Vision Res. Vol. 14, pp. 181-185. Pergamon Press 1974. Printed in Great Britain.

# EYE MOVEMENTS AND THE PULFRICH PHENOMENON

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(Received 9 August 1973)

**Abstract**—The path of a target oscillating in the fronto-parallel plane and differentially filtered to the two eyes appears elliptical in depth when the eyes *fixate* a stationary point. When the eyes *track* the target the path flattens out. Binocular records of eye movements indicate that the eyes follow the true physical path making only conjugate movements with no change in convergence.

It is generally accepted that the apparent elliptical path of a pendulum swinging in the fronto-parallel plane, when viewed with a neutral density filter over one eye, is due to the increase in visual latency of the attenuated eye (Pulfrich, 1922; Lit, 1949; Wilson and Anstis, 1969; Rogers and Anstis, 1972). The increased latency, either as a result of the decreased luminance level or the state of adaptation of the eye (Rogers and Anstis, 1972), alters the apparent position of any moving object in the field of view, creating a binocular disparity which is interpreted as a change in the apparent depth relative to the plane of convergence of the eyes. This explanation is satisfactory when the eyes fixate a stationary point and the target image sweeps across the retina [Fig. 1(a)], but it has also been reported that the illusion can be seen if the eyes follow the target (Gregory, 1966; Kirkwood, Ellis and Nichol, 1970).

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Two questions arise from these findings. Firstly, do the eyes follow the real (flat) path of the oscillating target [Fig. 1(b)] or do they follow the apparent elliptical path which would involve a continuous change in the convergence of the eyes as well as conjugate tracking movements [Fig. 1(c)]. The latter description is implied in Gregory (1966) and it is well known that the eyes can follow a target which physically moves in an elliptical path in depth (Rashbass and Westheimer, 1961). If, however, only conjugate tracking movements are involved, then the second question arises as to why the illusion is still observed, since the target will stay on the foveas of both eyes and any difference in latency is of no consequence, assuming good tracking. Alternatively, if the eyes follow the apparent path as in Fig. 1(c) then one might expect the change in depth signalled by the convergence system to be compensated for by the disparate position of the target on the two retinae again yielding the percept of the target moving along a flat path.

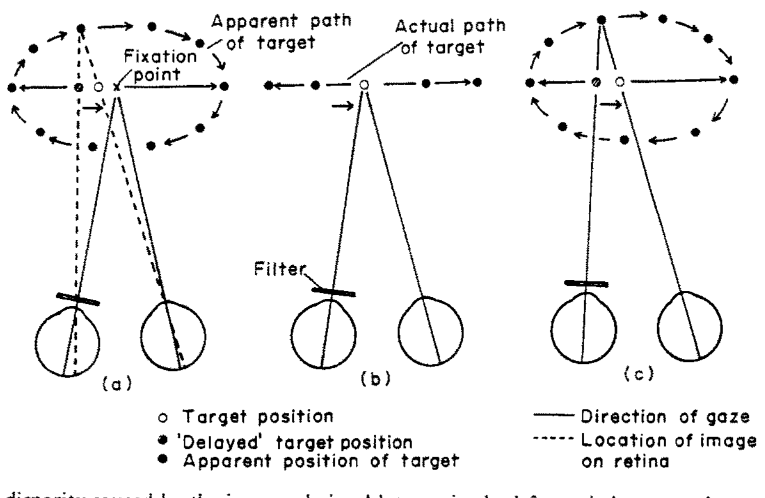


Fig. 1. The disparity caused by the increased visual latency in the left eye is interpreted as a change in depth of the moving target when the eyes fixate a stationary point in 1(a). In 1(b) and 1(c), two possible ways the eyes could track the differentially filtered target: following the real flat path in 1(b) and following the apparent elliptical path in 1(c).

Hence in theory it ought to be impossible to observe a Pulfrich effect when the eyes track the differentially filtered target. Two experiments were designed to answer these questions. In the first, we recorded binocular eye movements in order to see whether the eyes followed the real (flat) or apparent elliptical path. In the second experiment we obtained reports of the target's apparent path under three conditions: (a) with a differentially filtered target; (b) with a differentially filtered background; and (c) with both a differentially filtered target and background, since it occurred to us that (a) and (b) are normally confounded when a neutral density filter is used to attenuate the input to one eye.

