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The Pulfrich pendulum phenomenon in stereoblind subjects

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Abstract. The Pulfrich pendulum phenomenon, in which a pendulum swinging in the frontoparallel plane appears to swing in an ellipse when a neutral density filter is placed over one eye of the observer, was investigated in stereoblind subjects. It was found that such subjects can report the presence of the Pulfrich effect although they fail to fuse random-dot stereograms and fail to exhibit interocular transfer of the movement aftereffect. These findings suggest that 'stereoblind' subjects must retain some residual binocular mechanism for depth perception. Three possibilities are considered: (i) the stereoblind may be able to utilise contiguous temporal disparities as a cue for depth in the Pulfrich effect; (ii) they may retain some residual binocularity, sufficient to reveal the Pulfrich effect but not for other more demanding tasks for the binocular mechanisms; and (iii) they may retain some coarse magnocellular pathway disparity mechanism having lost their high-acuity parvocellular disparity system. There is little evidence to support any of these hypotheses, but the third shows promise.

1 Introduction

When a moving target is viewed with a neutral density filter over one eye, it appears displaced in depth. This effect is demonstrated most commonly with a pendulum swinging in the frontoparallel plane; the apparent path of the bob then describes an ellipse. The generally accepted explanation of this effect was credited by the eponymous Pulfrich (1922) to Fertsch, who had suggested that the effect arose because the filter imposes a delay in the transmission of signals by the eye with the filter over it. This explanation is illustrated in figure 1.[1] As is generally the case with pictures this figure represents a single moment in time, that is it explains the Pulfrich effect by translating a temporal delay in processing, brought about by the filter, into a spatial disparity, brought about by the movement of the pendulum.

Evidence for this explanation has come from Rogers and Anstis (1972) who showed that the effects of the filter over one eye can be cancelled by a physical delay of the stimulus presented to the eye with filter over it. Indeed nearly all of a sizeable literature is in accord with this traditional account of the effect. That we can utilise spatial disparity to see depth is without question and the existence of binocularly driven cortical cells preferring a spatial disparity between their receptive fields in the two eyes is established beyond doubt (Barlow et al 1967). Furthermore Carney et al (1989) found that placing a filter in front of a cat's eye produced a temporal delay in the cortical response and that this temporal delay was always associated with a shift in the spatial disparity tuning of the neuron. These temporal delays and disparity shifts were comparable with the magnitude of the Pulfrich effect seen in humans.

Sparked by some initial, informal observations with Dr J A Movshon that a well-documented stereoblind subject reported the Pulfrich effect, one of us (PT) has noted that in undergraduate practical classes it is not very unusual to discover a student who is unable to fuse random-dot stereograms and fails to show interocular transfer

[1] It might be noted here that this representation shows correctly that the real path of the bob and major axis of the ellipse of the apparent path lie at different depths, the former being somewhat closer to the observer. This fact, detailed by Levick et al (1972), has been largely ignored in subsequent representations of the effect.

of the movement aftereffect (MAE), but students who fail to report any Pulfrich effect are rare. This seems odd as precisely the same binocular mechanisms appear to be necessary to experience all three phenomena.

It is well known that few people, from 2% of the population (Julesz 1971) to 4% (Richards 1970), lack stereopsis. Experiments on animals suggest that abnormal visual input in early life, for example the occlusion of one eye or a strabismus, can lead to a lack of binocularly driven neurons; see Movshon and van Sluyters (1981) for comprehensive review. It seems reasonable to believe that children who do not receive simultaneous congruent binocular stimulation early in life, perhaps as a result of a squint or astigmatism, may fail to develop the neural apparatus for binocularity and will, therefore, have no stereopsis in later life; see Mitchell (1980) for review.

