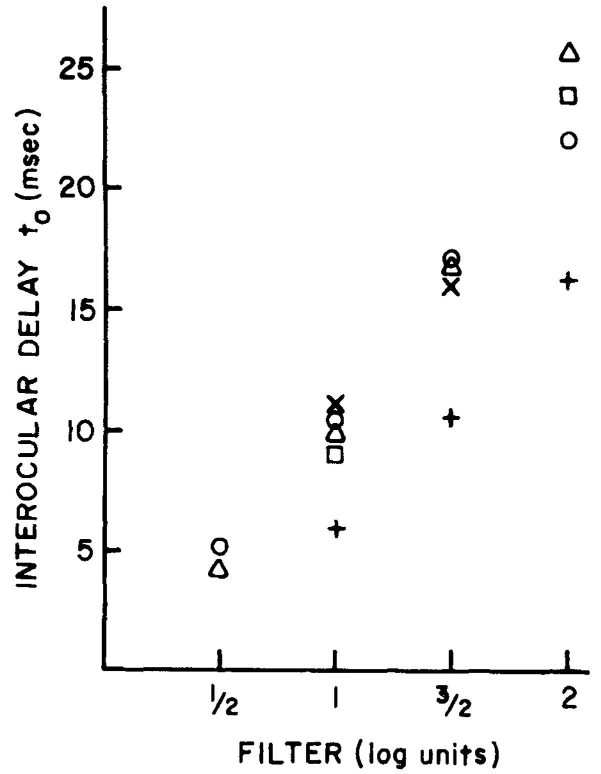


Figure 4. Interocular delay times vs. filter density. The triangles are the Rogers and Anstis results (1972). The squares and circles are, respectively, the direct and Pulfrich results for subject R.W. The xs and +s are, respectively, the direct and Pulfrich results for subject J.P.H. The direct results are averaged over dot rate. Each point corresponds to the mean of over 50 observations. The more precise Pulfrich results (obtained at 14 × 10^5 dots/sec) have a standard error of about ½ msec with about 20 observations per point.

velocity in the temporal disparity model, V_{td}. The smallest V_{td} would result from the two log-unit filter (t_0 = .022 sec) at viewing distance D = 1,040 mm. With interocular spacing S = 65 mm, this gives V_{td} = 163 deg/sec. This is more than an order of magnitude larger than any velocity observed or inferred by us (see below) or by Mezrich and Rose and would be even larger at closer distances and with weaker filters. Clearly, the temporal disparity model does not explain the phenomenon we observe. (See also Tyler, 1977.)

Although they are usually assumed to be the same (e.g., Mezrich & Rose, 1977), we believe this phenomenon is different from that reported by Ross. His dot rate was lower than ours, and to see his effect he needed interocular delay times three times larger and a binocularly common central square.[3]

Depth Measurements

Figure 5 presents the mean depth measurements, averaged over dot rate, of Experiment 2, for two subjects R.W. and J.P.H., as a function of filter density, for varying distances of observation, D. Depth is given in terms of the angle, θ. We note that a value θ = .040 deg corresponds to values of b = 1.6, 5.1, and 12 mm for viewing distance D = 380, 690, and 1,040 mm, respectively. Figure 5 shows the smaller depth observed by J.P.H., consistent with that subject's weak Pulfrich response, as noticed in the t_0 measurements. The order of magnitude of all these measured depths is consistent with that estimated by Tyler's subjects (Tyler, 1977).

From θ and t_0, we can calculate the inferred angular velocity $V_i = \theta/t_0$. For a pure Pulfrich effect, V_i would be the actual angular velocity of the spot that would, with an interocular delay t_0, result in the depth θ. Figure 6 plots V_i as a function of filter density. The values of θ used are those obtained for D = 690 mm and a dot rate of 14×10^5 dots/sec (as in the t_0 measurements). Figure 6 contains the results for R.W., the subject for whom we obtained consistent values of t_0. We will return below to the rise in V_i with filter density.