## EXPERIMENT 1

### *Method*

The target in all our experiments was a 1-cm high vertical line (0·5° visual angle) on an oscilloscope which oscillated horizontally to and fro with sinusoidal motion at 0·5 Hz and a peak to peak amplitude of 8 cm (4° visual angle). It was found that judgements of depth were easier using this stimulus rather than a simple spot. A fixed sheet of polaroid over the scope face and adjustable polaroid filters over the two eyes meant that the brightness of the line could be varied independently for the two eyes. The background consisted of the illuminated graticule of a second scope superimposed to be in the same plane using a half silvered mirror. The background was not polarized and was of equal luminance in the two eyes. Binocular eye movements were recorded using He–Ne laser beams (0·5 mW) reflected off small mirrors mounted temporally on close fitting scleral contact lenses (Matin, 1964; Steinbach and Pearce, 1972). The positions of the reflected beams were monitored using position-sensitive Schottky barrier diodes (United Detector Technology, Models SC-25 and SC-50) mounted about 15 cm from the eyes, with appropriate differential amplifiers. Both horizontal and vertical eye movements could be detected using this system although only horizontal recordings were made in this experiment. The absolute resolution of the system has been found to be better than 12" arc, but for recording eye movements the resolution was limited to 2 per cent of the range, i.e. 6' arc. Any changes of convergence produced by the eyes following an elliptical path in depth would show up on the eye movement records as a phase shift between the left and right eye traces. As a control, eye movement records were also obtained when the subject tracked a target which physically moved in an elliptical path with a depth of 9 cm. One of the authors (MJS) acted as subject; the task was to track the oscillating target as accurately as possible and to report on the direction and magnitude of its perceived path. A series of 20 trials was presented to the subject within a 30-min session under four conditions in a randomized order: (i) target to left eye filtered ($\frac{1}{4}$ L.U.); (ii) target to right eye filtered ($\frac{1}{4}$ L.U.); (iii) target to both eyes equally filtered ($\frac{1}{4}$ L.U.); (iv) neither eye filtered.

### *Results*

Typical eye movement records are shown in Fig. 2 for tracking one complete oscillation of the target. These are shown as Lissajous figures by plotting left eye movements against right eye movements. This is a convenient way of showing a small phase shift between two sinusoidal waveforms. If the waveforms are exactly in phase, the resulting Lissajous figure is a 45° line, but a phase difference between the waveforms produces an ellipse about the positive diagonal: the greater the phase difference the greater the minor axis of the ellipse. In Fig. 2(a) where the eyes tracked a differentially filtered target, there was little deviation from the positive diagonal suggesting that the eyes made only conjugate movements. By comparison, Fig. 2(b) shows the Lissajous figure of the eye movements when the same subject tracked a target which moved physically in an elliptical path in depth, where a clear phase shift between the left and right eye movement records can be seen, corresponding to the continuous change in convergence as the target rotated. Subjective reports whilst tracking the differentially filtered target confirmed our hypothesis: the subject reported a sizeable

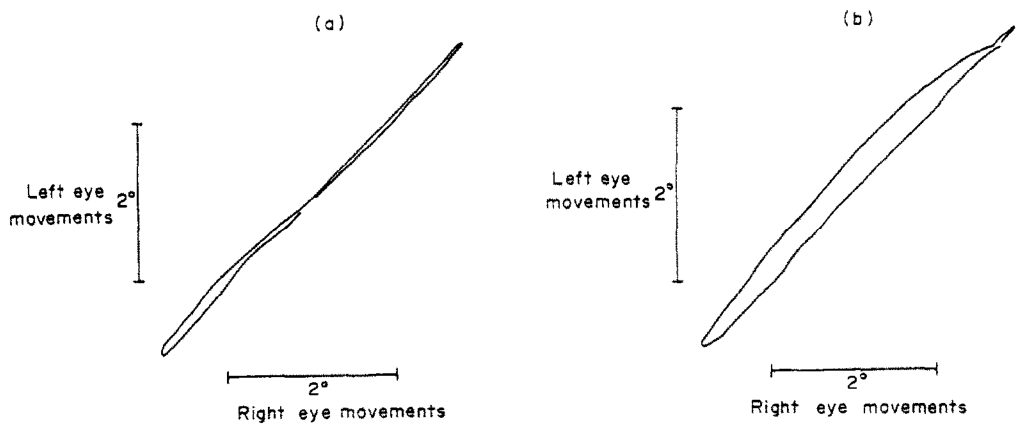


Fig. 2. Lissajous figures produced by plotting left eye movements against right eye movements. The subject tracked either an apparent (Pulfrich) ellipse 2(a) or a target moving physically in an ellipse in depth 2(b). Note the phase difference between the records in 2(b) corresponding to the continuous change in convergence of the two eyes.

