A NEW PULFRICH EFFECT BASED ON INTEROCULAR DIFFERENCES IN LINE ORIENTATION*

Raiten Taya, Yasuhiro Ohashi & Walter H. Ehrenstein

Introduction

When a pendulum swinging in the frontal-parallel plane is observed with an attenuating filter placed in front of one eye, it appears to move elliptically in depth. This striking phenomenon of stereomotion was first observed by Fertsch and subsequently elaborated by Pulfrich (1922) and has become known as the "Fertsch-Pulfrich effect" (Morgan, 1977) or just "Pulfrich effect" (Howard & Rogers 2002). If viewed, for example, with an attenuating filter over the *left* eye, the bob appears to rotate *clockwise* (as seen from above), displaced in depth on an elliptical trajectory. The Pulfrich effect has been explained by assuming that the target in the filtered eye is processed with a longer latency than the unfiltered (more intense) target in the other eye, thus causing a depth effect in the fused image (e.g., Lit 1949; Rock & Fox 1949; Wilson & Anstis 1969; Morgan 1977; Wake 1984, 1985; Wolpert, Miall, Cumming & Boniface 1993; Howard & Rogers 1995, 2002; Kitaoka & Ashida 2007).

The present study follows in part the method by Rogers & Anstis (1972) who used two horizontal slits illuminated from behind and viewed stereoscopically. Instead of the filter being put over one eye, it was put over one slit. Based on this method, Rogers, Steinbach & Ono (1974) studied whether the two eyes followed the apparent elliptical path. The target was a 1-cm high vertical line, oscillating horizontally to and fro with sinusoidal motion at 0.5 Hz. The fixation point was also a 1-cm high vertical line, and was always at the center of the frame. When the subject's gaze fixated on the static mark a clear Pulfrich effect occurred, however as soon as the subject tracked the oscillating target, its path appeared flat suggesting that "the brighter the faster" rule might apply only for peripheral view. However, as already noticed by Pulfrich (1922), the phenomenon appeared similarly regardless of whether a white moving disc was observed on a black background (BG) or a black moving disc on a white BG. This suggests that the contrast relationship between the targets and BG rather than the target's luminance or intensity alone is the decisive factor.

Here we aim to clarify, whether mere differences in intensity (brightness) suffice to account for the Pulfrich effect, or whether further factors such as differences in the spatial arrangement of the stimuli, might also have an effect. Therefore we used stimuli of equal luminance, size, and form that only differed in orientation. By this we especially try to challenge the latency assumption based on an interocular intensity difference that so far has dominated the discussion of the classical Pulfrich effect.

*Dedicated to Professor Lothar Spillmann on his 70th birthday

Experiment 1: Replacing differential brightness by differential orientation

Instead of traditional white and gray discs or slits, we used two lines as stimuli, a vertical line and the same line, but tilted. Both line stimuli were set at equal luminance, so that the interocular input does not involve differences in stimulus intensity, thus "the brighter the faster" rule does not apply in this case.

Method

Apparatus. Stimuli were presented on a computer screen (13 inches, Mac Standard monitor), and were controlled by a computer (Power Macintosh, 7100/80AV) and a software (Micromind Director, version 5). See Fig. 1.

General Stimulus Pattern. A pair of stationary red (15.9 cd/m2) squares (0.4 x 0.4 deg) served as fixation marks. The targets were vertical and tilted lines (1 deg long, 0.1 deg wide). Both were bright (102.6 cd/m2), presented at 8 deg of visual angle below the fixation points on a dark background (0.14 cd/m2). An incandescent light from the ceiling (97 lux on the table) provided a diffuse, ambient illumination of the room. Both targets oscillated to and fro with sinusoidal motion at 1/4 Hz within a range of 6 deg (successive 120 frames for one cycle; to allow for simulation of a smooth sinusoidal motion). The subject observed the screen through a stereoscope at a distance of 57 cm (see Fig. 1).

