The influence of target angular velocity on visual latency difference determined using the rotating Pulfrich effect[1]

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http://www.nickalls.org/dick/papers/pulfrich/pulfrich1996.pdf

Abstract

Visual latency difference was determined directly in normal volunteers, using the rotating Pulfrich technique described by Nickalls [*Vision Res.*, **26**, 367–372 (1986)]. Subjects fixated a black vertical rod rotating clockwise on a horizontal turntable turning with constant angular velocity (16·6, 33·3 or 44·7 rpm) with a neutral density filter (OD 0·7 or 1·5) in front of the right eye. For all subjects the latency difference associated with the 1·5 OD filter was significantly greater ($P < 0{\cdot}001$) with the rod rotating at 16·6 rpm than at 33·3 rpm. The existence of an inverse relationship between latency difference and angular velocity is hypothesised.

1 Introduction

The Pulfrich effect is a remarkable visual illusion, seen when a moving object is viewed binocularly with a neutral density filter in front of one eye (Pulfrich, 1922). For example, if a swinging pendulum is viewed in this way from a direction at right angles to its motion, then the pendulum bob appears to describe an elliptical orbit.

Although the Pulfrich effect has been extensively analysed for a pendulum and simple harmonic motion (Lit, 1949; Weale, 1954; Trincker, 1953; Levick, Cleland & Coombs, 1972), a number of other manifestations of the Pulfrich phenomenon have also been investigated. These include the 'rotating' Pulfrich effect (Nickalls, 1986a,1986b); apparent bending of unevenly illuminated rods (Barlow & McNaughton, 1980); a paradoxical decrease in apparent size when the target appears to come towards the observer (Weale, 1954; Spiegler, 1983); and an apparent hyperbolic path when the target moves with constant velocity in a plane which intersects the pupillary plane of the observer (Spiegler, 1986). Pulfrich effects have also been described in association with concentric rotation (Prestrude & Baker, 1968); bouncing balls (Wilson, 1965); motion of the observer (Enright, 1970), as well as in a variety of medical conditions which affect the optic nerve

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[1] This minor revision (December 2008) includes the age data for each subject (unfortunately omitted in the original published version—see section 2.7), fixes typos and adds some explanatory footnotes.

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(Larkin, Dutton & Heron, 1994), retina (Hofeldt, Leavitt & Behrens, 1985), or retinal illumination (Sokol, 1976).

The magnitude of the Pulfrich effect has been found to be a function of the plane of motion (Spiegler, 1986); the degree of binocular intensity difference (Lythgoe, 1938; Lit, 1949); viewing distance (Lit & Hyman, 1951); target size (Spiegler, 1983); target thickness (Lit, 1960c); and target velocity (Lit, 1960a, 1960b, 1964; Spiegler, 1983).

1.1 Mechanism

The mechanism underlying the Pulfrich phenomenon is not clear. The classical explanation proposed by Fertsch (see Pulfrich, 1922), is that the phenomenon is due to a unilateral increase in visual latency resulting from the decrease in retinal image intensity due to the filter (Williams & Lit, 1983; Carney, Paradiso & Freeman, 1989). Compelling evidence in support of a temporal delay model arises from the demonstration that a unilateral light-attenuating filter is able to delay a unilaterally time-advanced sequence of random-dot stereograms sufficiently to restore depth perception (Julesz & White, 1969; Ross & Hogben, 1975). A saccadic-suppression model has also been suggested (Harker, 1967) in order to explain the apparent asymmetrical path associated with a pendulum described by Trincker (1953).

However there are difficulties associated with the classical temporal delay model since the Pulfrich effect can be seen even with intermittent (stroboscopic) target presentation, possibly owing to some form of interaction (e.g. lateral inhibition) between successive inputs to the eyes (Lee, 1970). It is possible that the filter could introduce a spatial disparity by causing fusion of non-corresponding discrete positions, but this is unlikely in the case where the temporal interval between the motion samples is greater than the delay between the eyes (Morgan & Thompson, 1975). Furthermore, a Pulfrich-type effect can be produced without a delay by artificially increasing the target persistence in one eye (Morgan, 1975).

