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Apparent motion and the Pulfrich effect

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Abstract. The Pulfrich pendulum effect, obtained by viewing a moving object with a filter over one eye, was examined with target stimuli in apparent, rather than continuous, motion. The filter-induced depth effect persisted until a certain degree of intermittency in the presentations of the target was reached, and then it broke down. The degree of intermittency that could be tolerated before the depth effect broke down increased with the density of the filter. It could be argued that the filter determined a shift in the pairing of successive inputs to the eyes, such that the target position in the unfiltered eye was fused with the preceding target position in the filtered eye. However, it appears that the shifted-pairing effect cannot account for the depth impression seen when the target intermittency is less than about 30 ms. Below this value of intermittency a filter can produce a depth effect even when the delay it introduces is small in comparison to the intermittency of the input. The depth effect seen with intermittencies less than 30 ms appears to be of the same magnitude as that obtained with stimuli in continuous motion. It is concluded that a filter can cause two different kinds of depth shift with apparently moving stimuli.

1 Introduction

When a moving target is viewed with a neutral-density filter over one eye, it appears displaced in depth. If the target is oscillating like a pendulum, it appears to move in an elliptical path, the direction of rotation being clockwise (as if viewed from above) if the filter is over the left eye, and anticlockwise if it is over the right eye.

Pulfrich (1922), with whom the pendulum effect is generally associated, credits to Fertsch the suggestion that the effect arises because the filter imposes a delay in the transmission of signals by the filtered eye. If Fertsch's explanation is correct, it ought to be possible to cancel the effects of a filter by imposing a physical lag on the signals going to the uncovered eye, and this can in fact be done (Rogers and Anstis 1972). Further evidence for the lag hypothesis has been provided by Lee (1970a) and by Julesz and White (1969). For these reasons, and because there is no strong contrary evidence, Fertsch's hypothesis has commanded general acceptance.

Both Lee (1970a) and Julesz and White (1969) demonstrated that a filter-induced lag could determine which of several possible pairs of stimuli between the eyes were actually fused. Julesz and White used film strips to present a succession of random-dot patterns separately to the two eyes. Successive frames in the same eye were uncorrelated. However, each frame in one eye correlated with a frame in the other eye in such a way that if the correlated frames were presented at the same time, or with not too great a delay between them, they were fused to give an impression of a central figure. If the correlated frames were too much out of phase, on the other hand, the impression of depth was lost, presumably because the correlated frames were no longer fused. In these circumstances a neutral-density filter placed in front of the 'leading' eye could restore perception of the central figure. This is convincing evidence that a filter produces a lag in reception of signals by whatever mechanisms are responsible for stereoscopic fusion of stimuli from the two eyes.

Figure 1a shows how the lag hypothesis can explain the Pulfrich effect. The filtered eye signals an earlier target position than does the unfiltered eye, and there is thus at any one moment a spatial disparity, which causes a continuously-varying shift in the perceived depth of the moving target. Figure 1b shows a more abstract representation of the same state of affairs. The path of the target in each eye is shown by a sinusoidal curve relating distance and time. To determine the position of the target as signalled by the two eyes at a given moment in time, a 'temporal cross section' of the figure should be drawn by making a vertical line, as in the figure. The vertical line crosses the curves for the two eyes at different heights, that is at different spatial positions.

But it is equally possible to make a spatial cross section of the figure, by drawing a horizontal line across it. This horizontal line intersects the two curves at the same height, but in two different temporal points. The interpretation of this is that the target is signalled from corresponding points in the two eyes at different times. We shall term this difference a *contiguous temporal disparity*, by analogy with the term *simultaneous spatial disparity* which describes the state of affairs normally thought to explain the Pulfrich effect. The question we now wish to pose is whether there is any reason to favour a spatial over a temporal interpretation of the phenomenon, and whether we could ever hope to distinguish between them.

The spatial interpretation of the Pulfrich effect has been overwhelmingly favoured because there is abundant evidence that depth can be seen in static spatially-disparate displays, but no really good evidence that merely temporal differences between the eyes are important. There is no reason in principle, as Ross (1974) has pointed out, why temporal cues should not be useful in normal vision: but attempts to demonstrate their importance have not resulted in any clear conclusion (Ross 1974; Wist 1970). Therefore, if contiguous temporal disparity is to be implicated in the Pulfrich phenomenon, it must be on the basis of evidence that rules out the equally, if not more, plausible spatial interpretation.

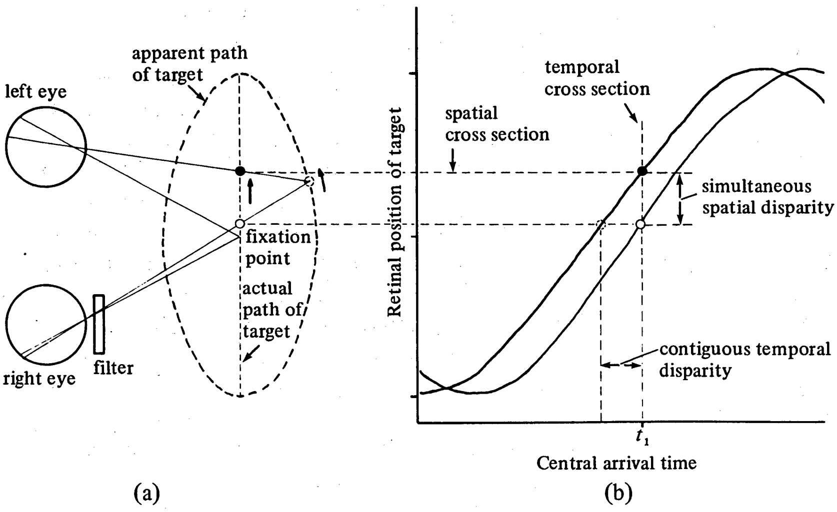

Figure 1. A conventional representation of the Pulfrich effect (a) and a Cartesian representation (b). Part (a) shows the apparent direction of the target in the two eyes at a particular moment, t_1. Part (b) shows the change in apparent direction of the target in the two eyes over time. The vertical line at t_1 (the temporal cross section) in (b) represents the same state of affairs as (a). It is also possible to draw a horizontal spatial cross section through the curves in (b); this corresponds to a single spatial position in (a) (as shown by producing the line) and to two different times in (b). The point of this spatio-temporal representation is to demonstrate that there are two ways of describing the filter-induced lag: by the spatial difference in temporal cross section, or by a temporal difference in a spatial cross section.