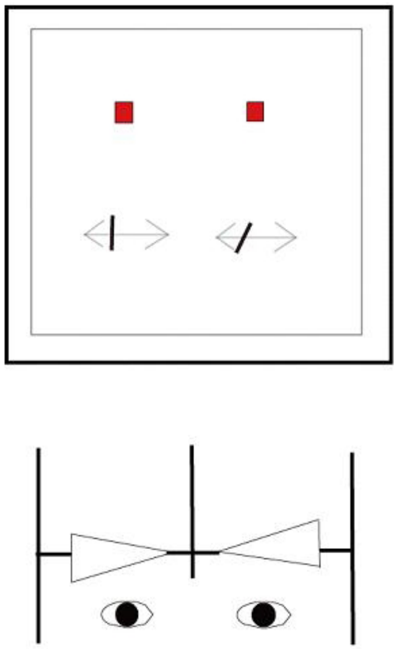

Figure 1: Experimental set-up

Stimulus variables. The line-stimulus for the left eye was always vertical, whereas the stimulus for the right eye was always tilted, deviating from the vertical in 3 steps by 12, 24, and 57 deg, respectively.

Subjects. Four subjects took part in this experiment. Two were female graduate students, and two were male (authors RT and YO). All participants had normal or corrected-to-normal visual acuity.

Procedure. The subject directed her/his eyes to the fixation marks (the red squares), and while keeping their gaze fixed, observed the target motion within her/his lower vision field. The shape of the trajectory was judged by using a 10-point scale of ellipses, consisting of 10 differently depicted ellipses with the ratio of the short/long diameter varying from 0.1 to 1.0 in steps of 0.1. The scale value “1” corresponds to a ratio of 0.1 (a rather elongated ellipse, almost corresponding to a frontoparallel trajectory), whereas “10” corresponds to a full circle. Subjects matched the perceived shape of the elliptical path by selecting one sample of the scale. They were allowed to use intermediate steps, for example “5.3”, if s/he felt that the given 10 steps were too coarse. Subjects were also allowed to repeat their matching several times; in this case her/his *final* match was taken as a valid response.

Results

In the first two tilt conditions (12 and 24 deg), the two stimuli were fused by all subjects so that they appeared as one jut-out 3D line. The fused target appeared to move in a frontoparallel, flat way throughout. Thus there was no “motion in depth” effect at all. In the third tilt condition, three subjects were unable to fuse the two line-stimuli. The relative position of these stimuli was fluctuating, but their respective center appeared to move uniformly, rotating clockwise in depth. See Fig. 2.

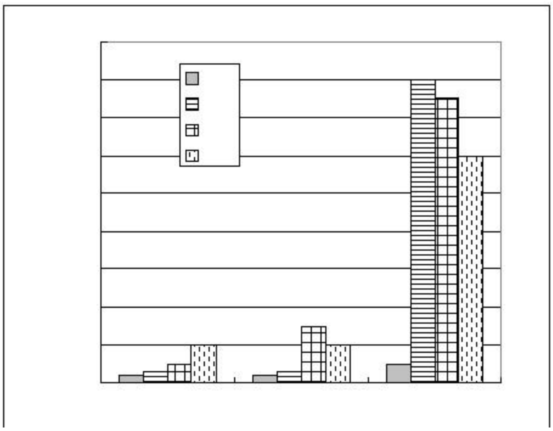

Figure 2: Results of Experiment 1

For one subject (YO) who could still fuse the targets, however, the resultant stereo line appeared to move at a frontoparallel, flat trajectory.

In this experiment, the tilted segment was always presented to the right eye, and the mass of these targets in rivalry spontaneously appeared to rotate clockwise in depth. When the observers intentionally tried, they could reverse the direction to counter-clockwise rotation. In that case, however, apparent depth was reduced to approximately half of that with clock-wise rotation.

Experiment 2: Non-fused stimuli of equal intensity

From Experiment 1 we may conclude that an analogue of the Pulfrich effect requires a non-fused disparity difference between the two eyes. A second experiment thus concentrated on the effect of fusion in relation to the Pulfrich effect.

Method

A new stimulus condition was chosen on which the two targets could not be fused. This was achieved by adding a vertical line-segment to the tilted segment shown to the right eye (see the upper line-figures in Fig. 3). As a consequence, the two vertical lines of the binocular stimuli could fuse, whereas the tilted stimulus segment remained non-fused throughout.

Subjects and Procedure. The same subjects participated as in Experiment 1; they also used the same procedure in judging the extend of stereomotion.

