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HOW DOES BINOCULAR DELAY GIVE INFORMATION ABOUT DEPTH?

DAVID C. BURR
Craik Laboratory, Department of Psychology, Cambridge CB2 3EB, U.K.
and
JOHN ROSS
University of Western Australia, Nedlands, W.A. 6009, Australia

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Abstract—Observers watched spots of light move stroboscopically (but apparently smoothly) against a background of dynamic noise. Binocular delay of the moving spots, without any binocular disparity, yields vivid stereoscopic depth. Acuity is 160 μsec, which corresponds to about 2″ of arc of virtual disparity. Delay combines additively with disparity.

INTRODUCTION

When a scene is viewed in which there are objects placed at various distances from the observer, each of the two eyes forms a somewhat different image. Disparities between the two images give information about depth which is known to be sensed by the mechanisms of binocular stereopsis. This is true even when the observer is afforded only a momentary glimpse of a scene (Dove, 1841). It follows that change in relative positions of elements in binocular images, due to motion of the scene with respect to the eyes, is not required for stereopsis. Indeed, it is widely believed that stereopsis relies exclusively on instantaneous binocular disparity. This belief is bolstered by the fairly recent discovery of a possible disparity sensitive mechanism, neurons responding maximally to input from a particular pair of binocular sites (Barlow, Blakemore and Pettigrew, 1967; Pettigrew, Nikara and Bishop, 1967).

Moving objects present a special problem since, when viewed with the eyes stationary, they sweep out a smear across an array of receptive sites on each retina. If binocular stereopsis is to establish depth accurately from paired disparity sites, then pairs of sites stimulated at the same instant must be favoured exclusively at the expense of sites stimulated at almost the same instant. The problem remains if the eyes track a moving object, since now the background sweeps across the retina, leaving a trail of activity behind. Does vision make use of information about the delay in stimulation of pairs of sites, as well as information about sites stimulated at the same instant?

The studies here deal with binocular delay and with depth seen as a result of delay. To minimize retinal smear due to motion, we employ targets in stroboscopic motion. The targets do not in fact move, but they appear to move. It is already well known that illusory motion may be perceived when a target is flashed briefly in a sequence of fixed display positions. We also employ briefly plotted visual noise points as a background to illusory motion. This arrangement has the virtue that whether the eyes are stationary or pursue the target, neither the target nor the background sweeps out a trail of stimulation on the retina.

It is known that binocular delay and motion can combine to give an impression of depth. The classical Pulfrich effect is a displacement in depth when one eye's view of an object in horizontal motion is dimmed with a filter, presumably delaying it. Morgan (1975) showed that dimming one eye's view of a target in horizontal stroboscopic motion caused it to be shifted in depth to a distance nearer the observer or further away, depending on which eye is dimmed and the direction of motion. This Pulfrich-like effect was found independently by Ross and Hogben (1975), who also showed that retarding one eye's view directly also had the same effect, confirming that dimming is equivalent to delaying. When one eye's view of stroboscopic motion is delayed the target can have never been viewed by the two eyes in two different positions at the one time. If the eyes are stationary then both eyes image the target in identical positions relative to points in the background, but at different times. If the eyes track the target they will image the target in different retinal positions relative to background points, but again at different times. In one case there is no direct disparity information; in the other case such disparity information as may be given is provided by sites stimulated at different times.

Our purpose is to measure the precision with which vision can fix the depth of a stroboscopically moving target when two binocular sequences are identical except for a delay, to discover how delay and disparity combine when the sequences are different and also delayed, and to consider possible mechanisms.

BASIC DISPLAY

The basic stereoscopic display used in the studies reported here is designed to cause an observer to see a target moving smoothly back and forth across the field of view, though in fact it moves stroboscopically. Figure 1 gives an analogy. A target moves behind an opaque screen, and is visible only in slits in the screen. Each eye observes it in the same places, defined by where the slits are, but at different times. Our target is a spot of light, plotted on each of two oscilloscopes, and brighter than noise points forming in the background. It is displayed at each of a sequence of points according to a timing scheme like that described in Fig. 2, so that it appears in a sequence of identical positions in the field of view of each eye, but always later, by a constant delay δt, in one of them. The spatial separation of the display points (Δx) and the period of the sequence (τ) are chosen to ensure the perception of smooth apparent motion.

The background is made up by a series of discrete points each chosen at random and plotted briefly at a rate of about 5 msec^{-1}, except when a target point is displayed. The gap in the plotting sequence is too small to be detected. Since all background points are received by both eyes in exactly the same positions and at exactly the same times, the random noise appears, in the binocular view, as a plane or surface on which a large number of specks of light tumble about in Brownian motion. The random distribution of the points ensures, on the one hand, a broad range of spatial frequency components and, on the other, constant average luminance over the display field.

The path followed by the apparently moving target can be thought of as its trajectory. As Fig. 2 makes clear, the trajectories observed by the two eyes differ in phase by a constant time δt. Because of the phase difference or delay, the trajectories, if they described real motion, would have a spatial separation δv, which we term *virtual disparity*; this is the instantaneous disparity that would be exhibited by points in continuous motion if they moved smoothly along the trajectories that describe the stroboscopic motion of our targets. There is no disparity in the conventional sense in our display, since, as Figs 1 and 2 show, targets are shown in exactly the same display positions to both eyes. The magnitude and sign of virtual disparity can be calculated and therefore defined as the product of (signed) angular velocity (ω) and delay or phase difference, i.e.

$$\delta = \delta t . \omega$$

$$= \delta t \; (\Delta x / \tau).$$

By convention we define δt as positive when the left eye's sequence leads the right. A positive value of δv implies crossed disparity, and a negative value, uncrossed disparity. With δt constant a point in motion should reverse depth as it reverses direction, since it reverses in virtual disparity when it reverses direction.