Velocities

In Experiment 3, a direct measure of the apparent coherent velocity, V_m, was obtained.

Dependence on filter. A striking feature of the results of the velocity measurements is that, uniformly, at every distance and dot rate, for both subjects, V_m increased as the filter density increased. The ratio of the velocity measured with a two log-unit filter to that measured with a one log-unit filter is $1.4 \pm .2$ for R.W., $1.6 \pm .2$ for J.P.H. This ratio has been averaged over dot rate and viewing distance. The same ratio for the induced velocity, V_i, is $1.3 \pm .1$ for R.W.

As an additional independent check on the dependence of velocity on filter density, the display was observed with one eye looking through two partially overlapping filters, so that the eye's view consisted of part 1/2 log-unit filter and part 3/2 log-unit, with a reasonably sharp edge separating the regions. This side-by-side comparison clearly showed a faster and deeper dot pattern through the darker filter.

Neither the Pulfrich model nor the random spatial disparity model provides a convenient explanation of this feature. In the former, the filter serves only to produce the interocular time delay t_0, and consequently, for a given velocity will affect the observed depth. The model gives no reason why a given velocity should be selected out of the spectrum present in the dynamic visual noise display. The situation is similar in the latter model. There the observed apparent motion is monocular, and it seems hard to understand why that motion should be affected by a filter in front of one eye.

Clearly, there must be other effects due to the filter in addition to the interocular time delay. Possibly the increase in apparent velocity with increasing filter density may be due to increasing spatial integration which might eliminate some of the smaller velocity