As a consequence of the work of Movshon et al (1972), Ware and Mitchell (1974), Mitchell and Ware (1974) and Mitchell et al (1975) it became established that people lacking stereopsis also fail to demonstrate interocular transfer of aftereffects or experience a reduced degree of transfer. Indeed, Movshon et al (1972) found that the extent of interocular transfer may provide an index of stereopsis. They measured interocular transfer in three groups of subjects: normal, stereoblind with no history of strabismus, and stereoblind with a clinical history of strabismus. Whereas normals showed a mean interocular transfer of the tilt aftereffect of 70%, the nonstrabismic stereoblind group showed a 49% mean transfer, and the strabismic group only a 12% transfer. Ware and Mitchell (1974) extended these findings by showing that even within a group of normal subjects the amount of interocular transfer is related to stereoacuity. It would appear that a stereoblind subject who failed to demonstrate any interocular transfer of aftereffects should also fail to see the Pulfrich pendulum phenomenon if this latter effect also depends upon the central fusion of spatially disparate stimuli. Evidence from Tredici and von Noorden (1984) and Westall (personal communication) confirms that there does exist a group of stereoblind subjects who fail to see the Pulfrich effect, but this does not exclude the possibility of a group of people who do experience the Pulfrich effect without showing other indices of stereopsis. Our intention here is to provide some evidence that such a group does exist and to indicate how it might be possible to experience the Pulfrich effect in the absence of other indications of binocularity.

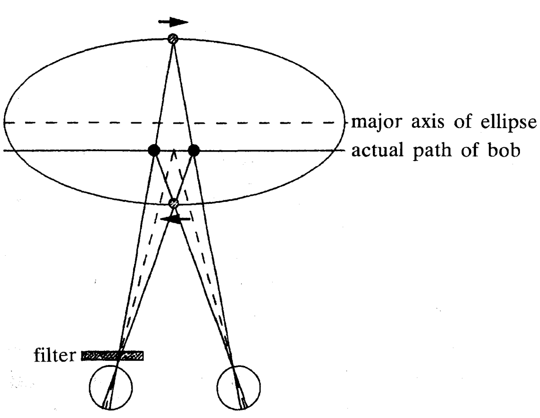

Figure 1. The standard representation of the Pulfrich pendulum phenomenon. The temporal delay in processing imposed by the filter is translated into a spatial disparity between the positions of the bob on the two retinae at one moment in time. With the left eye covered by a filter, the bob appears to rotate in a clockwise direction (viewed from above). That is, when moving right to left the bob will appear closer to the subject than when moving left to right.

2 Methods and procedures

2.1 *Screening for stereopsis*

Four subjects were found who could be described as stereoblind. The criterion used for this description was a failure to fuse a pair of random-dot stereograms. The stereograms used for this screening were taken from the book by Julesz (1971) *Foundations of Cyclopean Perception*, figure 8.1-2(A). This pair of stereograms has 100% binocular correlation and is the first in a series with diminishing binocular correlations that can be used for testing stereopsis deficiency. Four age-matched controls were used who had good stereopsis, defined as an ability to fuse successfully the stereogram pair in Julesz's figure 8.1-2(D), which has only 70% binocular correlation.

Of the four stereoblind subjects, three had a history of strabismus in early childhood with surgical correction after the age of two, and one (SA) developed a strabismus following a car accident at three years of age.

2.2 *Measuring interocular transfer*

Interocular transfer of the MAE was measured in all eight subjects. A 31 cm diameter disk, covered in a pattern of high-contrast random lines and rotating at 5.5 rev $\min^{-1}$, was viewed from a distance of 2 m. Each subjects completed three conditions and no two conditions were ever carried out on the same day. A simple sighting task determined eye dominance (Movshon et al 1972).

2.2.1 *Condition 1.* The subject's dominant eye was adapted to movement for 2 min while the nondominant eye was closed. After the adaptation period the disk was stopped and the duration of any MAE measured with just the dominant eye open. After a short rest the dominant eye was adapted for a second period of 2 min after which the stationary disk was viewed by the nondominant eye (with the dominant eye now closed) and the duration of any interocular transfer of the MAE recorded.

2.2.2 *Condition 2.* This was the same as condition 1, but the nondominant eye was adapted and interocular transfer from the nondominant to the dominant eye was recorded.

2.2.3 *Condition 3.* The MAE was measured with both eyes open during adaptation and test.