A test case can be arranged by using a target in apparent (stroboscopic) motion. If the stimulus for perception of movement is a series of successive spatial positions, a spatial disparity can occur only if the filter introduces a sufficient lag to cause central fusion of nonsimultaneous inputs to the eyes. To do this, the filter-induced lag would have to be at least half of the temporal interval between successive flashes to the same eye (the interflash interval, τ). We have attempted to explain this reasoning in figure 2, which represents four different cases of intermittent presentation, with a fixed value of filter-induced lag. In this diagram a dot on the curves represents the spatio-temporal coordinates of a particular target presentation; the curves themselves represent the locus of points at which the target could actually appear. In each pair of curves the right-eye curve is displaced to the right of the left-eye curve to indicate that the right eye has been filtered. The lag is equal to the horizontal separation between the members of a pair of curves, as in figure 1b. For simplicity the curves are shown as linear rather than sinusoidal; this does not affect the argument. The question to be asked about these curves is: which pairs of points will be paired between the eyes, and how will this affect perceived depth? Four cases are illustrated; in (a) the interval between target presentations, τ, is small with respect to the filter-induced lag; in (b) τ and the lag are equal; in (c) τ is slightly longer than the lag; and in (d) τ is more than twice the lag.

Lee (1970a) has suggested that the rule for pairing between discrete stimuli in the two eyes is that fusion occurs between the most-nearly simultaneous stimuli. In other words, we can find out what pairing will occur in figure 2 by drawing a vertical line through the point in one eye, and seeing which point in the other eye is horizontally nearest to it. In cases (a) and (b) this line actually passes through spatially disparate points, and it may confidently be predicted that depth will be seen in these displays if Lee's pairing rule is correct. The situation in (c) is a bit more complicated, since there are no exactly simultaneous points to be fused: but the most nearly simultaneous points are spatially disparate, so depth ought to be seen in this case as well. In (d), on the other hand, the most-nearly simultaneous points are not disparate, so there should be no depth seen in the display.

We may predict, then, that as the interflash interval τ progressively increases, the depth effect will eventually break down, and that this point of breakdown will increase as the filter is made more dense, i.e. as the lag increases. There may be a range around τ equal to twice the filter-induced lag where the display is ambiguous; there should be no depth effect when τ is greater than twice the lag. Lee (1970b) has already explained this last prediction, and has presented data that fail to support it.

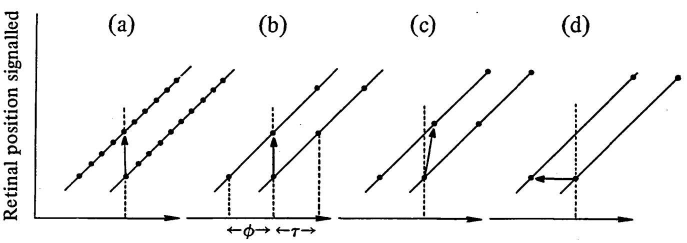

Figure 2. Representation of four possible relationships between a fixed phase difference, ϕ, and a variable interflash interval, τ. Each point on the lines represents the spatio-temporal coordinates of an actual target presentation. The line on the left in each pair is for the left-eye signal, the line on the right is for the right eye; the horizontal distance between the two lines represents the phase difference. The horizontal distance between points on the lines represents τ. The four cases shown are: (a) $\tau < \phi$; (b) $\tau = \phi$; (c) $\phi < \tau < 2\phi$; (d) $\tau > 2\phi$ (the most-nearly simultaneous inputs are now the most-nearly spatially contiguous).

However, the depth effect he observed with his intermittent display was so weak that he felt justified in concluding that it was not a true Pulfrich effect at all. We have pursued this point in detail, by examining the effects of different interflash-interval/filter combinations. Subsequent experiments in this series were aimed at establishing the generality of effects seen in the first experiment, and at setting up crucial tests of various hypotheses.

2 Terminology

We measured the *filter-induced lag* in these experiments by introducing a *signal phase difference* between the two eyes. It is important to bear in mind the distinction between the hypothetical filter-induced lag, and the procedure we used to measure it. The *signal phase difference* was arranged by presenting a target in sinusoidal horizontal motion to one eye, and to the other eye a target that was out-of-phase with the first by a certain amount (which can be expressed equivalently in degrees of phase, time, or spatial discrepancy). When the displays were intermittent the targets were always flashed to the two eyes *at the same time*, i.e. there was no *interocular delay*. If inputs to the eyes were out-of-phase in an intermittent display, this meant that when they occurred, they were in different spatial positions. It must be made clear, that when we express a phase difference by a temporal measure (ms) we do not mean that the inputs to the eyes were presented at different times. Rather, we mean that when the targets were presented, they occurred in different places, and that it would have taken the spatially trailing target that time to catch up with the leading target. The interval between successive target presentations to the same eye is the *inter-flash interval*, τ.

The logic of using a signal phase difference to cancel out a hypothetical filter-induced lag, is illustrated in figure 3. If the filter-induced lag had led to a depth effect by causing central fusion of retinally disparate stimuli, then the depth effect can be removed by ensuring that the stimuli that are fused are no longer disparate. If, as must be the case if only retinal disparities are involved, pairing is taking place between stimuli separated by the distance the target 'travels' during the interval τ, then to make these stimuli nondisparate we shall have to move the leading one backwards through τ ms. In other words, we have to arrange that retinally simultaneous stimuli are disparate, in order to ensure that *centrally* simultaneous

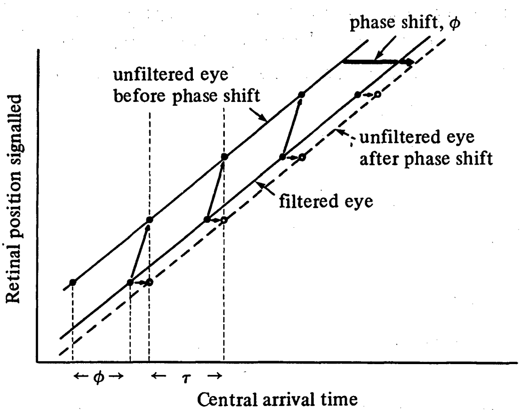

Figure 3. An illustration of how the phase difference between inputs to the two eyes may be used to cancel the filter-induced lag. The top curve for the unfiltered eye shows the state of affairs before the cancelling phase shift is introduced. The most nearly simultaneous central inputs from the two eyes are spatially disparate: the hypothetical pairing is shown by the oblique arrows. The broken curve shows the state of affairs after a phase shift equal to τ. Centrally simultaneous points are now nondisparate, as indicated by the fact that the arrows are horizontal.

events are nondisparate. Thus, when τ is longer than the filter-induced lag, as in figure 3, the necessary cancelling signal phase shift is exactly equal to τ itself. When τ is smaller than the filter-induced lag, the cancelling phase shift will be an integral multiple of τ, as may be verified by drawing the appropriate versions of figure 3.