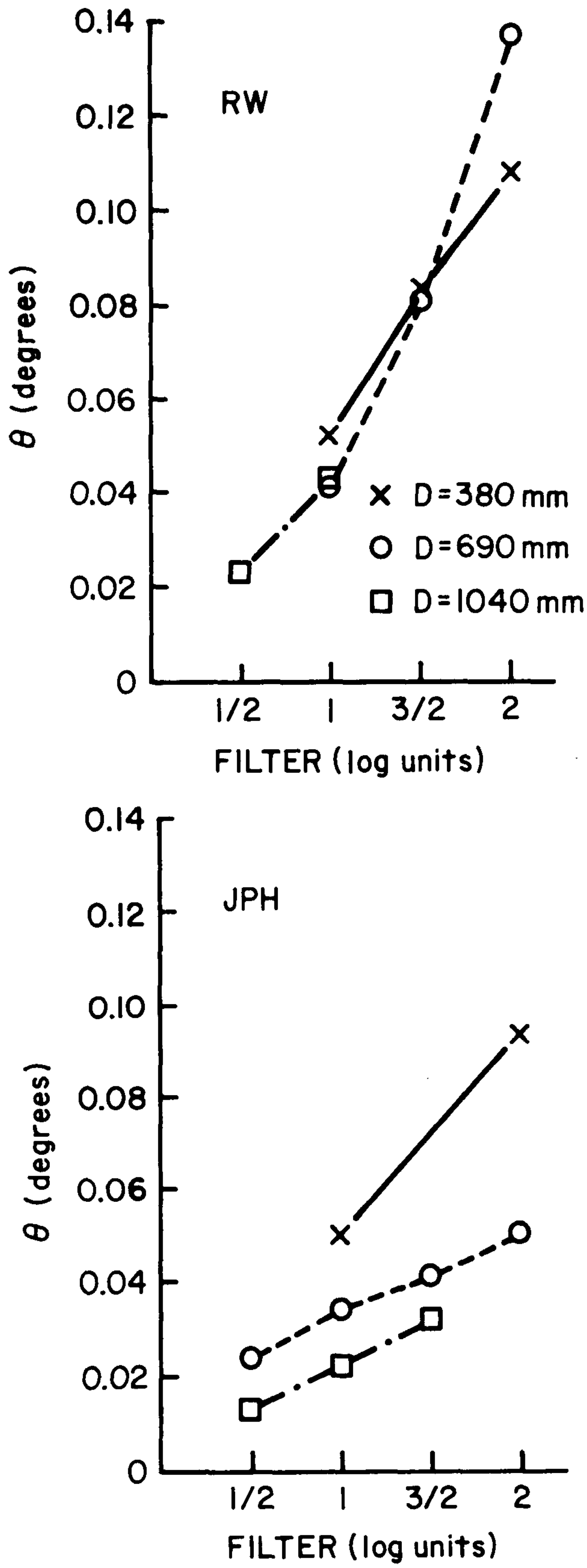


Figure 5. Apparent depth, as characterized by the angular parameter θ (roughly the binocular disparity) vs. filter density, for various observing distances D, averaged over rate of dot presentation, for two subjects. Each point corresponds to the mean of over 50 observations.

components from the spectrum of apparent motion in the dynamic visual noise.

Dependence on viewing distance, D, and on dot rate. At fixed dot rate, decreasing D increased V_m. Roughly, cutting D in half increased V_m by a factor of 1.5. Similarly, when the dot rate was halved (but all other parameters were unchanged), the mean increase in V_m was a factor of 1.12.

The relation between the dependency on these two parameters will depend on the nature of the patterns used by the eye for detecting apparent motion. Doubling D doubles the linear dimensions within a given viewing angle and thus quadruples the area. Doubling the dot rate increases the dots along a given horizontal length by a factor of two but, since the TV raster remains fixed, only doubles the dots in a given area (a point apparently overlooked by Mezrich and Rose). Thus, if the eye detects apparent motion only of individual dots along a horizontal line, the dot rate should scale as the distance, while if the dots per area are more important, it should scale as the square root of the distance. The very weak dependence on dot rate suggests that the latter is the case: The eye is looking at patterns larger than individual dots.

The observed increases in V_m may be expected for two reasons. One is the removal of the smaller apparent velocities from the original noise spectrum. Decreasing either D or the dot rate increases the angular separation of two dots presented successively and, hence, the apparent angular velocity between them.

The spatial frequencies involved provide the other reason. That our measured V_i of about 4 to 6 deg/sec is the optimal speed for detecting 1-cycle/deg gratings (Kelly, 1979; Pantle, 1974; Watanabe, Mori, Nagata, & Hiwatashi, 1968) suggests that the eye is looking at patterns of about ½ deg width. Decreasing D or the dot rate makes this and smaller size patterns rarer, necessitating the use of larger patterns. The grating measurements show that larger speeds become optimal for larger patterns, consistent with our observed increase in V_m.

Figure 5, however, shows that θ does not depend on D for R.W., although it does for J.P.H. Furthermore, halving the dot rate decreased θ by a factor of .9 for both observers. Wist, Brandt, Diener, & Dichgans (1977) observed a decrease in depth with decreasing spatial frequency. Since the spatial frequency should be proportional to something like the square root of the dot rate, our dependence of θ on dot rate is not inconsistent with the numbers quoted in Wist et al.

What is surprising, however, is the different dependencies on D and on dot rate of θ and V_m. The simplest Pulfrich model would have these two quantities proportional to each other. Indeed, Wist et al. find the dependencies of Pulfrich depth and perceived velocity on spatial frequency to be much the same.[4] The random spatial disparity model does

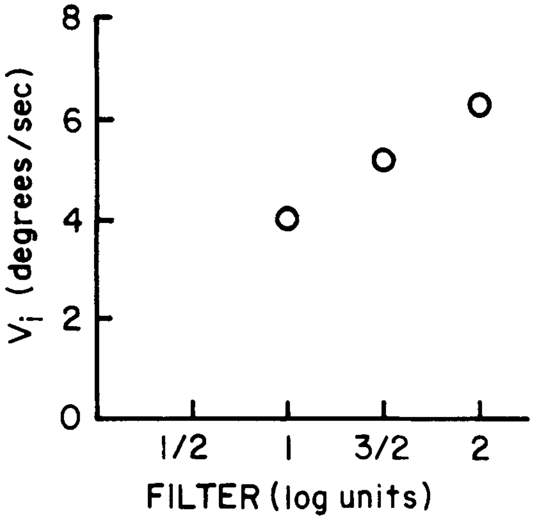


Figure 6. Inferred velocity $V_i = \theta/t_0$ for subject R.W. at viewing distance D = 690 mm and dot rate 14 × 10^5 dots/sec.