GENERAL METHOD

The basic display is shown on a pair of point plotting oscilloscopes, one for each eye. Observers sit in a light-

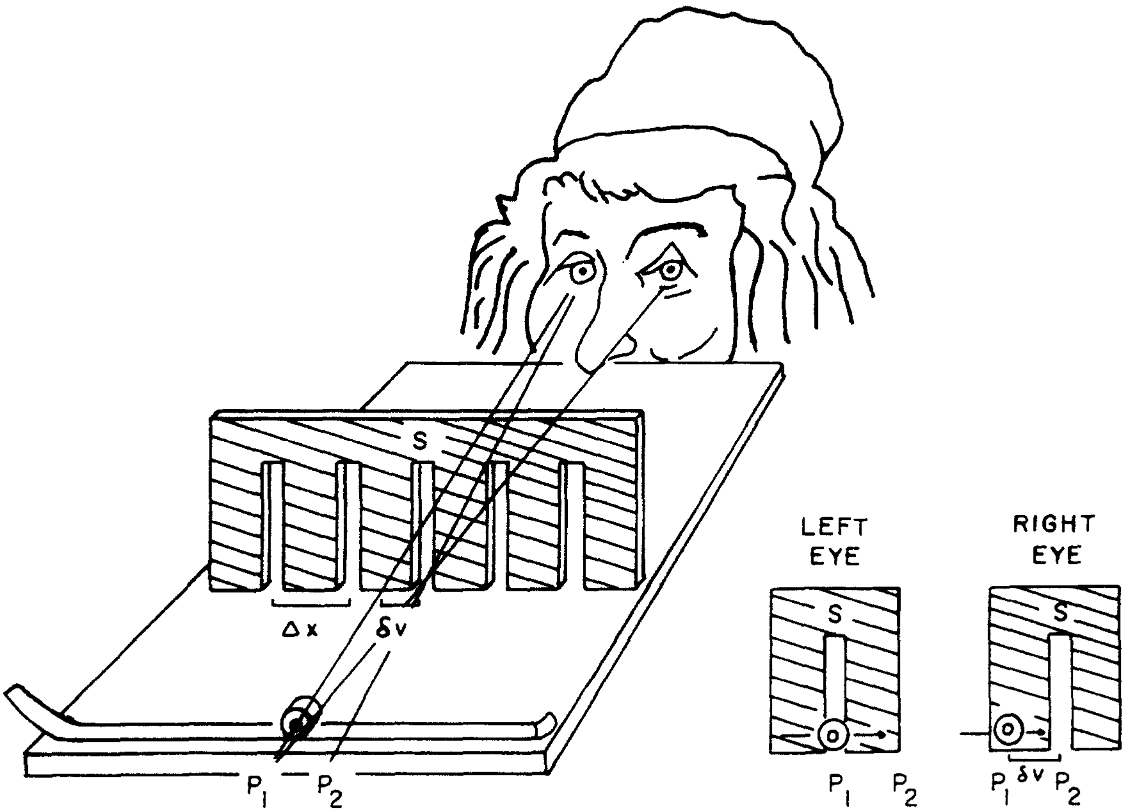

Fig. 1. This scene is analagous to the basic display used in our experiments. A man observes a cotton reel as it rolls from his left to his right behind a series of slits, each separated by a distance of Δx. The reel is periodically visible at successive slits at intervals τ, giving it an apparent velocity of $\omega = \Delta x/\tau$. At the instant depicted, the cotton reel is visible to the left eye, but hidden from the right eye's view. At a time δt later, it will be visible to the right eye only. Thus there is no instantaneous disparity, but if the screen were transparent the disparity, measured at the plane of the screen, would be δv.

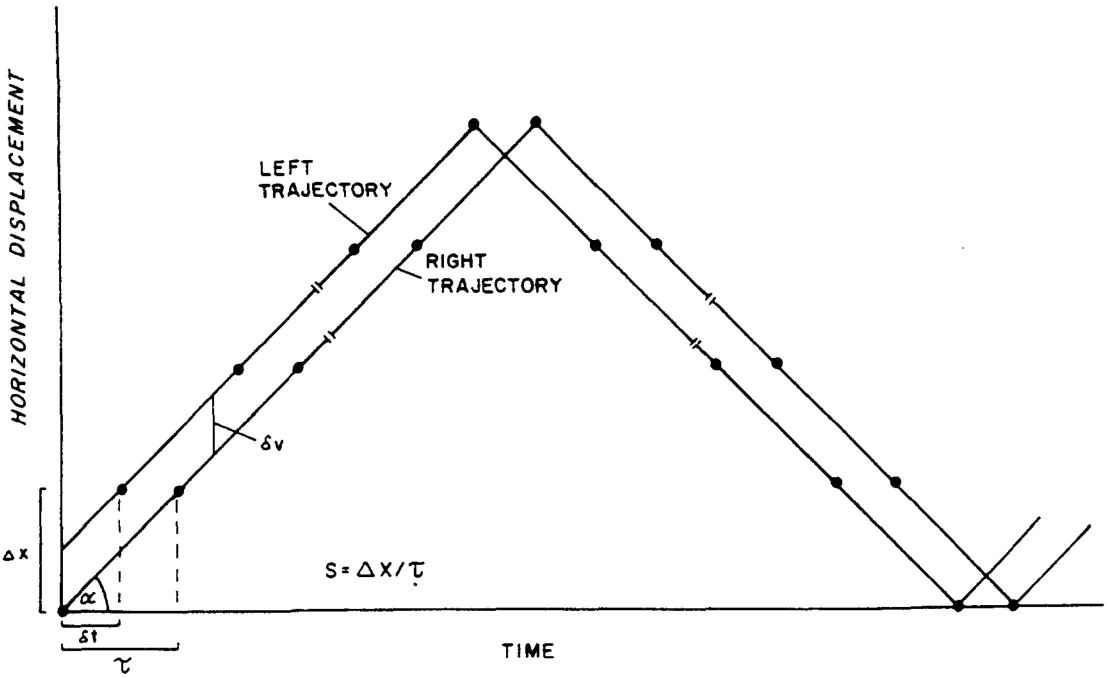

Fig. 2. Plotting sequence for the basic display. In each field a spot of light is displayed in successive horizontal positions as specified by its trajectory. The apparent velocity of the spot is given by $\omega = \Delta x/\tau$, where Δx is the distance between sequence points and τ is the period of the sequence. The spot appears in the same sequence of positions to each eye, but to the left eye a time δt before the right. Thus although there is never a disparity between the two stimuli defining the trajectories, the trajectories themselves would be separated by a distance δv. This distance, which we term the *virtual disparity*, corresponds to the disparity which would exist between the two spots of light, were they in real motion.

proof cubicle, viewing the faces of two Tektronix 602 oscilloscopes, each equipped with fast fade P15 phosphor. The oscilloscopes are optically separated with crossed polaroid filters so that only one is visible to each eye. Alignment is achieved with a beam-splitter. The display is controlled by a PDP 8-E computer which can choose and position points accurately anywhere within a 256 × 256 grid. Background points are sampled at random from a hardware random number generator. They fall with uniform probability over the 256 × 256 possible display positions. Calculated target points are displayed as and when required, the timing, which is computer controlled, being calibrated by a Marconi TF2416 counter/timer. Point brightness can be varied by an intensity level control, by refreshing each point, or by a combination of the two.