2.3 *Measuring the Pulfrich pendulum phenomenon*

The Pulrich effect was measured with the use of a motor-driven pendulum that described a 90° arc swing centred at six o'clock. The pendulum arm was 32 cm in length and the bob was a small yellow ball. The period of the pendulum was constant throughout at 1.75 s. Subjects sat 1.2 m from the pendulum; a chinrest was provided to promote stable eye position. The subject's task was to position a marker directly under the apparent swing of the bob; this marker was positioned initially by the experimenter randomly in front of or behind the path of the bob. At the beginning of the session, after a few minutes familiarisation with the general procedure, the subject made ten settings by positioning the marker under the path of the bob. This was done without any filter over the subject's eyes. After these baseline settings, a 1.07 log unit neutral density filter was placed over the subject's dominant eye. The subject was then asked to describe what he or she saw and to position markers under the bob at its closest position to *and* at its furthest position from the subject, ie at the ends of the minor axis of the bob's apparent elliptical path. This procedure was carried out with the subject fixating a point just behind the midpoint of the pendulum swing and with the subject tracking the pendulum. The whole procedure was then repeated with the filter placed over the subject's nondominant eye.

3 Results

3.1 *Interocular transfer of MAE*

All subjects reported robust MAEs when both adaptation and testing were binocular; MAE durations for the normal and stereoblind groups were of comparable size. Interocular transfer of the MAE was very different in the two groups. In figure 2 the transfer from dominant to nondominant eye and vice versa is plotted for all subjects. All four normal subjects showed transfer from each eye to the other, the mean transfer for these subjects being 65% from dominant to nondominant and 55% from nondominant to dominant, a result in accord with those of Movshon et al (1972) and Mitchell and Ware (1974). Three of the stereoblind subjects reported no interocular transfer in either condition, and the other members of this group (SA) reported transfer from the nondominant to the dominant eye but no transfer from the dominant to nondominant eye. This last finding was unexpected as greater transfer is usually reported from dominant to nondominant eyes than vice versa.

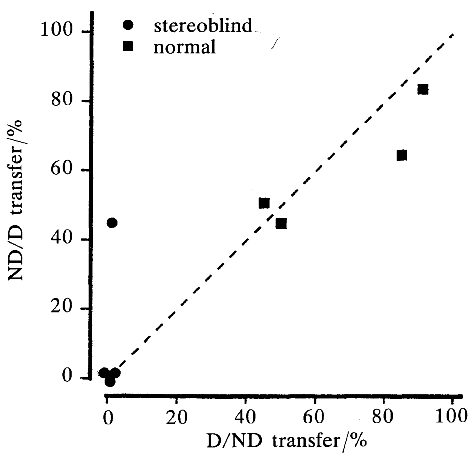

Figure 2. Interocular transfer of the movement aftereffect. Three of the four stereoblind subjects showed no transfer either from dominant to nondominant eye (D/ND) or vice versa (ND/D). The fourth subject showed some transfer from nondominant to dominant eye. All four normal subjects showed incomplete transfer from one eye to the other.

3.2 *Pulfrich effect*

The results for the Pulfrich effect are shown for both groups of subjects under two conditions: while fixating a stationary point behind the centre of the true path of the bob (figure 3) and while tracking the pendulum (figure 4). In each figure the results for the dominant eye being filtered and for the nondominant eye being filtered are shown. All the normal subjects were able to make satisfactory settings for all the conditions. In the tracking condition each member of the stereoblind group was able to complete the task with the filter covering the dominant eye. However, with the filter over the nondominant eye three members of the stereoblind group were unable to make any sensible depth judgments. This group found the fixation condition even harder: two subjects, including one of the authors (VW), could not make any reliable settings at all and another was only able to provide data when the filter covered the dominant eye.

These results are of considerable interest in that they suggest that in the normal group tracking and fixation produced comparably sized Pulfrich effects and in the stereoblind group the effects were more robust with tracking than with fixation.