not require strict proportionality, as depth and velocity are determined in parallel processing, but greater depth and greater velocity must also occur together here (cf. Tyler, 1974, Figure 1A). The decreased luminance at lower dot rates produces too small a change in temporal integration time to account for our observed differences of θ and V_m (Rogers & Anstis, 1972).

Comparison of V_m with V_i. The results for V_i, shown in Figure 6, may be compared with those for V_m obtained for the same subject under the same conditions. The simplest Pulfrich model would have V_i (obtained by inference from the observed depth) and V_m (obtained by direct measurement) be the same. Although the experimental uncertainties are large, especially for V_m, we nevertheless find that V_i is always greater than V_m, the ratio V_i/V_m ranging from 1.4 to 2.8.

These differences, as well as the different behavior of θ and V_m with change of D and of dot rate, suggest that higher processes enter. For example, the apparent velocity V_m may not be a purely monocular phenomenon but may involve additional processing after stereoscopic fusion (Julesz & Payne, 1968; see also Wist et al., 1977). Even the ordinary Pulfrich effect varies with subject and is modified by classical depth cues, and we have seen both these effects here.

Tracking. It has been previous noted (Tyler, 1974; Ward & Morgan, Note 1) that, if the eyes attempt to track the coherent velocity, that velocity is increased. We easily confirmed this observation during our attempts to measure V_m. The more we attempted to track the coherent motion, the larger our observed V_m.

This effect is basically a property of apparent motion in dynamic visual noise. Perceived velocity is a combination (along with other information) of the velocity of an object's image across the retina, the *image velocity*, and the *eye velocity* incurred by any attempt to track the object, that is, to reduce the image velocity.[5] An increase in either of these velocities results in an increased perceived velocity. The situation is the same for apparent velocity as for real motion. If the eye tracks just enough so that successive flashes of light cast their images on the same retinal spot, then the image velocity of the flashing light will be zero, but the eye velocity will serve as the source of perceived velocity. With dynamic noise as a source of apparent motion, however, there is a difference. Here, no matter how the eye tracks the motion, it can never reduce the image velocity. The apparent motion comes from a dot or dots in one frame being associated with one or several in a subsequent frame. Since, in both frames, the dots are randomly distributed and uncorrelated, the fact that the eye has moved between frames cannot affect the image velocity of this apparent motion. Hence, tracking does not reduce the image velocity at all. The same image velocity is thus augmented by the tracking eye velocity, and the resultant perceived velocity is thus greater when the eye tracks than when it fixates, as is observed.

CONCLUSIONS

A number of results have come from this study of the stereophenomenon obtained by binocularly viewing dynamic visual noise with a neutral density filter over one eye. Some aspects are now clearer. These include the understanding of the effects of tracking and that the temporal disparity model cannot explain the phenomenon. Some new aspects of the phenomenon have been uncovered. The increase of the apparent velocity with filter is both new and easily observed. Arguments have been advanced that the observed apparent motion involves not a dot-to-dot correlation, but rather the correlation of larger collections of dots, possibly on the order of .5 deg of visual angle. When the dynamic visual noise becomes sparse in regions of this size, due to decrease in dot rate or viewing distance, the apparent velocities show a corresponding rise.

No definitive test distinguishes the Pulfrich model from the random spatial disparity model. It would certainly seem to be the case that whenever there is motion, apparent (as in dynamic visual noise) or real, there must be a Pulfrich effect. However, the variation in the ratio V_i/V_m reflects a decoupling of the depth and velocity that goes beyond the simplest Pulfrich model. Here, as for the random spatial disparity model, the different behavior of depth and velocity, particularly with dot rate, indicates that higher processing effects must be entering. Since such effects also modify the classical Pulfrich phenomenon, a Pulfrich model is still consistent with all the observations.