3 General methods

Displays were generated on the cathode-ray tube (CRT) of a Tektronix 502A dual-beam oscilloscope, turned on its side so that inputs to the y axis deflected the beams horizontally. A high-frequency signal was fed to the x axis so that targets appeared as bars about 1 cm high. A Feedback Instruments TWG 500 variable-phase function generator was used to drive the targets horizontally. Intermittent presentation of targets was achieved by driving them off-screen between presentations, using for this purpose a second input from solid-state timing circuits to the second input of the amplifiers, which were operated in the differential mode. Presentations were approximately 1 ms in duration. Movement of the left-eye target was controlled by the reference output of the TWG 500, and movement of the right-eye target by the variable-phase output. The targets were horizontally separated by 6 cm on the screen and were fused with the aid of a Duval stereoscope placed 10 cm from the screen. The signals were 1·0 Hz sinusoids, 11 deg peak to peak; mean velocity was approximately 22 deg s^{-1} and a 1 ms phase difference was equal to a mean disparity of about 1·32 minutes of arc subtended at the eye. The phase differences were calibrated by an Advance timer-counter.

Differential filtering of the eyes was achieved by crossed-Polaroid filters in front of the eyes and a rotatable sheet of Polaroid (HN 32) in front of the CRT. The angle of the rotatable Polaroid sheet was read from a protractor permanently fixed to the lower half of the screen.

In different procedures, either the observers used the phase control on the function generator to 'flatten' out the path of the apparently elliptically-moving target; or the experimenter made an adjustment and the observer had to say 'clockwise' or 'anticlockwise'. The graticule light was always lit to provide visual context, and disparities were adjusted so that when the target was seen to rotate in depth it orbited around the fixation point which was the intersection of a horizontal and a vertical graticule line. A dim ceiling light permitted the experimenter to make adjustments and read notes. Relative luminances of the targets in the two eyes were equated by ensuring that as the absolute luminance increased the two targets reached threshold simultaneously. The absolute luminance was then set to make the targets just visible at a standard filter density.

The observers were the authors and (in different experiments) two visitors (CM and HR) to the Psychological Laboratory. Instructions were to fixate as steadily as possible; 'tracking' of the target was expressly forbidden.

4 Experiment 1

4.1 *Method*

In this preliminary study, observers attempted to adjust the phase control on the function generator until the apparent path of the sinusoidally oscillating line was flat. Different combinations of interflash interval τ and filter density were used, at least five settings being made at each combination (in cases of variability sometimes more were taken). As far as possible each subject was tested every day until the series of observations was complete. A single daily session lasted for $1-1\frac{1}{2}$ h; with occasional exceptions the filter density was not changed inside a session. To remove variability due to progressive dark-adaptation (Standing et al 1968) there was a 5 min 'warm-up' at the start of each session in which the observer looked at the screen but did not make settings. The observers were the authors; results were checked with observations at two filter values by a third subject (HR) who did not know the purpose of the experiment.

4.2 *Results*

The results for the three subjects are given separately in figure 4. Each point represents the median of at least five settings; variability tended to increase with τ, as illustrated by the data for one subject in figure 5.

The data show that with a continuously-presented target ($\tau = 0$) there was a clear depth effect at all values of the filter investigated. To make the path of the target apparently flat, phase differences of up to 60 ms had to be put in opposition to the filter. When the interflash interval was increased, judgements first of all become more variable (figure 5) and then finally the impression of depth broke down. This occurred long before the impression of motion disappeared. The point at which depth broke down depended on the filter density; longer interflash intervals could be