As plotted on each oscilloscope the sample square is 7 × 7 cm, and is 60 cm from the observer, thus subtending 6.7 square degrees of arc. The minimum separation between adjacent points is 6.7/256 degrees, or approximately 1.6′ of arc.

Responses are made by pressing one of four interrupt buttons. These are sensed, scored and tallied by the computer, which types out response totals at the end of each viewing session.

Viewing the display described above yields a vivid sense of depth. The moving target appears to travel in a rectangular path, coming clearly in front of the background on one pass and shifting behind when it reverses direction. This is to be expected since, as explained above, virtual disparity reverses sign with direction. The path appears clockwise from above for positive delays (left eye leads) and counterclockwise for negative delays. Furthermore, the magnitude of the shift in depth increases as the delay increases.

The phenomenon is robust. Smooth apparent motion in depth can be observed provided the period is not too great ($\tau \lesssim 200$ msec) and the target does not move too quickly ($\omega \lesssim 15^\circ\ \text{sec}^{-1}$). Most experiments reported here fell comfortably within these limits.

In all the experiments, except where otherwise noted, observers were free to use eye movements and could look at the display as long as they wished before making a response. For the most part responses were made very rapidly except when working at the smallest delays. It also seemed, both to the observers and the authors, that seeing the target as moving and in depth did not require eye movements, although they may be necessary to make fine discriminations about relative depth.

ACUITY

We firstly measured acuity in terms of the smallest binocular delay at which observers could correctly identify relative depth, and in terms of virtual disparity as calculated from delay.

Procedure

A forced choice paradigm was used, in which the observer was presented with one of 12 conditions, representing six magnitudes of delay, each positive (left eye leads) or negative in sign. All delays were 1 msec or less.

The observer's task was to report direction of rotation (clockwise or counterclockwise), which is possible only if he can discriminate the depth of the target from the depth of the background. Responses were made by pressing the appropriate interrupt button. Ten sessions were run for each observer, 60 trials per session (five from each condition), yielding 50 observations per condition.

The target moved at an apparent speed of $4.2^\circ\ \text{sec}^{-1}$, the interstimulus distance (Δx) being 12.5′ of arc and the period of the sequence (τ) 50 msec for all conditions.

Results

Figure 3 shows the percentage of clockwise and counterclockwise responses for each delay condition. The lower scale shows delay, δt, in microseconds, while the upper shows the corresponding virtual disparity, δv, in seconds of arc. The broken vertical lines intersect the plot at the 75% performance levels, which we take as the measure of acuity.

Both observers are remarkably sensitive to small delays. Judgment of depth is better than chance for delays less than 200 μsec. The acuity estimate is calculated to be 160 μsec for both DR and JH. This corresponds to a virtual disparity of 2.4″ of arc.

It can be observed that response curves are not precisely centred at zero delay. This could reflect a small response bias, but it is more likely to be due to very small luminance differences between the two oscilloscope displays which bias the effective value of δt. As noted above, dimming and delaying have equivalent effects in this context.

Discussion

The estimate of acuity for virtual disparity agrees well with published acuity estimates for retinal disparity as such. Berry (1948), ten Doesschate (1955) and Ogle (1950) all report stereoacuity thresholds in the range 2″–5″ of arc, with variation from individual to individual.

A second way of looking at the findings is in terms of sensitivity to binocular delay. Expressed in terms of time rather than converted to virtual disparity, acuity is about 160 μsec. This value agrees fairly well with that found by von Békésy (1969) for stereopsis with targets in true rather than apparent motion. It should, however, be noted that von Békésy's method confounds delay with disparity in spatial position, since targets are in full view at all times. Although a delay as small as 160 μsec may not be sensed directly, and is certainly not perceived directly as a difference in time of arrival, the visual system is nevertheless capable of using information about delay to determine the spatial location of a target.

Is the limit spatial or temporal?

The first experiment shows that binocular vision is highly sensitive to virtual disparities, but it is not clear whether the limit is one of space, virtual disparity, or of time, delay as such. This next experiment was designed to disentangle the two by using a different target speed. Since virtual disparity depends on velocity, the same delays will yield a different set of virtual disparities at different speeds.

Method

The method was identical to that of the first experiment except that the target appeared to move at half the speed (2.1° sec^{-1}). This was achieved by halving