Two problems remain for the random spatial disparity model. This model implies the existence of some depth when uncorrelated displays are presented to the two eyes. The evidence here is unclear. The very lack of agreement on this point suggests that the random spatial disparity effect may be a weak phenomenon, whereas the stereophenomenon is a striking effect. The other problem pertains to the lack of definition of this model when the interocular delay time, t_0, is significantly less than the interframe time of the display, τ. Here τ was 20 msec, while t_0 ranged from about $\tau/4$ to slightly more than τ with no qualitative changes in the stereophenomenon. While the standard Pulfrich effect with apparent motion has been demonstrated to exist for $t_0 << \tau$ (Morgan, 1976; Morgan & Thompson, 1975), the random spatial disparity model is not well defined under these conditions where the two eyes see the same display most of the time.

In any event, the full understanding of how subjective order is produced from a chaotic stimulus goes beyond the simplest models and evidently depends in a basic way on several information-processing channels. This striking stereophenomenon provides a window for us to study their interaction.

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NOTES

1. That there is a spectrum of apparent velocities in dynamic visual noise is consistent with the demonstration of Ward and Morgan (Note 1) that, by having the subject conceive of a region of a dynamic visual noise display as moving, it is possible to elicit smooth eye tracking.

2. The Pulfrich explanation would argue that the reverse stereophenomenon would be most obvious when the random dot display has about equal densities of light and dark patches at any given time. Unfortunately, Tyler does not give the dot densities.

3. To better understand Ross' results, one of us (R.W.) constructed a videosynchronized pseudorandom dichoptic delay generator capable of presenting two dynamic visual noise displays separately to the two eyes. The displays could be uncorrelated, or correlated with an interocular time delay of up to ± 160 msec, and the dot rate could be varied from the rates at which we had been working down to those at which Ross worked. The results showed the depth and streaming effect we have been observing for interocular delays less than 60 msec, but not for greater delays. Since this is about the time that the afterimage of a given display remains, it is not surprising that it should serve as an upper limit on observed correlations between the two eyes.

When Williams inserted a central square seen simultaneously by both eyes, to obtain a better replica of Ross' display, depth was then observed for interocular delays greater than 80 msec, consistent with Ross' observations. Additionally, depth was also observed when the two eyes were presented displays that were uncorrelated except for the central square. This point is particularly interesting, as different workers have reported conflicting results. MacDonald found neither depth nor coherent streaming when the two eyes viewed uncorrelated displays. We observed a similar lack of depth when the subject changed the convergence of his eyes, so that his two eyes viewed different, uncorrelated parts of the dot pattern. However, Julesz and Tyler (1976) report depth for uncorrelated displays in the presence of a zero-disparity fixation marker in the center of their displays.

It therefore seems that a central image seen simultaneously by both eyes is essential to the observation of depth for both the uncorrelated displays and the correlated displays with interocular delays greater than 80 msec. This strongly suggests that the phenomenon observed by Ross is most likely dependent on classical depth cues, such as interposition. In any event, it seems clear that it is different from the one we have been studying here.

We should note, however, that Tyler (1977) observed fluctuating random depths for binocularly uncorrelated displays. It is unclear whether he had a central image which might induce classical depth cues. The question of whether or not one sees any depth from uncorrelated displays is essential to Tyler's random spatial disparity hypothesis and must be viewed as currently unresolved.

4. We should note, however, that the velocity referred to there is an estimated velocity (Diener, Wist, Dichgans, & Brandt, 1976), while V_m is a matched velocity.

5. The existence of separate systems responsive to these two velocities, long referred to in the literature (e.g., Kaufman, 1974), has recently been explicitly exhibited neurologically in monkeys (Kase, Noda, Suzuki, & Miller, 1979).

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