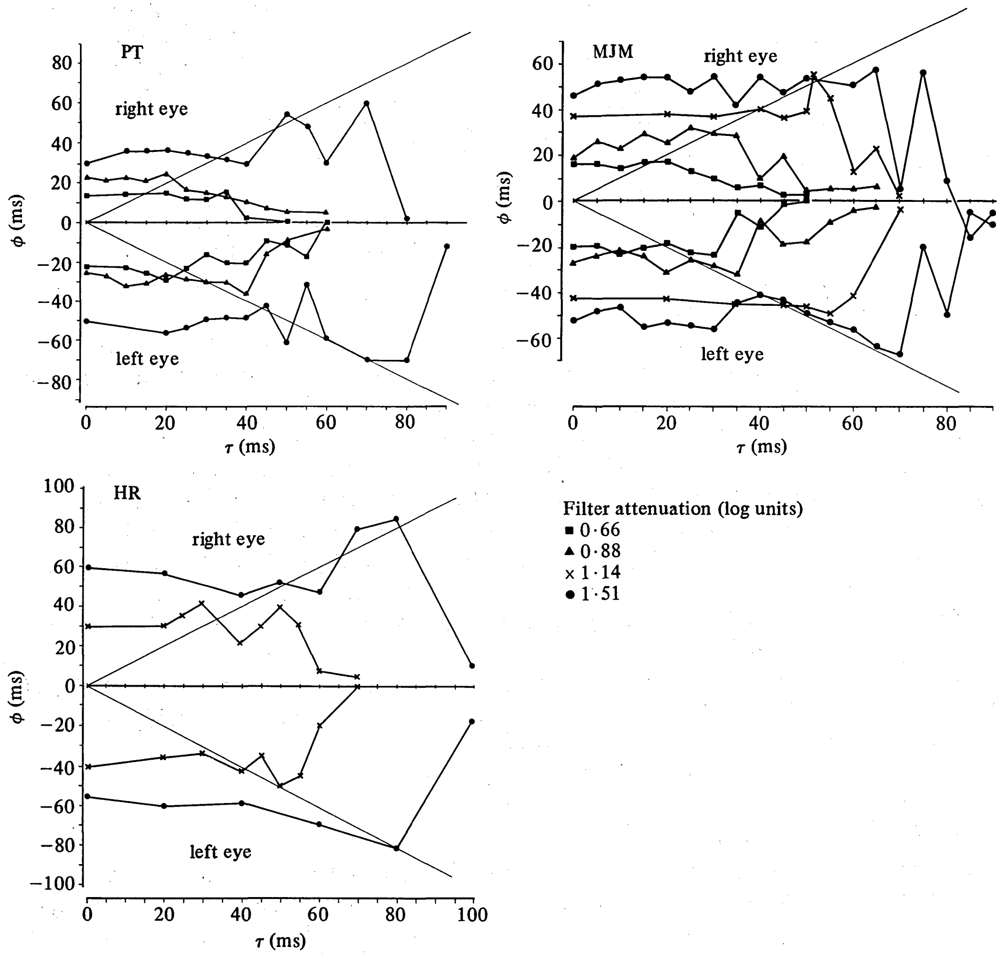

Figure 4. Results for three observers (PT, MJM, HR) in experiment 1. The observer's task was to select a phase difference, ϕ, in the signals going to the two eyes, such that the depth effect due to a filter over one eye was cancelled. The value of the filter (in log units) is shown as a parameter on the curves; for curves in the top half of the figure the filter was over the right eye, for curves in the bottom half it was over the left eye. Each point represents the median of at least five settings; each series of settings was made at a different interflash interval τ. The diagonal lines show the expected relationship if ϕ is set by the observer to be equal to τ.

tolerated with denser filters. Up to the point of breakdown, the function relating magnitude of depth (i.e. magnitude of cancelling signal phase shift) to τ is tolerably flat, except that there is some tendency for it to rise just before it breaks down (see particularly for HR, 10 deg, right-eye, and for MJM, 10 deg left-eye).

4.3 *Discussion*
If the logic summarised in figure 2 is correct, we can make the following predictions about the effects of the interflash interval and filter density:
Prediction 1: The filter-induced depth effect should break down when the interflash interval is double the lag produced by the filter. Therefore:
Prediction 2: The greater the lag (i.e. the denser the filter) the greater the interflash interval that can be tolerated before the effect breaks down.
Prediction 3: Up to the point where the interflash interval is the same length as the filter-induced lag the size of the effect should be constant; thereafter it should increase linearly with the interflash interval until it finally breaks down (see figure 3).

Qualitatively, these predictions fare quite well; quantitatively they are not very accurate. Consider, for example, the data for HR, 1·14, left eye (figure 4). The phase shift needed to cancel depth at $\tau = 0$ was 40 ms, and we would be justified in taking this as the best measure of the lag induced by the filter, since it is uncontaminated by considerations of 'alternative pairing'. Thus we predict that the size of effect should be approximately constant as τ is increased up to 40 ms, and then increase up to an asymptote at $\tau = 80$ ms, at which point it should break down. The last prediction is very obviously in error, as it is in nearly all the functions plotted in figure 4; for the fact is that the effect breaks down considerably too soon. The other predictions are more difficult to assess. Constancy of the effect up to $\tau = \phi$ cannot be refuted by the data; and in some of the functions, but by no means in all, is there evidence for an increase in the effect when τ is greater than the phase lag; but, particularly with respect to the last point, the evidence is inconclusive. Further evidence will be presented in experiment 2.

Why is the point of breakdown less than that predicted by Lee's pairing rule? We are reluctant to abandon the 'alternative pairing' hypothesis entirely, for we have no better explanation of the fact that the point of breakdown does depend upon the density of the filter. A different version of the rule that would fit with our data is

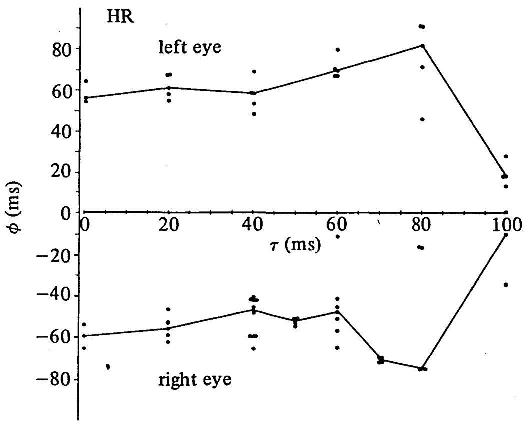

Figure 5. Individual settings made by HR in experiment 1 with a filter of 1·51 log units attenuation in front of the right eye (top of figure) and the left eye (bottom of figure). Each point represents a single setting: note that settings become more variable at the higher values of τ. Other conventions as in figure 4.

that pairing is not determined by purely temporal considerations, as Lee has suggested, but by a combination of temporal and spatial factors. In diagrams such as those in figure 2 we can refer to an 'interval' between events, which is measured by the scalar quantity of the space–time vector joining these events. Suppose that pairing is determined by the interval between events, not just by the scalar of the time vector as Lee suggested. We shall assume that when two intervals are the same, pairing is ambiguous; when they are unequal, the pairing with the shorter interval is chosen. Quantitatively it is not possible to offer any precise predictions, since the scaling of space and time axes is arbitrary; indeed, only by making assumptions such as those we have outlined, and then working back from the measurements, could a suitable equivalence between spatial and temporal vectors be established. All we would wish to suggest at present is that Lee's rule is too simple. With the proposed modification we can account for the major finding that the point of breakdown depends upon filter density, without being subject to the criticism that 'alternative pairing' does not imply breakdown in depth until τ is twice as great as the phase lag.

There remains, however, the problem that quantitatively the functions are not a particularly good fit to the predicted relationship between the cancelling phase shift and the interflash interval. A possible reason is that the present method of measurement is not appropriate. Where there is possible ambiguity in pairings, the observer may well choose different alternatives on different occasions. The increasing variability as we get nearer the point of breakdown indicates that something of the sort may be happening. To take a median as an expression of trend may be misleading; the proper procedure would be to obtain a psychophysical function relating probability of a clockwise judgement to the phase difference between the eyes. That was the aim of the next experiment.