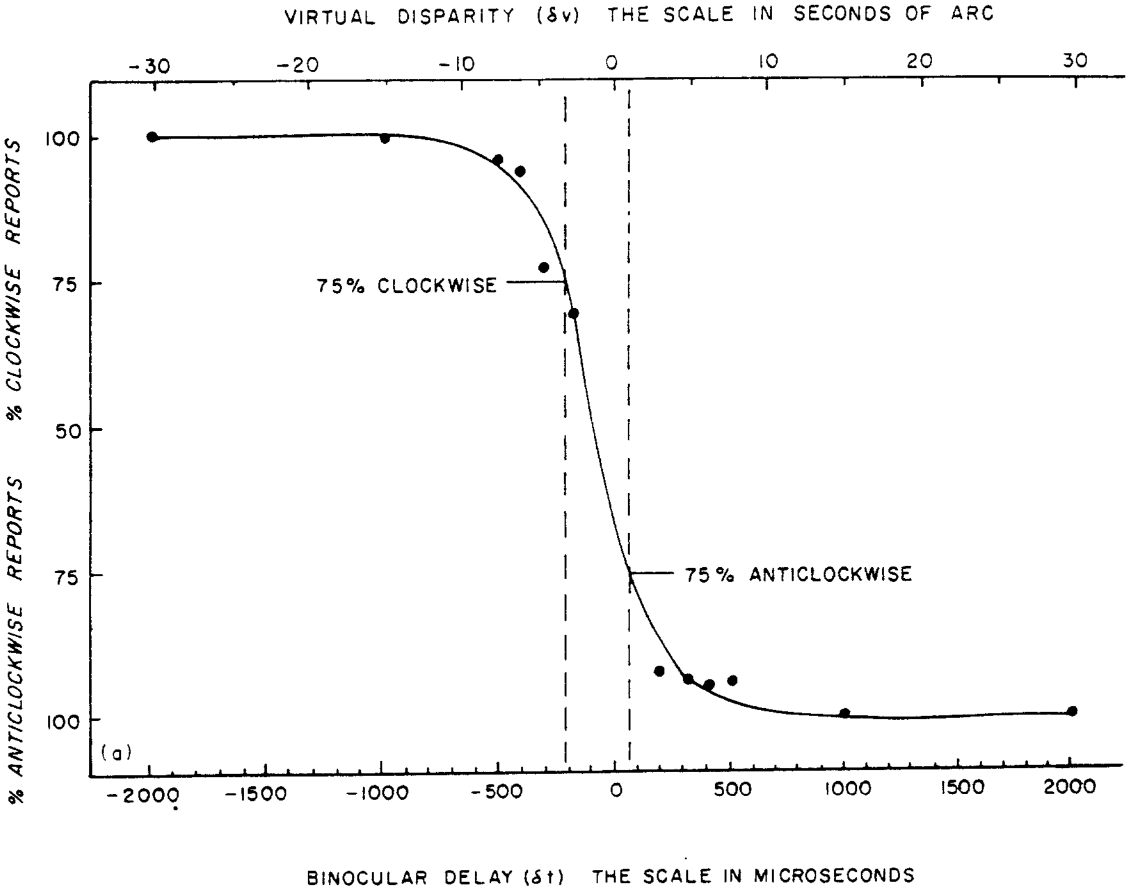

Fig. 3. DR.

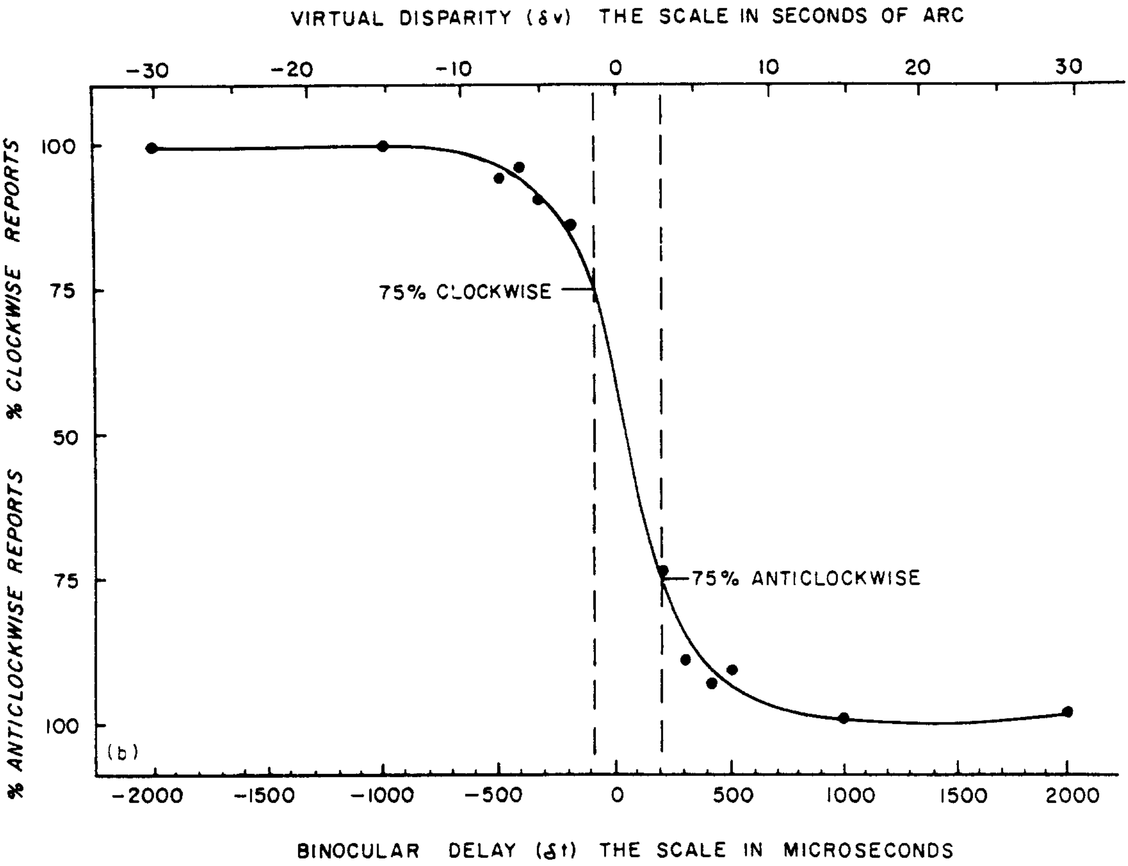

Fig. 3. JH.

Fig. 3. Results of the first acuity experiment, plotting the percentage of clockwise and counterclockwise reports against the binocular delay, expressed both in microseconds (lower abscissa) and secs of arc of the corresponding virtual disparity (upper abscissa). Acuity is calculated by averaging the values of δt (or δv) which yield 75% clockwise and those which yield 75% counterclockwise reports. The virtual disparity acuity for both DR and JH was 2.4" of arc, corresponding to a measured delay of 160 μsec.

Δx, reducing it from 12.5' of arc to 6.25' of arc, everything else, including δt values, remaining unchanged.

Results and discussion

Figure 4 shows results for DR and JH. The acuity for virtual disparity is 2.1" of arc for DR, and 4.0" of arc for JH. The corresponding delay values are 280 and 580 μsec.

At least for DR, the better observer generally, acuity for virtual disparity remained about the same as at the higher speed, while acuity in temporal terms was only half as good. Although the data are not conclusive, it is strongly implied that resolution of virtual disparity is limited spatially, not temporally. This in turn suggests that delay is not sensed directly but is somehow converted into a disparity, which can be resolved to the same accuracy as retinal disparity.