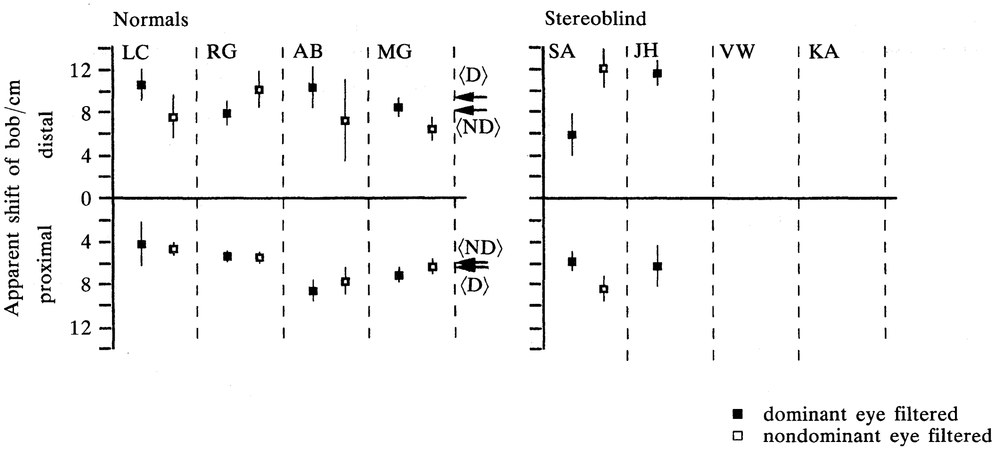

Figure 3. The Pulfrich effect when fixating a stationary point. For normal subjects the effect appeared to be slightly greater with the filter over the dominant eye. The distal apparent shift of the bob was a little greater than the proximal shift, in accord with the expectation of the standard explanation of the effect (see figure 1). For the stereoblind group only two subjects were able to make sensible settings and only one could do so with the filter over the nondominant eye. Data points show the mean of ten observations; error bars show ± 1 standard deviation. The arrows show the overall means with the dominant ⟨D⟩ and nondominant ⟨ND⟩ eye covered.

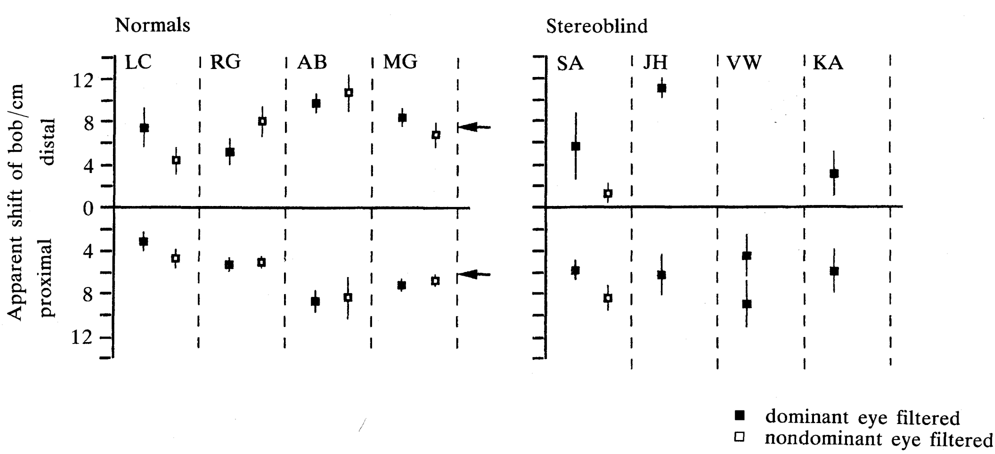

Figure 4. The Pulfrich effect when tracking the pendulum bob. For normal subjects the effect was comparable in size with the fixation condition although no difference could be discerned according to which eye was covered with the filter. All stereoblind subjects experienced the Pulfrich effect with the filter over the dominant eye; only one could complete the task with the filter over the nondominant eye. Data points show the mean of ten observations; error bars show ± 1 standard deviation. The arrows show the overall means.

4 Discussion

These experiments demonstrate that subjects who may be regarded as stereo-blind in so far as they fail completely to fuse stereograms and fail to exhibit interocular transfer of the MAE, can see the Pulfrich effect under some conditions, particularly when tracking the pendulum bob. On the basis of our results to date it would be premature to speculate upon all the various possible reasons for our results. We believe, however that three possibilities deserve brief consideration.

4.1 *Temporal disparity theory*
If some people fail to fuse stereograms because they lack a system that can use spatial disparities to extract depth, they might still experience the Pulfrich effect if a binocular system that can use temporal disparities remained intact. Using a display that might be regarded as a temporal analogue of the random-dot stereograms of Julesz (1960), Ross (1974) demonstrated that showing dynamic random-dot patterns to one eye slightly later than to the other leads to the plane of the dots being shifted in depth. Spatial disparities cannot be responsible for this effect as successive points in the display are plotted randomly in two dimensions. Ross noted that the perception of depth generated by this display was "vivid and unmistakeable (sic), even for some observers with poor stereopsis for displays based on disparity". This observation fits well with the present findings; stereoblind subjects might be able to experience the depth in Ross's display although they would be unable to do so with more conventional spatial disparity displays. Unfortunately other clear evidence that temporal cues can be used has remained elusive (see Tyler 1974), although Morgan and Thompson (1975) demonstrated that the Pulfrich effect persists when targets in apparent (stroboscopic) motion are used.