5 Experiment 2

5.1 *Method*

The apparatus was the same as in the previous experiment. The only difference in procedure was that the subjects, instead of adjusting the phase difference between the eyes themselves, made judgements on settings made by the experimenter. The phase dial was set to a certain value and the observer had to say whether the resulting display was "clockwise" or "anticlockwise". At each interflash interval the experimenter first of all presented a wide range of phase settings to obtain an idea of the region or regions in which the subject was indifferent between the two kinds of judgement, and then made further readings inside these regions. A pseudo-random sequence of settings was employed to equate the momentary probabilities of 'clockwise' and 'anticlockwise' responses. At least ten readings were made at each of the data points to be presented, unless the contrary is specifically mentioned. With 1·14 log units of attenuation in the left eye, the values of τ of 20 and 80 ms were used to obtain two different psychophysical functions. The observers were MJM and PT (who tested each other) and one other, CM, who did not know the purpose of the experiment until later.

5.2 *Results*

Figure 6 shows the percentage of 'clockwise' judgements made at phase differences, ϕ, varying from -11 ms (clockwise) to 88 ms (anticlockwise) and at two different interflash intervals ($\tau = 20$ ms and $\tau = 80$ ms). The functions at $\tau = 20$ ms were very regular; judgements changed from 100% 'clockwise' to 100% 'anticlockwise' in a range of 8 ms even in the least practised subject (CM). The functions at $\tau = 80$ ms are much less regular and seem to show two major indifference regions, one around

$\phi = 0$ ms and the other around $\phi = 80$ ms. The indifference point at $\tau = 20$ ms is 44 ms (mean of 3 subjects; $\sigma = 5 \cdot 3$ ms).

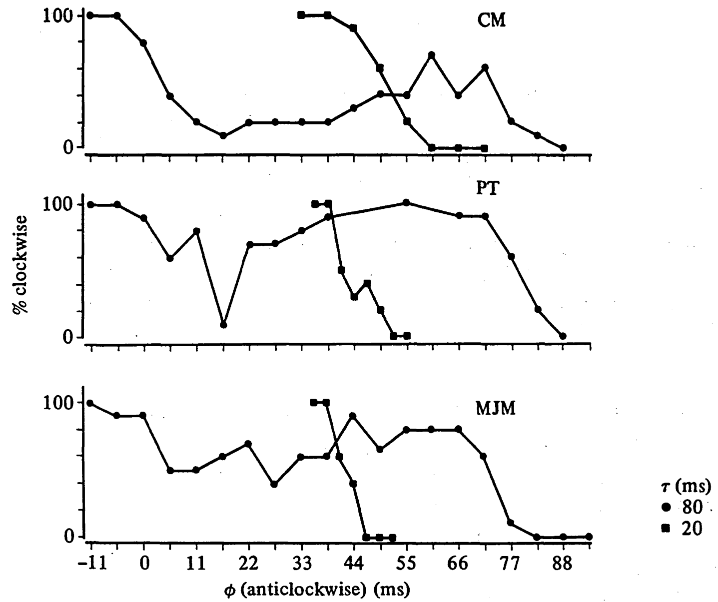

Figure 6. Psychophysical functions for three observers in experiment 2, relating probability of seeing the display 'clockwise' (ordinate) to the experimenter-set phase-difference, ϕ, between the inputs to the two eyes (abscissa), with $1 \cdot 14$ log units of attenuation in the left eye. The two curves for each subject are for different interflash intervals, τ. For further explanation see text.

5.3 *Discussion*

The bimodal function with $\tau = 80$ ms can be accounted for by the 'alternative pairing' hypothesis. We assume that the filter-induced phase lag is about 40 ms, which was the value found with the shorter interflash interval, and which was also (data not presented here) the value found at $\tau = 0$. This means that at $\tau = 80$ ms the signal from the filtered eye will fall between signals from the uncovered eye. According to the ideas presented earlier, fusion should occur between the pairs with smaller spatial disparity. Now the spatial disparity between the two eyes is determined by the phase difference between them. At zero phase difference, simultaneously arriving events are nondisparate; therefore, these should be fused even though arriving centrally 40 ms apart, and the display should be seen as flat. At 80 ms phase difference, however, a target presentation to one eye is nondisparate with respect to the *succeeding* flash in the eye with the phase lag; therefore, these two flashes should fuse and the display again seen as flat. There should thus be one indifference point at zero phase difference and another at 80 ms, as the data seem to show.

We consider next the results with $\tau = 20$ ms. The smoothness and consistency of these functions accords badly with the hypothesis of 'alternative pairing'. However, since the postulated filter-induced phase lag of 40 ms is twice as long as the interflash interval, it is possible that a signal from the unfiltered eye is being paired with the antepenultimate flash in the filtered eye. Alternatively, the depth shift at the shorter interflash interval has nothing to do with 'alternative pairing'. To settle this we examined a critical test case in which τ was still small (30 ms) but the filter-induced phase lag was smaller still. Now, if there is any effect due to 'alternative pairing' it should be cancelled by a phase shift of 30 ms, or by some integral multiple of 30 ms. Any other value, particularly a smaller one, would be inconsistent with 'alternative pairing'. We examined that prediction in the next experiment.

6 Experiment 3

6.1 *Method*

For each of the three observers (PT, MJM, HR) a filter density was chosen such that the phase lag it produced, as measured by the cancelling phase lag at $\tau = 0$, did not exceed 30 ms. Then, using the forced-choice procedure of experiment 2, the indifference point was established when the τ was 30 ms. In addition, it was determined for HR at 35 ms. To remove any possible effects of response bias towards 'clockwise' or 'anticlockwise' judgements, MJM and PT were given a mixture of left-eye-covered and right-eye-covered trials in a session, and the mean of the two functions was taken as the best estimate. Data for HR were taken with right-eye filter only.

6.2 *Results and discussion*

The 'alternative pairing' hypothesis predicts that if there is any depth effect at all with $\tau = 30$ ms, it would require a phase-difference of 30 ms for cancellation. However, as figure 7 shows, the indifference points were at 18 ms (HR), 17 ms (PT), and 8 ms (MJM). The hypothesis is clearly refuted.