1.2 Preliminary study

In preliminary studies involving the ‘rotating’ Pulfrich effect (Nickalls, 1986a) it was noticed, contrary to expectation, that the latency difference for a given illumination appeared to vary significantly with turntable speed. In view of this discrepancy, the present study was designed to investigate the influence of turntable speed on latency difference.

2 Methods

Latency difference was determined directly using the technique described by Nickalls (1986a), which makes use of a ‘rotating’ Pulfrich effect. With this technique, an observer with a neutral density filter in front of the right eye, binocularly fixates a horizontally clockwise rotating target from within the plane of rotation. By varying the viewing distance, the observer identifies a null-position (known as ‘transition’) at which the target appears not to rotate at all, but appears to move only from side-to-side. The latency difference can then be calculated from the viewing distance at transition (see Equation 1).

2.1 Apparatus

The rotating target used in the present study was a black vertical rod (1·5 mm diameter) mounted 11·9 cm from the center of a horizontal clockwise-rotating turntable, and was clearly visible against a white background. Rotational cues from both the turntable and the ends of the rod were screened out by viewing through a 5 cm wide horizontal slit as described by Nickalls (1986a).

The turntable was mounted at eye-level, on a trolley which ran backwards and forwards on a straight 3·5 m track. The observer (fixed) was positioned at one end of the track, and was able to vary the position of the trolley, and hence the viewing distance, by turning a small hand-wheel. The subject's head was immobilised using chin and forehead rests in the usual way.

The angular velocity of the turntable (Garrard SP mark 2 record player) was determined using a diffuse-scan opto-switch, and displayed continuously in revolutions per minute (rpm; Ω) to one decimal place. The overall mean rpm (range) for each turntable speed for all observations described in this paper are as follows: 16·6 rpm (16·3–16·9); 33·3 rpm (33·0–33·9); 44·7 rpm (44·3–45·1). The maximum variation in turntable speed during a set of 10 observations (see Procedure) was ±0·3 rpm.

2.2 Illumination

The illumination was the same for all observations. The illumination of the both the front screen and the background screen was from above in order to maintain a uniform luminance throughout the full range of movement of the turntable apparatus.

The luminance of the front screen and background (both white) was measured using a narrow angle 40A Opto-meter (Model R, United Detector Technology Inc.) which incorporated a silicon PIN photodiode with a foot-lambert lens. All luminance readings were made from a distance of 20 cm in front of the front screen; background readings were made through the viewing slit. The mean (range) luminance of both the front screen and the background screen over the full range of viewing distance was 114 cd.m^{-2} (109–121; $n = 8$) and 124 cd.m^{-2} (116–130; $n = 8$) respectively.

2.3 Filters

Two different Wrattan neutral-density filters (Kodak) were used, having optical densities (OD) of 0·7 and 1·5. During each experiment one of these filters was placed in front of the right eye, using special goggles which prevented any extraneous non-filtered light from reaching the filtered eye.

2.4 Separation of rotation centres of the eyes

The semi-separation (a) of the rotation centres of the two eyes (required for Equation 1), was determined by measuring the inter-pupillary distance (IPD) when the eyes were both parallel and at right angles to the line joining the two eyes. The IPD was measured using a corneal-reflection pupillometer (Essilor Ltd., Bristol, UK). The IPD values presented in the Tables are the mean (rounded to the nearest 1 mm) of five sequential measurements.

2.5 Transition viewing distance

The viewing distance at 'transition' (d_{T}) was measured from the centre of the turntable to the line joining the centres of rotation of the two eyes. This was done by first measuring the distance from the centre of the turntable to the front of the cornea. An additional 1·5 cm was then added to this value to account for the distance between the front of the cornea and the rotation centre of the eye (Fry & Hill, 1962). For all studies the viewing distance at transition was within the range 90–270 cm.