Results

In all conditions and for all of the four observers the two vertical lines were fused, but the tilted line remained non-fused and tilted-segment appeared unstable,sometimes in front of the fused line, sometime behind it. This *mass* or *perceptual center* (see Beghi, Vicario & Zanforlin 1984) that fluctuated between the fused vertical and tilted lines always appeared to rotate clockwise and motion in depth appeared clearly even in the 12-deg condition of minimal tilt (see Fig. 3). The more tilted the stimulus segment for the right eye, the deeper the rotation appeared. The matched depth increased linearly with this tilt factor ($F_{1,3} = 48.0$, $p<0.01$)

Discussion

As mentioned in the Introduction, no Pulfrich effect is obtained when the subject tracks the moving target (Rogers et al. 1974) in which case the two images are well fused. Similarly, no depth effect occurred in Experiment 1, when the line targets were fused. In case of fusion, the relative position of the two fused targets was fixed, as in case of a physically solid object moving at a flat, frontoparallel trajectory.

In case of non-fusion or segregation of the two targets, however, binocular disparity may become more flexible or diffuse. It is as if the stereo mechanism attempts somehow to compensate for the failure of proper fusion in the short-range by extending its information to the long-range motion path.

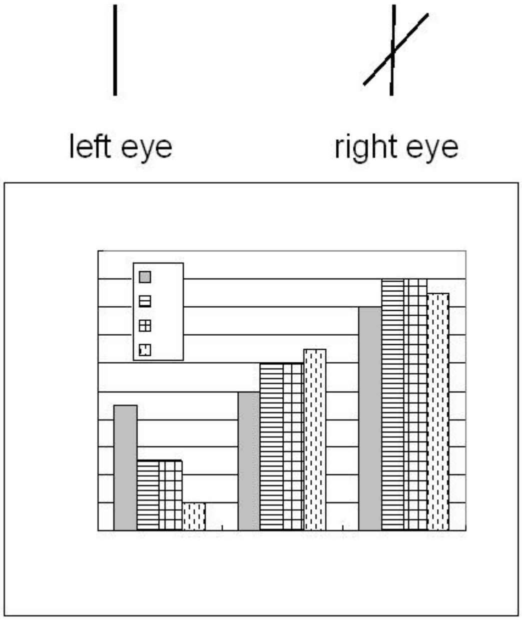

Figure 3: Results of Experiment 2

Experiment 3: Non-fusion under unequal-intensity conditions

When the vertical line and the slightly tilted line were fused, they resulted in the percept of a solid bar jutting out of the screen surface, but moving along a flat, frontoparallel trajectory (Experiment 1). Thus fusion prevents motion in depth or stereomotion for equal-intensity stimuli. In the classical Pulfrich experiment with unequal-intensity stimuli, fusion does not seem to be critical in that it prevents the stereomotion effect. Apparently there are different effects of fusion, which should be distinguished from fusion itself. Howard & Rogers (1995, 2002) define binocular "fusion" as the condition under which similar images presented to the two eyes appear as one and are processed simultaneously rather than successively. This definition may not suffice in that it fails to distinguish between the conditions outlined above under which fusion prevents or allows for motion in depth. Here we might further differentiate. For unequal-intensity conditions, a white disc superimposed to a gray disc appears to be only fused as long as the stimuli stand still. As soon as they start to move, we can discriminate different gray components, that is, the Pulfrich effect appears as different depths on the trajectory. The dimmer the gray disc component the more profoundly the elliptical trajectory appears (Lit 1949).

On a dark BG, a bright disc and a dim disc are easily fused and appear hence as one disc. The following experiment supplements the conventional dark BG by a light-gray BG, on which a bright disc appears whitish, whereas the gray disc appears blackish and both are less likely to become perceptually fused. Would the mass of these non-fused targets on the light-gray BG appear to move more deeply than the fused target on the dark BG?

Method

The BG was either dark or light gray. The two (white and gray) discs appeared fused on the dark BG, but appeared in rivalry on the light gray BG.

Apparatus and Stimulus Pattern. The experiment was carried out in a room different from the one used before. Stimuli were presented at a computer monitor of 19 inches *(Eizo, FlexScan1921)*, and the size and luminance of each stimulus area was changed a little. Fixation points were a pair of stationary red (3.4 cd/m^2, x .635, y .331) squares (0.5 x 0.5 deg). The target was a white (19.1 cd/m^2) or a gray (6.5 cd/m^2) disc (0.35 deg in diameter). The background was dark (0.1 cd/m^2) or light gray (11.7 cd/m^2). The room was illuminated by incandescent lights from the ceiling (270 lux on the table) that provided diffuse, ambient room illumination. The subject observed the targets through a stereoscope at a distance of 115 cm.