Pulfrich effect whenever his eyes fixated the stationary background in conditions (i) and (ii) but on tracking the target the subject consistently reported that the path was flat.

## EXPERIMENT 2

*Method*

The target line was a 1-cm high vertical line oscillating through a horizontal path of 8 cm as in Experiment 1. The background in this case was an identical 1 cm stationary line produced on the second scope and superimposed in the same plane using a half-silvered mirror. The line was positioned at the centre of the target's oscillation but was displaced vertically by 1 cm so that it stood just above the target's path. Polaroid oriented at 90° to that of the first scope enabled the balance of luminance between target and background lines to be altered separately for the two eyes. A third scope was used to produce a third line which could be held still or made to oscillate along an identical path to the target line. This line was not polarized so its luminance was always equal to the two eyes. For any given condition only two scopes were used so that there was only one oscillating target line and one stationary background line visible, and either or both could be polarized to provide differential luminance to the two eyes. The experiment was carried out in a darkened room with no other objects or surroundings visible. The three conditions were: (a) the oscillating target line was differentially filtered and the background line of equal luminance to the two eyes; (b) the background line was differentially filtered and the target line of equal luminance; (c) both target and background lines were differentially filtered but in opposite directions with respect to the eyes so that when the target was dimmer to the left eye than to the right the background was dimmer to the right eye than to the left or vice versa. Within each condition subjects were asked either to fixate the stationary background line or track the moving target line as well as possible. Half the trials in each case were presented with the target (or background) attenuated to the left eye and half to the right eye. In all cases the subject was asked to report on the direction of apparent rotation (if any) of the target line irrespective of whether he was fixating or tracking. A forced choice procedure was used in which the subject had to respond with either "clockwise", if the direction of rotation in depth was clockwise as seen from above, "counterclockwise", or "flat" if the target appeared to oscillate in the fronto-parallel plane.

Six practised subjects took part in the experiment. The first three subjects were presented with a randomized series of 12 trials in each of the three conditions; in half they were instructed to fixate the stationary line and in the other half, track the moving target. The order of presentation of the three conditions was different for each subject. The second three subjects were given a randomized series of 24 trials covering all three conditions with instructions to fixate in 12 and to track in the other 12.

*Results*

The combined results for all six subjects are shown in Table 1. In condition (a) which is similar to the "classical" Pulfrich situation with just the target differentially filtered, subjects reported the direction of rotation as counterclockwise (14 out of 15 reports) when the right eye was attenuated and clockwise (15 out of 15 reports) when the left eye was attenuated, whilst the subjects fixated the background. When subjects tracked the target, 24 out of the 30 reports were "flat" verifying the subjective reports given in Experiment 1. In condition (b) where only the background line was differentially filtered, 23 out of 30 reports were of "flat" during fixation, which is not surprising since the moving target was equally bright in both eyes. However, during tracking subjects gave consistent reports of the direction of rotation depending on which eye received the filtered background line: counterclockwise (14 out of 15 reports) when the background to the right eye was attenuated and clockwise (12 out of 15 reports) when the background to the left eye was attenuated. Condition (c) where both target and background were differentially filtered but in opposite directions provided the most interesting and conclusive set of results. During fixation subjects reported the direction of rotation in accordance with the differential