Giving Ross's temporal disparity theory the benefit of considerable doubt, we presented three stereoblind subjects (none of whom had served as a subject in the main experiments reported here) with a display of dynamic visual noise viewed with a filter over one eye. None reported any perception of depth even though all three reported the traditional Pulfrich effect.

4.2 *Residual weak binocularity theory*
It could be argued that our so-called stereoblind subjects are merely stereo-weak. This theory requires us to believe that a residual binocularity is only revealed in the Pulfrich effect because this is a very undemanding task for the system; in contrast, the fusing of random-dot stereograms is a more difficult task and hence the stereo-weak fail it. We took some care to make certain that the spatial disparities in the stereograms (that our subjects failed to fuse) were comparable with the spatial disparities arising from the filter being applied to one eye in the Pulfrich effect (that they did experience). Similarly we have found that the same filter that produces a Pulfrich effect in a stereoblind subject does not produce a depth effect when viewing dynamic visual noise.

4.3 *Two depth systems—parvocellular and magnocellular*
There is evidence from recent physiological studies that stereopsis can be supported both by a high-resolution parvocellular pathway and by a low-resolution magnocellular pathway (see Schiller et al 1990). If the parvocellular system was more prone to damage in early life, then our experimental results might be explained by proposing a surviving low-spatial-frequency magnocellular depth mechanism in our stereoblind subjects. We considered the possibility that the high-spatial-frequency information in the random-dot stereograms that could not be fused might have prevented the perception of depth from the low spatial frequencies, perhaps in a manner analogous to the invisibility of the low-spatial-frequency Abraham Lincoln in Harmon and Julesz's (1973) celebrated figure.

To provide support for this idea we attempted to demonstrate an ability in stereoblind subjects to fuse random-dot stereograms that have been low-pass filtered. We have now tested three such subjects (the same group as reported in the section 4.1) and although two were unable to fuse such stereograms the third subject (GS) could. This subject, who has no clinical history of strabismus, failed to fuse standard random-dot stereograms but experienced a robust Pulfrich effect when fixating and when tracking. She exhibited some interocular transfer of the MAE (36% from the dominant to the nondominant eye and 23% from the nondominant to the dominant eye) though much less than our normal group (see figure 2). As reported above this subject failed to see depth in the dynamic visual noise display. When shown stationary low-pass-filtered stereograms she was unable to identify any figure in depth within them but when the stereograms were moved from side to side she reported correctly and confidently that there was a square in depth in the figure. As soon as the movement stopped the depth disappeared. The observation may indicate the survival of a magnocellular disparity mechanism in an apparently stereoblind subject.

Finally, Tredici and von Noorden (1984), who found a high correlation between the ability to see the Pulfrich effect and random-dot stereograms, also reported that "Several patients who readily perceived the Pulfrich effect had no stereopsis on random dot stereogram testing. These patients were subsequently retested with random dot stereograms and were all eventually found to have stereopsis". It is possible that our small group of subjects falls into this category and that with persistence all might have demonstrated an ability to see depth in the random-dot stereograms, as our subject GS did when shown moving low-pass-filtered stereograms.

5 Conclusion

We have demonstrated that some so-called stereoblind subjects can experience the Pulfrich effect. This poses something of a problem to conventional accounts of stereoscopic depth perception and of the Pulfrich effect. None of the explanations of these findings that we have devised is very convincing but the demonstration that a subject who failed to fuse standard stereograms can successfully fuse low-pass-filtered moving stereograms does point the way to future experiments with subjects with poor stereoacuity. It may transpire that a magnocellular stereopsis system survives in some subjects who fail conventional tests of stereopsis. This idea may not be outrageous (a small ocular misalignment in early life might well damage the high-acuity parvocellular stereo system while leaving the coarser magnocellular system intact) and should be amenable to falsification.

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