Subjects. Five subjects, three of whom having participated in the previous experiments together with two new subjects (female graduate students), participated in this experiment.

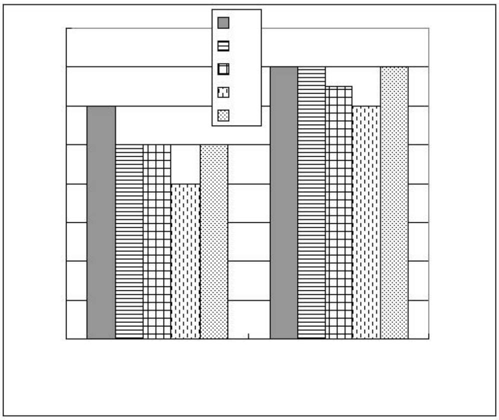

Figure 4: Results of Experiment 3

Results

The two target discs appeared to be fused on the dark BG, but to rival each other on the light-gray BG. The matched results are shown in Fig. 4. The mass of non-fused targets on the light gray BG appeared to move more deeply than the fused targets on the black BG, as we expected. The mean matched depth was 5.0 on the dark BG, and 6.7 on the light gray BG. This difference is statistically highly significant (t = 8.5, df = 4, p <0.01).

A supplementary observation

The quantitative findings may be supplemented by a qualitative observation concerning the light-gray background condition. Both, white and gray discs were delineated with a black line. As a consequence, these two targets showed fusion of their contours, whereas they rivaled with respect to their inner areas, that is, one disc only was ever seen through the stereoscope, but the inner area of this target appeared sometimes whitish and sometimes blackish. The target appeared to move a little deeper than the fused targets on the dark BG, but not so deep as the mass of targets with no black contours on the light gray BG. Thus, also in these cases of disc targets, the mass of non-fused targets appeared to rotate deeper on the elliptical trajectory.

Concluding remarks

The present study shows the importance of non-fusion for the Pulfrich effect to occur; i.e., a perceptually segregated interocular input is necessary for equal-intensity stimuli. Although fusion does not prevent the Pulfrich effect under conditions of unequal-intensity stimuli, a significantly stronger stereomotion effect appears if the unequal-intensity stimuli are presented on a background that facilitates their perceptual segregation.

The relation of perceptual segregation of binocular input and stereomotion requires further explanation. Recently Read & Cumming (2005) have shown that the Pulfrich effect can be accounted for by flexible correlations between the activity in pure disparity sensors (like most neurons in the primary visual cortex, V1) and a separate population of pure motion sensors, including, but not necessarily requiring, joint motion/disparity sensors (like neurons in area MT). Based on our present data, we would predict that neurons involved in figure-ground segregation (found in area V2; Qiu & von der Heydt 2005) might critically contribute to the Pulfrich effect as well.

Our finding of a new effect of stereomotion (apart from the original stimulus domain -- differences in brightness -- of the Pulfrich effect) for stimuli that are materially equal and only differ with respect to their spatial orientation challenges theories that are based on a mere intensity-latency tradeoff. In the other preliminary experiments we further found that stereomotion effects can also be obtained with stimuli that are equal in brightness, but differ in size or shape. A Pulfrich effect appeared very clearly with two white discs presented on a dark background when one disk was a few times larger than the other or when one target was a white disc and the other a white square of similar size.

The difference between the two targets however should not, however, be too large, as already observed for the conventional Pulfrich effect: When the dimmer disc is too dim so that it tends to merge with the dark background, the target appears to move nearly in a frontoparallel fashion. The same absence of a depth effect is found when one disc is more than ten times larger than the other.

Varying the differentiation between targets can lead to surprising observations. A clear stereomotion direction obtained for an equally sized white disc combined with a white square is reversed and becomes even more pronounced when the white square is replaced by a gray square. These puzzling effects of different stimulus properties on stereomotion need to be further investigated.

Some of the peculiar properties of the Pulfrich effect and related phenomena seem to closely rely on functions specialized for peripheral vision. It is well known that different parts of retina vary in their response to temporal and spatial stimulation in that the periphery shows a distinct preference for targets of low spatial frequency and high rates of temporal modulation or velocity (Sekuler & Blake 2002; Ehrenstein 2003). In peripheral view, we perceive the motion attributes (such as speed and direction) well, but only poorly perceive the static properties of targets (such as tilt, size, shape, or color).