The data for MJM and PT further show that the target presented with $\tau = 30$ ms was equivalent to one continuously presented ($\tau = 0$). This strongly argues that whatever causes the depth effect at $\tau = 30$ ms is also what causes the conventional Pulfrich effect. And yet, as we have seen, there is no way of accounting for this effect at $\tau = 30$ ms by retinal disparities. There is simply no 'energy' on the retina corresponding to a periodicity of 17–18 ms, which was the cancelling phase shift for HR and PT.

This does not mean that the 'alternative pairing' hypothesis is wrong for the longer interflash intervals; indeed, the evidence argues very strongly for it. The conclusion is that we have two very different effects to deal with in this situation: one of them is equal in magnitude to the Pulfrich effect sensu stricto, and found at

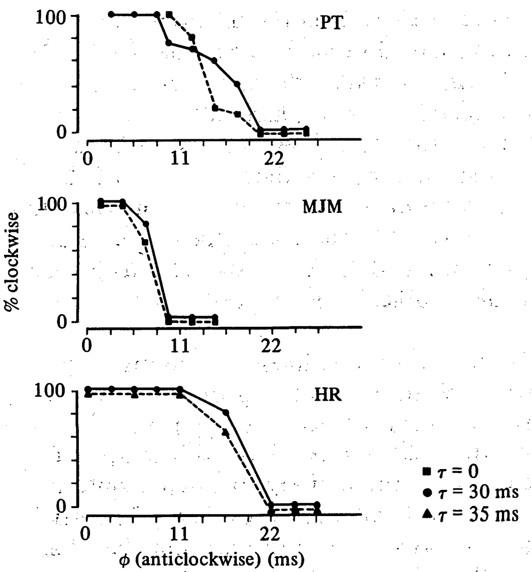

Figure 7. Results for three observers in experiment 3, presented as in figure 6. For HR and PT a 0·88 log unit filter was used; for MJM a 0·66 log unit filter. Other conventions as in figure 6.

interflash intervals at least as large as 30 ms; the other determined by 'alternative pairing', and therefore, equal in magnitude to τ. We do not know at present exactly when the Pulfrich effect gives way to 'alternative pairing'. Some preliminary work indicates that the point of transition is in the region of 30–40 ms, but we should not wish to insist upon this value until further work has been done.

7 Experiment 4

The final experiment in this series provides a check on the generality of the findings. The stimulus arrays were generated on-line by the digital-to-analog converter of a Modular 1 computer, and indifference points were found by a computer-controlled double staircase with a random element.

7.1 *Methods*

The CRO and method of viewing were as in previous experiments. The main difference in the displays was that the frequency was lower (0·8 Hz) and the target lines were of greater luminance. In front of the observer was an array of buttons, two of which were labelled 'clock' and 'anti'. Pressing either of these initiated a trial which consisted of 3 cycles of the waveform, at the end of which the target returned to the mid-cycle point in the centre of the field. The phase difference on each of the staircases was gradually reduced from its starting value of 20 ms until the observer's response changed; then it oscillated around the indifference point depending on the observer's responses. The size of each step was randomly chosen between zero (no change) and 10 ms. Data were collected on a Bryan $X-Y$ plotter.

7.2 *Results*

The plot of an illustrative testing session is shown in figure 8. The session starts with the staircases at their extreme values, and with no differential filtering. The indifference point is around zero phase difference, as would be expected. Then the left eye is subjected to 1·14 log units of attenuation; a new indifference point is found at around 20 ms phase difference (note that this is smaller than the phase equivalent found in previous experiments in this series; the reason presumably is that the targets were of much greater luminance, cf Lit 1949). These settings were established with $\tau = 0$. Next, τ was increased to 60 ms. The result was that the filter no longer produced depth and the indifference point was at or around zero. Finally, τ was reduced to 20 ms, and the depth effect was recovered, although it was more variable than at $\tau = 0$.

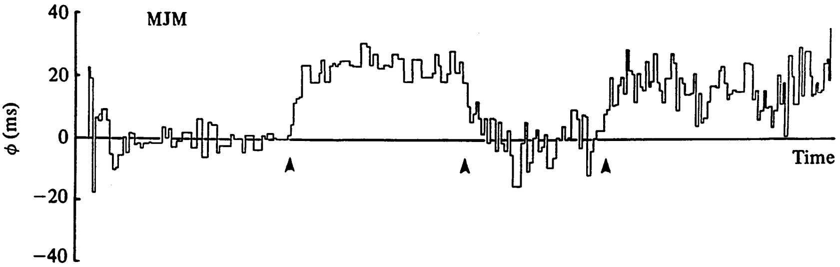

Figure 8. Results of a representative testing session in experiment 4. On each trial the computer generated a phase difference between the inputs to the two eyes, depending on the observers previous responses. At the end of each trial the subject responded 'clockwise' or 'anticlockwise' by pressing a button. Phase differences were determined by a double staircase with random element. At the start of the session neither eye was filtered; then at the first arrow a 1·14 log unit filter was placed over one eye, with continuous target presentation ($\tau = 0$). At the second arrow, with the same filter in place, an interflash interval $\tau = 60$ ms was introduced—the depth effect was lost. Finally, the depth effect was reinstated by changing τ to 20 ms (third arrow).

These data confirm the effects of the interflash interval found in the other experiments. Note that there may have been a second indifference point at 60 ms when τ was 60 ms, but the staircase method was not adapted to find it.

8 General discussion

The conclusions may be summarized as follows:

a. There is a Pulfrich effect even with intermittent target presentation. The magnitude of the effect, provided the intermittency is not too great, is comparable to that seen with continuous presentation.

b. When the target intermittency is increased there comes a point at which the depth effect breaks down; higher levels of intermittency can be tolerated with denser filters.

c. At the higher levels of intermittency there is a depth effect due to 'alternative pairing'; this is revealed by the finding that there are two indifference points, one being at the point where the cancelling phase shift is equal to the interflash interval.

d. At lower levels of intermittency the depth effect seems not to result from alternative pairing, for the cancelling phase shift is not an integral multiple of τ. Instead, it is equal to the value required with continuous target presentation. Presumably this is a true Pulfrich effect.