2.6 Latency difference

Each of the latency difference determinations presented in the Tables is the mean of 10 sequential measurements. The latency difference (Δt sec) was derived from three parameters namely (1) the viewing distance (d_{T} cm) at which the 'transition' null-point is perceived, (2) the value of half the separation of the rotation centers of the eyes (a cm), and (3) the angular velocity of the turntable (Ω rpm). The latency difference was calculated using Equation 1, in which the angular velocity (Ω) is in revolutions per minute (rpm)—see Appendix for derivation.

$$\Delta t = (1/3\Omega)\tan^{-1}(a/d_{\mathrm{T}}) \qquad (1)$$

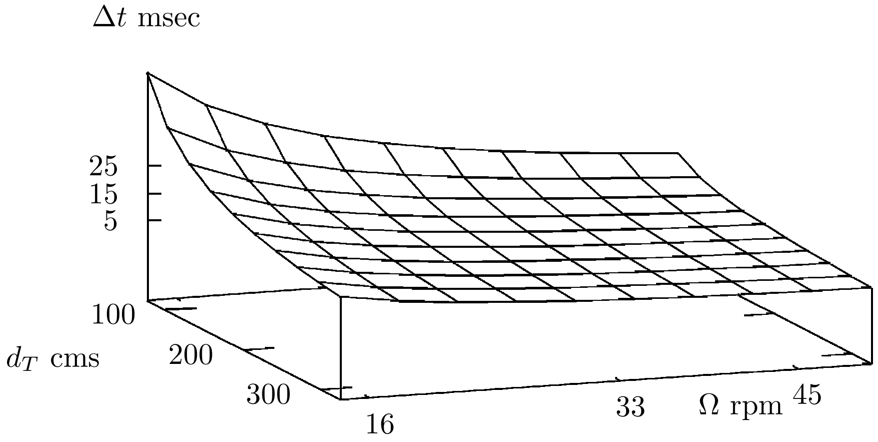

Figure 1: Variation of latency difference (Δt) with turntable speed (Ω) and transition distance (d_{T}) as described by Equation 1 with $a = 3{\cdot}2$ cm ($IPD = 6{\cdot}4$ cm).

Equation 1 is depicted graphically in Figure 2.6. Owing to the non-linear nature of Equation 1 it follows that for a given number of observations, the mean d_{T} does not correlate accurately with the associated mean Δt. Consequently, the mean Δt values for each subject given in the Tables are derived from the individual Δt values.

In addition, the format of Equation 1 is significant in that a relatively large error in the viewing distance at transition (d_{T}) is associated with only a very small error in the calculated latency difference (Δt). For example, if $a = 3{\cdot}2$ cm,

$\Omega = 33$ rpm and $d_{\mathrm{T}} = 120$ cm, then an error of ± 1 cm in d_{T} is associated with an error of only $\pm 0{\cdot}13$ msec in Δt.

2.7 Subjects

A number of studies were performed on a total of 14 normal experienced volunteers whose ages ranged from 22 (PO)–54 (RC) years. All subjects had normal depth perception as determined using the Wirt Fly test.

The age (yrs) of each subject was as follows[3]: PN (22), PO (24), MH (27), IJ (28), SM (29), SY (30), AM (32), SR (35), MK (35), RWDN (36), MC (37), NGH (40), EAN (44), RC (54).

2.8 Procedure

The latency difference was determined for a number of combinations of turntable speed (16·6, 33·3, 44·7 mean rpm) and filter density (OD 0·7, 1·5).

The subjects were investigated in two sessions. During one session, the following combinations of filter optical density and turntable speed were used: (0·7 OD/33·3 rpm; 0·7 OD/44·7 rpm; 1·5 OD/33·3 rpm). During the other session, the following combinations were used: (1·5 OD/16·6 rpm; 1·5 OD/33·3 rpm). Note that the only combinations of filter density and turntable speed which could be used, were those for which the viewing distance at transition was within the range of the physical track (3·5 m) that the turntable moved on (see Nickalls 1986a for details of the laboratory setup).