DISPARITY MATCHING

In making preliminary observations we noted that the magnitude of displacement in depth seemed to vary smoothly with change in virtual disparity, in much the same way as it does when real disparity changes. The next experiment was designed to measure depth displacement due to virtual disparity by matching a strip of the background, having real disparity, to the depth of the binocularly delayed target on a traverse in one direction. We make use of the fact that Julesz's random dot stereogram technique (1960) can be extended to dynamic random noise of the kind we use to form our background (Ross and Hogben, 1974).

Method

Here the method of adjustment was used. As in the two previous experiments, a target dot appears to move across a field of noise, except that now it sweeps always in one direction, left to right, on successive sweeps. Using a method described by Ross and Hogben (1974), a sharply defined horizontal strip of the background is made to appear to stand on a plane in front of the rest of the background, by plotting individual points within the strip so that each has a true horizontal disparity. The observer's task was to adjust the disparity of these points until the plane of the strip coincided with the plane of the moving target. Observers were unaware of the virtual disparity of the target and the true disparity of the strip.

They pressed response buttons which increased or decreased true disparity, relying solely on their perception of the strip as advancing toward them or receding from them as they did so.

Spatial disparity could be varied only in discrete steps of 1.6′ of arc, corresponding to the 256 grid resolution within a field subtending 7°. Values of virtual disparity were therefore chosen to be multiples of 1.6′ or arc, on the ground that observers might not otherwise be able to find a match. Eleven values of virtual disparity were used: 0′, ±1.6′, ±3.1′, ±4.7′, ±6.3′, ±7.8′ of arc.

The conditions were presented in random order to the observer, who pressed either of two response buttons to increase or decrease strip disparity until a match was found. He then pressed a third button, which alerted the computer to record the match and initiate a new trial.

As in the first experiment Δx was set at 12.5′ of arc and τ at 50 msec. Only one session of 55 trials, five for each condition, was run for each observer.

Results

In every trial of every condition, the selected disparity for the noise strip exactly equalled the virtual disparity of the target. Given the discrete quantization of available disparities into steps 1.6′ of arc apart, the exactness of the match is not revealing, but the results do show that depth varies with virtual disparity in the same way as with true disparity over a considerable range.

DEPTH CANCELLATION

The previous experiment showed that virtual and true disparity match over a considerable range, but the resolving power of the experiment was insufficient to reveal the exactness of the match, since it was limited by quantization of disparity. In this experiment we combine true and virtual disparity, pitting the one against the other. A target is displayed with both a true disparity and a virtual disparity of opposite sign. This is achieved by plotting moving targets at different positions within the stereoscopic fields of view (left eye and right eye) to give disparity, as well as plotting the one before the other, to give delay. The purpose is 2-fold. Firstly we wish to resolve matches between true and virtual disparity more finely. Secondly, we wish to see how true and virtual disparity combine. Does one dominate the other? Or do they combine on a basis of equal potency as cues to depth?

Method

As in the first two experiments reported, the target moved back and forth across the screen. However, in this experiment the target itself is plotted with a true disparity of 4.7′ or arc (a value selected arbitrarily from the range used in the last experiment). This was achieved by displacing the whole sequence of target display points in one eye's field of view. The disparity is negative (uncrossed) when the target moves from left to right, and positive (crossed) on the return journey. Viewed with no binocular delay, the target appears to move clockwise in depth about the

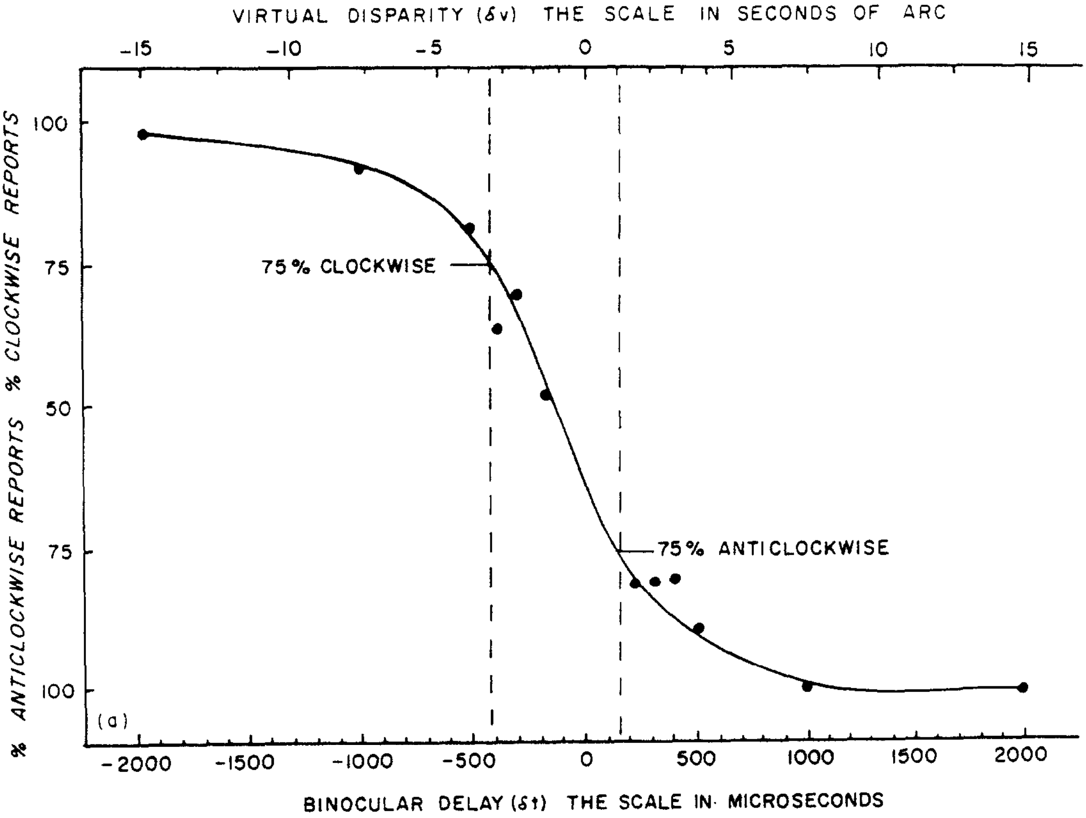

Fig. 4. DR.