Thus, motion in depth may occur rather generally provided that two similarly moving targets are slightly different, not only in brightness, but also in size, form and spatial orientation. This is reminiscent of the approach of the early Gestalt psychologists, especially on the concept of φ-*motion* (Wertheimer 1925, p. 26). When a long line segment is presented on the left in one moment and a short line segment on the right in the next moment, the segment appears to move from left to right and to shrink in size; i.e., the long segment before the movement is identified with the short segment after the movement. Similarly, in our present Pulfrich experiments, the moving white disc would be identified with the moving gray disc, the moving vertical line segment would be identified with the moving oblique line segment, and the moving small disc would be identified with the moving large disc, and so on. The resulting stereomotion phenomenon should be considered to reflect peculiar Gestalt conditions of spatio-temporal organization; consequently, the Pulfrich effect may serve as a rather general paradigm of perceptual investigation.

Summary

We examined the response latency theory of the Pulfrich effect of stereomotion. A pair of stimuli was stereoscopically presented moving sinusoidally to and fro on the computer screen. Stimuli were equal in luminance, form, and size, however they differed in orientation. A vertical bar was shown to the left eye and a bar, deviating from the vertical by various degrees, to the right eye. When the tilt of the right-eye stimulus was moderate so that it could be easily fused, no depth effect appeared. However, as soon as its tilt exceeded the fusion threshold, movement in depth was perceived, similar to the conventional Pulfrich effect. The significance of non-fused dichoptic input was further investigated by using two conventional, white and gray discs that were fused easily on a dark background, but in rivalry on a light-gray background. The movement in depth appeared more profoundly in the light-gray BG than in the black BG. Thus, our new Pulfrich effect depended critically on the condition of non-fusion. The results demonstrate the limitations of the response latency theory. Rather than being merely based on interocular intensity differences, the Pulfrich effect is shown to follow peculiar Gestalt rules of spatio-temporal differentiation.

Keywords*:* Binocular vision, Pulfrich effect, stereomotion, latency theory, Gestalt conditions

Zusammenfassung

Beim Pulfrich-Effekt erscheint eine in der Ebene dargebotene Reizbewegung tiefenerstreckt, wenn die Reizintensität für ein Auge (z.B. durch einen Graufilter) abgeschwächt wird. Nach einer gängigen Theorie benötigt der schwächere Reiz längere Verarbeitungszeit, resultiert der Pulfrich-Effekt somit auf unterschiedlichen Verarbeitungszeiten zwischen den Augen. Wir prüften diese Theorie mit beidäugig intensitätsgleichen, lediglich in ihrer Raumlage verschiedenen Reizen. Sinusförmig auf einem Bildschirm hin- und herbewegte Linien wurden durch eine Stereobrille beobachtet, so dass linksäugig stets eine senkrechte Linie, rechtsäugig die ansonsten gleiche Linie, jedoch in variierender Abweichung von der Senkrechten zu sehen war. Bei geringer Abweichung fusionierten die Bilder beider Augen und eine Tiefenbewegung blieb aus, zeigte sich dagegen deutlich, sobald der Neigungswinkel die Fusionsschwelle überschritt. Die Fusionsabhängigkeit wurde zusätzlich für ungleiche Reizintensitäten geprüft. Eine weiße und eine graue Kreisfläche, die auf einem dunklen Hintergrund leicht, auf einem hellen aber nur schwer fusionierten ergaben deutliche Tiefenbewegung bei hellem, aber nur schwache bei dunklem Hintergrund. Diese neue, fusionsbedingte Pulfrich-Variante verdeutlicht die Grenzen der Verarbeitungszeit-Theorie und verweist auf komplexere Gestaltbedingungen einer raum-zeitlichen Differenzierung.

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Addresses of the Authors:

Raiten Taya
Graduate school of Humanities and Social Sciences,
Okayama University
700-8530 Tsushima-naka 3-1-1,
Okayama, Japan
e-mail: taya@cc.okayama-u.ac.jp

Yasuhiro Ohashi
Department of Pre-elementary Education,
Sanyo Gakuen College
703-8531 Hirai 1-14-1,
Okayama, Japan
e-mail: ohashi@sguc.ac.jp

Walter H. Ehrenstein
Leibniz Research Center for Working Environment and Human Factors,
University of Dortmund,
Ardeystrasse 67,
44139 Dortmund, Germany
e-mail: ehrenstein@ifado.de