Table 1. Total of responses for six subjects

| | | Fixation | | | Tracking | | |
|---|---|---|---|---|---|---|---|
| | | Clockwise | Anti-clockwise | Flat | Clockwise | Anti-clockwise | Flat |
| (a) | *Right* Target filtered | 1 | 14 | 0 | 3 | 2 | 10 |
| | *Left* Target filtered | 15 | 0 | 0 | 1 | 0 | 14 |
| (b) | *Right* Background filtered | 3 | 2 | 10 | 0 | 14 | 1 |
| | *Left* Background filtered | 0 | 2 | 13 | 12 | 0 | 3 |
| (c) | *Right* Target + *Left* Background filtered | 0 | 14 | 1 | 10 | 2 | 3 |
| | *Left* Target + *Right* Background filtered | 14 | 0 | 1 | 1 | 14 | 0 |

filtering of the target as in condition (a) (28 out of 30 reports) but on tracking the target nearly all of the subjects' reports were *reversed* in direction corresponding to the differential filtering of the background as in condition (b) (24 out of 30 reports). Thus if the target were attenuated to the left eye and the background attenuated to the right eye, the target line would appear to rotate clockwise in depth during fixation and counterclockwise during tracking. There were no apparent differences between the results of the two groups of subjects which might have resulted from the different ordering of conditions.

## DISCUSSION

The results of Experiment 1 suggest that when the eyes track an oscillating target which is reduced in luminance to one eye, the eyes only make conjugate movements in phase with each other and with the target's path apart from the occasional saccade. That the eye movements were in phase with the target is not surprising as the target's path is repetitive and therefore highly predictable (Michael and Jones, 1966). Thus it would appear that the target stays on the foveas of both moving eyes so that any difference in latency caused by the reduction in luminance is unimportant. The subjective reports of Experiment 1, together with the results from condition (a) of Experiment 2 that the Pulfrich effect disappears during tracking, are thus consistent with the eye movement data. The question then arises as to why our results differ from previous findings and the commonly held view that the Pulfrich effect can be seen whilst tracking the target. The answer lies in the method used to attenuate the target: a neutral density filter in front of one eye not only reduces the luminance of the target but also of the background. When the background is attenuated as in condition (b) of our Experiment 2 and the eyes follow the target, the difference in latency caused by the differentially filtered background as it is swept across the retina produces a disparity which is interpreted as a change in depth of the background with respect to the target. It would seem that the brain attributes some of the change in relative depth to the target rather than the background, particularly if the background is extensive, not unlike the way motion is attributed to the smaller or surrounded object in the case of induced movement (Duncker, 1929).

When subjects were asked to comment on the background rather than the target in condition (b) it was frequently reported that the background line appeared to move back and forth in depth. In other words, when a moving object is tracked against a differentially filtered background, some of the change in depth produced by small latency difference in seeing the background is attributed to the target's motion causing an induced Pulfrich illusion. To conclude, the only thing that is important in producing a Pulfrich effect is the relative luminance of the objects which move across the retinae whether these be "target" or "background" or whether the subject fixates a stationary point or follows a moving object.

*Acknowledgements*—MJS and HO were supported by National Research Council of Canada grants A7664 and A0296 respectively.

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**Résumé**—Le trajet d'une cible oscillant dans un plan fronto-parallèle et filtrée différemment pour les deux yeux apparait elliptique en profondeur quand l'oeil fixe un point immobile. Quand les yeux suivent la cible, le trajet s'aplatit. L'enregistrement des mouvements des deux yeux indique que les yeux suivent le vrai trajet physique, avec seulement des mouvements conjugués et pas de changement de convergence.

**Zusammenfassung**—Der Weg eines Sehzeichens, das in einer fronto-parallelen Ebene oszilliert und für beide Augen differentiell gefiltert wird, erscheint in der Tiefe elliptisch, wenn die Augen einen stationären Punkt fixieren. Wenn die Augen das Sehzeichen verfolgen, verflacht sich der Weg. Binokulare Registrierungender Augenbewegungen zeigen an, dass die Augen dem wahren physikalischen Weg folgen, wobei sie nur konjugierte Bewegungen ohne Veränderung der Konvergenz ausführen.

**Резюме**—Траектория объекта, осциллирующего во фррнто-параллельной плоскости и диференциально подаваемого на оба глаза, кчжется эллиптической в глубину, когда глаза *фиксируют* неподвижный пункт. Если глаза *прослеживают* объект, траектория уплощается. Ьинокулярная регистрация движений глаз показывает, что глаза следуют за истиной физической траекторией, совершая только сопряженные движения, без изменения конвергенции.