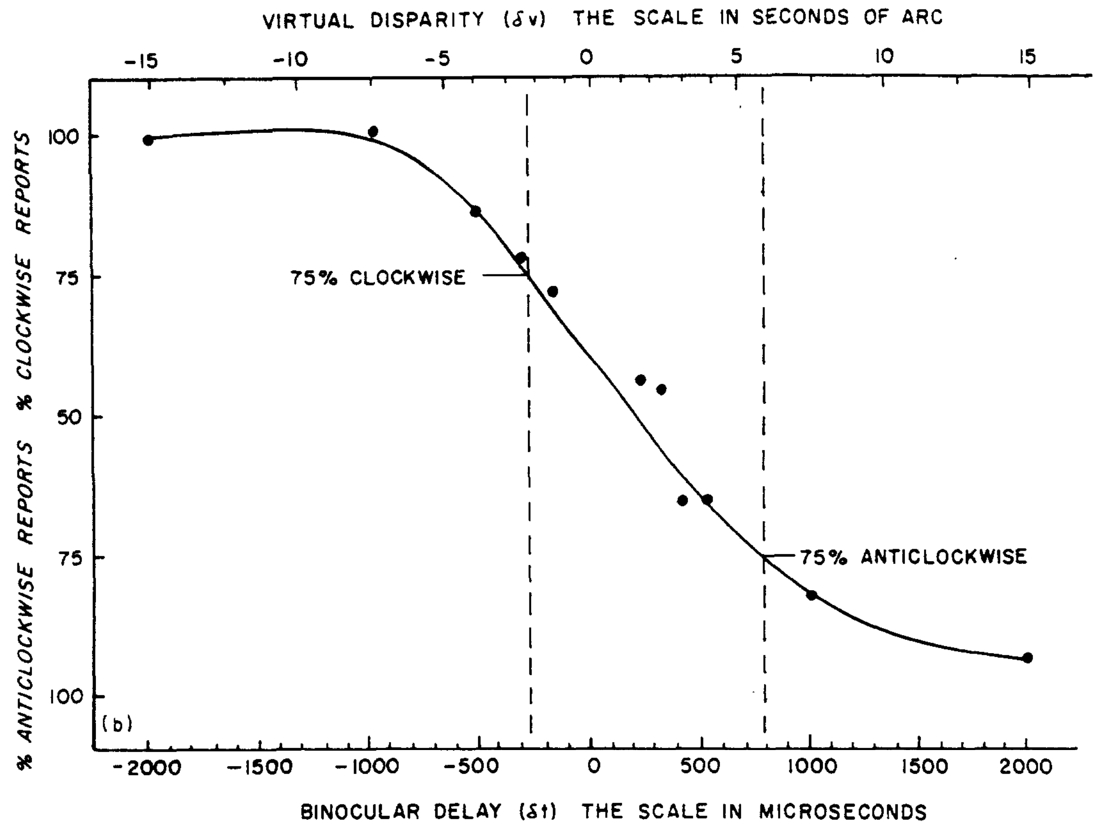

Fig. 4. JH.

Fig. 4. Results of the acuity experiment where the spot moved at a speed of 2.1° sec^{-1}, half that of the previous experiment. The virtual disparity acuities are calculated to be 2.1" and 4.0" of arc for DR and JH, respectively, with corresponding delay values of 280 and 530 μsec. At least for DR, the disparity acuity remained much the same, suggesting a spatial rather than temporal limit.

noise field—in front of it when travelling to the left, and behind when travelling to the right.

A range of 12 virtual disparities was selected (corresponding to delays which varied within a 2 msec range), half less than 4.7' of arc and half greater. Since velocity is fixed ($\Delta x = 12.5'$ of arc, $\tau = 50$ msec, $\omega = 4.2^\circ$ sec^{-1}) the choice of virtual disparities corresponds to a choice of delay values.

All virtual disparities are opposite in sign to real disparities. In the absence of true disparity an observer should therefore report counterclockwise motion, on the basis of the results of earlier experiments. True and virtual disparity therefore have opposite effects. Given the combination of a true disparity of 4.7' of arc and an unknown virtual disparity, greater or lesser in amount, observers were required to report whether the motion they saw was clockwise or anticlockwise.

Results and discussion

Figure 5 shows the percentage of clockwise and counterclockwise reports plotted against virtual disparity, for the two observers DR and JH. The curve closely resembles that shown in Fig. 3, which describes acuity results, except that it is centred about 282" of arc (4.7'), not zero.

The 75% response rate points are shown in Fig. 5 as broken vertical lines. Within the range they enclose, observers are uncertain as to the direction of motion of the target, which implies that they saw it in the plane of the background, or not separated clearly from the plane of the background. Since this region straddles 4.7' of arc, the true disparity of the target, we can conclude that a virtual disparity exactly cancels a true disparity of the same magnitude. In other words, virtual and true disparity have exactly the same kind of effect, as is suggested by the quality of depth perception in both cases, and by the findings of the previous experiment.

Whereas Fig. 3 gives evidence about absolute acuity for virtual disparity or delay, Fig. 5 can be interpreted in terms of discriminative acuity, where the observer is required to discriminate a true disparity from a virtual disparity of the opposite sign. Acuity is 3.5" of arc for DR and 4.1" of arc for JH. These values are slightly higher than the absolute acuity values at the same target velocity.

DISCUSSION

The displays used in these studies rely on binocular delay for the stereoscopic illusion of depth, except when true binocular disparity of a conventional kind is also introduced for comparison. Otherwise there is no disparity in the positions at which targets appear in the fields of view of the two eyes, as they step along in stroboscopic motion. All that differs is the time at which the two eyes are afforded a glimpse of the target at each step of the stroboscopic sequence. One eye's view is slightly delayed with respect to the other's. Except for this slight delay, both eyes view exactly the same sequence, against identical backgrounds made up of dynamic noise points.