The 'alternative pairing' effect requires no further comment. We shall concentrate on the depth effects seen in experiment 3, with weak attenuation and $\tau < 40$ ms. Arguments have been presented to show that the depth effect in this experiment cannot have been due to pairing of retinally-disparate stimuli in the two eyes. An alternative explanation is that the temporal lag induced by the filter determined the depth effect per se, without involving an additional retinal disparity. The argument here is that, in normal conditions of viewing, contiguous retinal temporal disparities arise when we view moving objects (or when the eyes are moved). For example, figure 9 illustrates that an object moving from left to right in front of the fixation point stimulates points in the left eye slightly in advance of corresponding points in the right eye, and vice versa when the object is moving in the same direction behind the fixation point. A few simple calculations will convince the reader that the temporal disparities arising in this way are not negligible. Therefore a case can be argued that contiguous temporal disparities are a cue to the relative depths of moving objects. Perhaps a filter in front of one eye, by introducing a delay in the

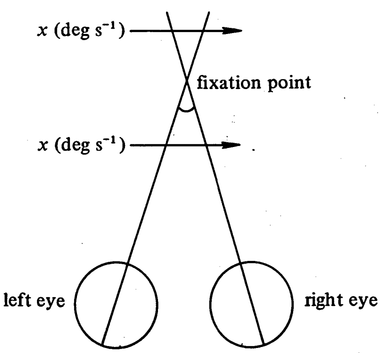

Figure 9. Moving targets stimulate corresponding retinal positions at different times, depending on their position relative to the fixation point. A target moving from left to right in front of the fixation point stimulates points in the left eye before the right, but the same target moving behind the fixation point has the opposite effect. Further explanation in text.

signals arriving from corresponding retinal positions, reproduces the cues that normally result from a target moving in depth.

The trouble with this explanation is its rather ad hoc character, for any further attempt to test it seems to end up as another Pulfrich effect. A word of caution is necessary here. Some attempts have been made to investigate the role of temporal disparities by experiments involving interocular delay in the presentation of stationary targets (Wist 1970; Ross 1974). There is no reason why this should work, since it is only when either the eyes are moving or the target is moving that a phase-difference between the eyes is a cue to depth in normal viewing. As one might expect, the results of these experiments have been difficult to interpret. It is no use trying to overcome this problem by combining *moving* targets with interocular delay, for movement of the target during the delay can introduce a spatial disparity (Mach 1872).

The difficulty of testing the temporal disparity hypothesis means that other explanations should be considered. First, although it is difficult to account for the present data by retinal disparities, it could be maintained that disparities are involved at some other level. Suppose that at the level of convergence between the two eyes (the cyclopean eye) inputs from the eyes arrive not discretely, like the inputs to the retina, but continuously as they would from nonintermittent stimulation. In other words, continuity is somehow restored to the input by the 'filling in' of intermediate points. This has much in common with the gestalt theory of apparent movement, and is open to the usual accusations of naivety and isomorphism. But before dismissing it out of hand, one ought perhaps to ponder the point that at lower levels of target intermittency there was an exact equivalence between the effects of intermittent and continuously-presented targets.

Finally, the possible role of eye movements should be considered. It has been shown by Rogers et al (1974) that movements of the eyes, when they are differentially filtered, can result in a depth shift of stationary cues. Now, the background cues in the present experiment were continuously visible, unlike the target; hence the depth shifts in the target could have been a secondary result of depth shifts in background cues brought about by eye movements. We think that this is unlikely for two reasons. First, the observers in this experiment were instructed not to move their eyes, and when Rogers et al gave these instructions their effect disappeared. Second, this explanation does not predict the complex effects of the interflash interval found in the present experiment. We conclude that temporal disparities are a possible explanation of the results at the moment, but that there is urgent need for independent evidence that they are involved in normal vision.

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References

Alpern M, 1968 "A note on visual latency" *Psychological Review* **75** 260-264

Bannister H, 1932 "Retinal reaction time" *Physical and Optical Societies Report of a Joint Discussion on Vision* pp 227-234 (London: The Physical Society)

Edmund C, 1928 "On the duration of the luminous impression" *Acta Opthalmologica* **6** 414-424

Julesz B, White B J, 1969 "Short-term memory and the Pulfrich phenomenon" *Nature (London)* **222** 639

Lee D N, 1970a "Spatio-temporal integration in binocular-kinetic space perception" *Vision Research* **10** 65-68

Lee D N, 1970b "A stroboscopic stereophenomenon" *Vision Research* **10** 587-593

Lit A, 1949 "The magnitude of the Pulfrich stereophenomenon as a function of binocular differences of intensity at various levels of illumination" *American Journal of Psychology* **62** 159-181

Mach E, 1872 "Über Analoga der persönlichen Differenz zwischen beiden Augen und den Netzhautstellen desselben Auges" *Sitzungsberichte der Königlichen Böhmischen Gesellschaft der Wissenschaft (Prag)* 65-74

Prestrude A M, 1971 "Visual latencies at phototopic levels of retinal illuminance" *Vision Research* **11** 351-361

Pulfrich C, 1922 "Die Stereoscopie im Dienste der isochromen und heterochromen Photometrie" *Naturwissenschaft* **10** 553-564

Rogers B J, Anstis S M, 1972 "Intensity versus adaptation and the Pulfrich stereophenomenon" *Vision Research* **12** 909-928

Rogers B J, Steinbach M J, Ono H, 1974 "Eye movements and the Pulfrich phenomenon" *Vision Research* **14** 181-185

Ross J, 1974 "Stereopsis by binocular delay" *Nature (London)* **248** 363-364

Sachs E, 1946 "Abnormal delay of visual perception" *Archives of Neurology and Psychiatry* **56** 198-206

Standing L G, Dodwell P C, Lang D, 1968 "Dark adaptation and the Pulfrich effect" *Perception and Psychophysics* **4** 118-120

Wist E R, 1970 "Do depth shifts resulting from interocular delay in stimulation result from a breakdown of binocular fusion?" *Perception and Psychophysics* **8** 15-19

Historical note

C Pulfrich of Jena was not the first to describe the 'stereophenomenon' that bears his name, and indeed, he never observed it: for, as he tells us in his 1922 paper, he had been blind in his left eye for the last 16 years. The blindness resulted from a 'blütige Verletzung des Auges' in his youth, details of which 'sanguinary injury' are not given. Pulfrich was a famous designer of stereoscopic instruments, including rangefinders for naval gunnery, which as he proudly notes, were personally praised in a lecture at Jena by ex-admiral Scheer, commander of the German high seas fleet at Jutland. Pulfrich also designed stereocomparators and the 'blink microscope' for detecting movements of celestial bodies. The principle of these instruments is to present separately to the two eyes pictures of the night sky taken at different times. If any luminous body has moved in the interval between the taking of the two pictures, it will be imaged on the eyes with a disparity relative to the fixed stars, and will stand out in depth. In the 'blink microscope' the two pictures are flashed in rapid temporal succession to the two eyes, so that the disparate body is seen in apparent movement. (This principle is now used to detect imperfections in complex electronic circuits.) The disparity in the stereocomparator is measured by moving the two pictures together or apart until the relevant image is seen in the same depth plane as a fixed marker, imaged with a constant disparity on the eyes. The separation between the plates is then read from a vernier gauge.