We find the same vivid sense of depth when the observer is confronted with binocular delay as we do with binocular disparity. Stereopsis, that is to say, accepts delay as just as natural and potent an indication of depth as it does a true binocular disparity, when targets are seen as moving. So much was known before, or at least strongly suggested by the findings of Morgan (1975). The point about the findings reported here is that binocular delays are direct, not achieved by dimming, and that they are small in comparison with the period of the stroboscopic sequence which gives rise to the illusion of smooth motion. The period of the sequence is typically 50 msec. The target, that is to say, appears briefly to each eye once every 50 msec, each time in a new position. Delays are typically much smaller, often 1 msec or even less. Since virtual disparity is equal in magnitude to the product of binocular delay (δt) and velocity of stroboscopic motion, which in turn is given by the step size of the sequence (Δx) divided by the period (Δt), it follows that virtual disparity (δv) is small in proportion to the step size of the sequence. In fact the ratio $\Delta x/\delta v$ is equal to the ratio $\Delta t/\delta t$.

The very disproportion between virtual disparity and the step size of the sequence means that we must reject, as an explanation for our findings, the conventional explanation for the Pulfrich effect. When targets are viewed in true motion, they will stimulate all available retinal sites along the projection of their path of motion. If one eye's view is delayed either directly or by light attenuation (however slightly), then the target as viewed by one eye will fall, at every instant, on one site while, at the very same time, the target as viewed by the other falls on a different site; one, that is to say, associated with a different visual direction. Hence, in the case of true motion, a binocular delay, however slight, is associated, by virtue of the very continuity of motion, with continuous binocular disparity.

Stroboscopic motion is discrete, not continuous. The target in these studies jumps several minutes of arc between its brief appearances. When there is a binocular delay then at the instant the target is displayed to one eye, no target is ever displayed to the other eye. There is no intermediate position at which the delayed eye views the target at the same time as the non-delayed eye views it at any stage of the stroboscopic sequence. Thus the conventional explanation for the Pulfrich effect, which relies on simultaneous stimulation of the two eyes at two different sites, cannot apply in this case.

Because of the discontinuous structure of the stroboscopic sequence one might well expect that each site stimulated in one eye would be paired with another in the other eye, the one stimulated most nearly in time. If so, there should either be no effective disparity, if binocular delay is very much smaller than

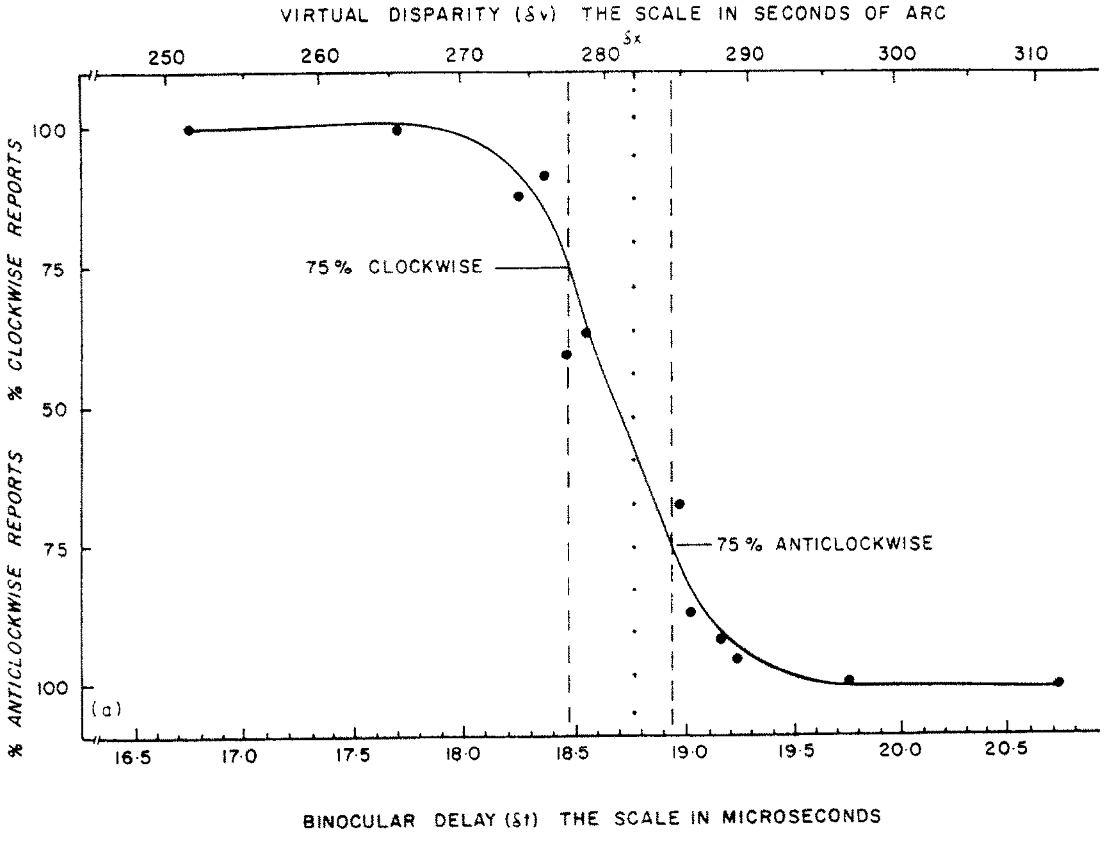

Fig. 5. DR.

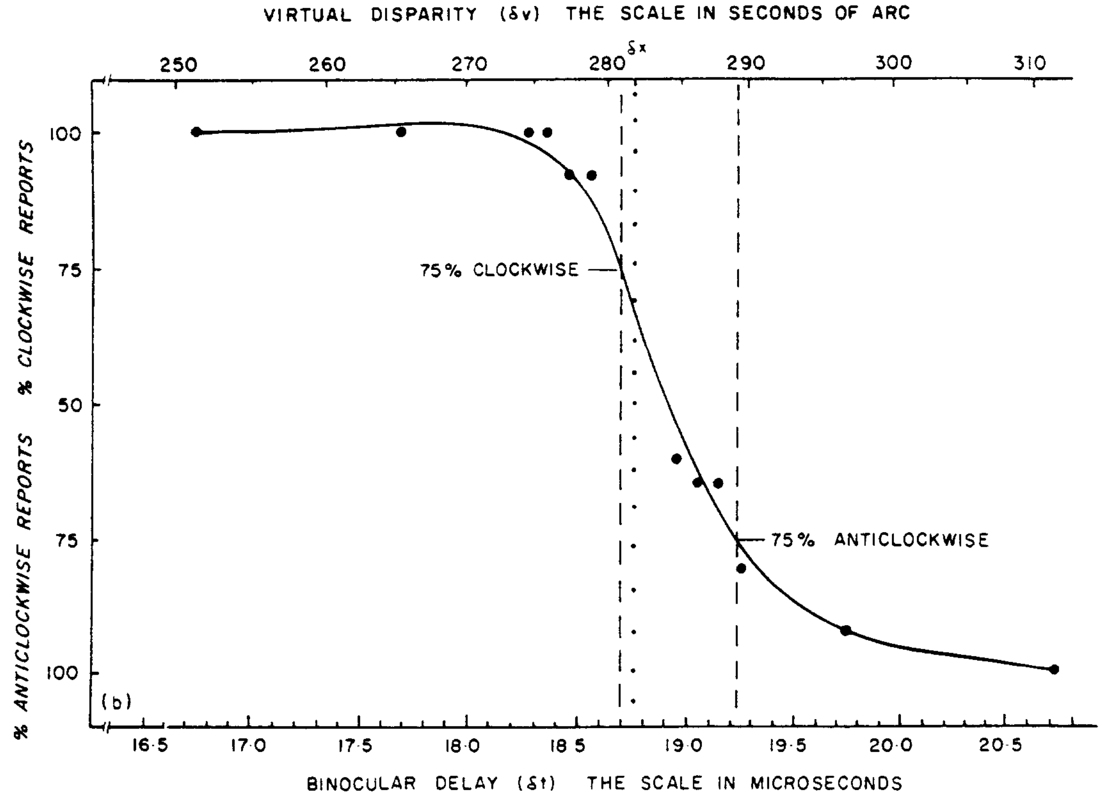

Fig. 5. JH.

Fig. 5. These curves plot the results of the depth cancellation experiment. The dotted line passes through 282" of arc (4.7'), the value of the spatial disparity present. For both subjects this line falls inside and near the middle of the 75% criterion lines. The acuity for depth cancellation is 3.5" and 4.1" of arc for DR and JH, respectively.

the period of the sequence, or an effective disparity equal to the step size of the sequence, if delay is half the period of the sequence, or more. We find, however, that effective disparity always equals our calculated virtual disparity, even for very small binocular delays, which means that disparity changes smoothly with delay. Differential depth can be detected when delay is 200 μsec or less, or when it is about ¼% of the period of sequence.

Under conditions where smooth motion is perceived, though motion is in fact stroboscopic, virtual disparity behaves exactly like true disparity. We find: (i) acuity for virtual disparity is about 2" of arc, which is in good agreement with established values for disparity; (ii) the depth of a moving target is matched exactly to the depth of a background when the virtual disparity of the target agrees with the disparity of the background; (iii) virtual and true disparity of the moving target cancel one another exactly when they have the same magnitude but are opposite in sign.

Virtual disparity so exactly mimics actual disparity in giving the same vivid sense of depth and in the three respects listed in the previous paragraph that one must suspect that delay is somehow converted to disparity. Are eye movements the mechanism of conversion? If both eyes pursue the apparently moving target, so as to centre the target on each retina each time it is displayed, background points will fall in disparate retinal positions in the two eyes. Alternatively, if both eyes are locked to a common track, the background points will be in correspondence, but the targets will not, since the eye subject to delay will have moved by the time its target appears, so that the target will exhibit disparity on each step of the sequence. Disparity due to eye movements will, however, match calculated virtual disparity only if pursuit velocity of both eyes corresponds exactly to target velocity. The cancellation experiment shows that virtual disparity exactly cancels true disparity of the same magnitude, with a discriminative acuity of 3.5" of arc for the best observer. If eye movements are to translate delay into disparity with this accuracy, they must tolerate a retinal slip of 3.5" of arc per msec (the delay which gives a virtual disparity of 4.7' of arc). Retinal slip velocity cannot then exceed 3.5" of arc per 19 msec, that is 0.5°/sec, which means that eye movements must match target motion to an accuracy of 99% if disparity due to eye movements is to explain our results.

Such accuracy is suspiciously good, particularly bearing in mind that the target is displayed to each eye only once every 50 msec, at steps typically 12.5' of arc apart, which removes the opportunity for continuous servo-correction of pursuit movements from image slip on the retina. The movement control system has only periodic opportunities for correction. We are therefore forced to consider other explanations for our findings, while not entirely rejecting the possibility that eye pursuit is more accurate than has been suspected. Indeed, some might be tempted to exploit our methods as a means of measuring eye movements indirectly, rather than by direct means. We may also note that the moving targets appear to stand out in depth, away from the background, when the observer fixates. As we could not be absolutely sure that the eyes were always stationary when observers fixated, we observed short stroboscopic sequences, made up of only seven steps, with a period of 25 msec. These sequences are complete in 150 msec, which is too short a time to allow eye pursuit movements to catch the sequence (Westheimer, 1954). Depth is nevertheless observed, the target appearing to move on a path in front of, or behind the background, depending upon the sign of its virtual disparity. Thus, though eye movements may possibly convert delay to disparity when they do occur, they are not necessary for a target with virtual disparity to appear to move in depth. Of course, since all measurements reported here were made with the eyes free to move, we do not yet know acuity for virtual disparity, nor how closely virtual disparity mimics true disparity, in the absence of eye movements.

Though the eyes need not move in order for depth to be perceived by virtue of binocular delay, the target must appear to move, and to move horizontally. If the step size of the sequence is set to zero, so that the target appears repeatedly in the same position, no shift in depth is observed at any delay. This might be expected since the target's velocity is now zero, and, consequently, its virtual disparity is also zero. If the target moves vertically, not horizontally, there is again no shift in depth at any binocular delay. Once again, since there is no horizontal component of motion, there is no binocular disparity in the horizontal.

Under the conditions of our experiments motion that is stroboscopic looks smooth. Vision therefore fails to distinguish the discrete case from the continuous. When this occurs a delay is handled as if it were a disparity. We can therefore state the conditions under which delay and disparity will be treated as equivalent. We are left with a question: what is the mechanism which makes them equivalent? Undoubtedly the answer will emerge when we have a clearer understanding of how it is that vision analyzes motion.

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