The 'Pulfrich phenomenon' was first noticed as a nuisance (Störung) in the day-to-day use of these instruments. The first hint of this that came to Pulfrich's attention was in a paper by the astronomer Max Wolf, which appeared in the *Veröffentlichungen der Badischen Sternwarte zu Heidelberg* (1920). Wolf made stereo-measurements of 1053 stars from the observatory on the Königstuhl, the mountain that dominates Heidelberg on the other side of the Neckar from the romantic 'Philosophers' Walk'. Wolf noticed that as he moved the plates in his instrument, curious things started to happen. A star that had seemed in the same depth plane as the fixed marker when the plates were stationary now moved in front, now moved behind, as the pair of plates was shifted from one side to the other. This joint movement of the plates relative to the marker was necessary to bring the marker into line with the star being measured; it was puzzling that this movement disturbed the observer's depth judgement when it involved no change in disparity. The matter was sufficiently serious to be taken up by the manufacturers of the instrument, the Carl Zeiss factory at Jena. *Herr Ingenieur* Franke and *Herr Studienassessor* Fertsch speedily established that the effect was not seen in all plates. Thus, it was a property of the negatives, not of the instrument. From there, it was short work to show that the cause of the phenomenon was unequal development of the two negatives, which presented pictures of different brightness to the two eyes. Pulfrich describes the sequel:

> "Herr Fertsch, who was the chief contributor to understanding of the phenomenon ... then realised that it could be explained if one assumed that the movement of the marker over the brighter background was experienced earlier in time than the movement over the darker ground."

Pulfrich's generosity in describing the real originator of his idea has had its just reward: the effect is universally known as the 'Pulfrich phenomenon'. The one-eyed inventor's attempt to exploit his phenomenon to make heterochromatic brightness matches had a less happy result. He reasoned that if the targets in the two eyes were varied both in brightness and in colour, then the equivalent intensity of two colours could be established by finding the intensity difference at which the depth effect was not seen. The gratuitous assumption here was that retinal latency as a function of perceived brightness is independent of wavelength. The assumption, for many reasons documented by Lit (1949), has not proved to be useful.

Pulfrich was not immune to the feelings of philosophical awe which his phenomenon has kindled in so many who have seen it subsequently, and who have contemplated the interchangeability between space and time in the visual system. Unfortunately, he does not seem to have known of Minkowski's famous address to the 80th Assembly of German Natural Scientists and Physicians at Cologne, 1908:

> "The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.'

But he does quote an earlier authority:

> "Du Sieh'st mein Sohn, zum Raum wird hier die Zeit" (*Parsifal*, Act 1, Scene 1, end).

Curiously, an even earlier authority on relativity had described what amounts to a vindication of Pulfrich's geometry, without commenting on its general significance. Herr Professor Mach, in 1872, delivered a paper to the Imperial Bohemian Academy of Sciences in Prague, in which he described the research of Dvorak on episcotistotic presentation of a moving target. The technique involved giving the two eyes temporally staggered views of the sinusoidally-moving target through slits cut in a rotating wheel. If Pulfrich's geometry is correct, this should produce an impression of a target orbiting elliptically in depth, as indeed it does. Dvorak further found that the depth disappeared if the eyes tracked the target. It is a pity that this last observation has not found its way into later papers describing the 'Mach–Dvorak effect', for the point is insufficiently realised that Pulfrich's explanation demands the same to be true of his effect. It should not matter that signals are delayed from one eye relative to the other, so long as they all come from the fovea, or from some other corresponding position on the retinae. It is easy to confirm that Dvorak was right about his effect; the situation with the Pulfrich pendulum is more complicated (cf Rodgers et al 1974).

The modern use of the stereophenomenon to measure differences in 'retinal reaction time' began with Bannister's (1932) work at the Cambridge Psychological Laboratory. Bannister showed how to calculate latency differences from depth shifts, and carried out observations under different absolute and relative intensities in the two eyes. He somewhat unfairly says that Pulfrich described his phenomenon "without any explanation of the physiological basis". On the contrary, Pulfrich had clearly claimed that the origin of the effect must be an increase in retinal, or some other latency with decrease in luminous energy. He related this to other phenomena described by Helmholtz and Exner, and to the 'brightness equation' (Heligskeitgleichung) of astronomers, who were well aware that reaction time depends upon intensity; he also, like Bannister, speculated that the increased integration time demanded by poor illumination accounted for the difficulty of reading in dim light. True, Bannister had the advantage of a demonstration of the increased latency in the conger eel by Adrian and Matthews: but this can hardly be called a physiological 'explanation' any more than the facts described by Pulfrich, since its basis at that time was not understood, and is still a matter for considerable speculation.

Bannister's observations were greatly extended by Lit in his classic (1949) paper, and a method for deriving absolute latencies from $\Delta t - \Delta \log I$ functions was invented by Alpern (1968). Prestrude (1971) has recently re-discovered a measure of Δt originally proposed by Edmund (1928) (attributed by the latter to Tscherning), and has analysed the results using Alpern's technique. Edmund's method involves aligning moving stimuli, seen separately with the two eyes under different conditions of illumination. An unexplored suggestion of Edmund is that the Pulfrich effect is due to greater persistence in the adapted eye.

Although Pulfrich's application of his effect to heterochromatic matches was mistaken, and although as a clinical tool for the diagnosis of syphilis (Sachs 1946) the stereophenomenon has been superseded by other methods, we may agree with Pulfrich that this 'nuisance' has turned out to have its own intrinsic value.