In 9 subjects repeat latency difference determinations were made for the 1·5 OD/33·3 rpm combination (see Table 3) following a mean interval of 182 days (range: 1 day–14 months) in order to check reproducibility. A repeat determination for the 0·7 OD/33·3 rpm combination was made in one subject (RWDN).

The illumination was the same for all observations. Each subject was given 20 mins to dark adapt to each filter (see Standing, Dodwell & Lang, 1968).

For each combination of turntable speed and filter density, the latency difference was determined as the mean of a series of 10 sequential measurements. For each measurement of latency difference, the turntable was initially positioned at either the near or the far point of the track (i.e. either close to or far away from the subject). The subject was then asked to fixate the horizontally rotating target, and at the same time to adjust the position of the turntable using the small hand wheel, until the null-point (transition) was identified. During each series of 10 measurements a bracketing technique was used, whereby the initial position of the turntable was alternately varied from the point nearest to the observer on one measurement ('near'), to the point farthest from the observer for the next

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[3] This data, which was unfortunately omitted from the original published paper, may be significant since artificial pupils were not used in these experiments. However, there is good evidence (Lit, 1960a) to suggest that under these circumstances pupillary changes alone are unlikely to be the cause of the observed variation of visual latency difference with turntable angular velocity. Lit (1960a) used artificial 2 mm pupils in a similar study observing a vertical rod moving with constant linear velocity, and still observed comparable changes, both in magnitude and direction. Furthermore, in view of the known slight reduction in pupil size with increasing age (Birren JE, Casperson R and Botwinick J (1950); Age changes in pupil size *Journal of Gerontology*; <u>5</u>, 216) it is significant that the data from the present study shows that the within-subject differences *between* the calculated latency differences (Δt) associated with the turntable angular velocities used, are independent of observer age throughout the range 22–54 years (RWDN, December 2008).

measurement ('far'). A typical series of 10 sequential measurements is shown in Table 1.

Table 1: A typical series of 10 sequential measurements of visual latency difference (subject SY; age 30 yrs; IPD 64 mm).

OD = 1.5			
Initial turntable position	Ω (rpm)	d_{T} (cm)	Δt (msec)
near	33·6	117·5	15·48
far	33·5	116·3	15·68
near	33·5	114·8	15·89
far	33·5	110·7	16·48
near	33·4	125·6	14·57
far	33·5	109·6	16·64
near	33·5	126·4	14·43
far	33·4	113·7	16·09
near	33·3	118·3	15·51
far	33·3	107·1	17·13
n	10	10	10
mean	33·4	116·0	15·8
SEM	0·03	2·01	0·27

3 Results

Each determination of latency difference is the mean of 10 sequential measurements (see Table 1). The range of the calculated SEM for Δt for all subjects was 0·11–1·80 msec. The data is shown in Tables 1–5 and in Figures 2–4. Paired and unpaired data were analysed using a two-tailed Student's t-test.

3.1 Influence of filter density on latency difference

This data, which is presented in order to serve as a comparison with other latency difference studies in the literature, is presented in Table 2 and Figure 2.

These results indicate that for each subject ($\Omega = 33{\cdot}3$ rpm), the latency difference using the 1·5 OD filter was greater than that that using the 0·7 OD filter. The mean (±SEM) within-subject difference in Δt ($6{\cdot}3 \pm 0{\cdot}52$ msec; $n = 10$) is significant ($P < 0{\cdot}001$). In this group the mean (±SEM) latency difference using the 1.5 OD filter ($15{\cdot}0 \pm 0{\cdot}58$ msec; $n = 10$) is significantly different ($P < 0{\cdot}001$) from that using the 0·7 OD filter ($8{\cdot}7 \pm 0{\cdot}23$ msec; $n = 10$).

In nine subjects repeat latency difference determinations were made (see Table 3) following a mean interval of 182 days (range: 1–439). There was no significant within-subject difference between the two determinations ($P > 0{\cdot}1$); the mean (±SEM) within-subject difference in Δt being $0{\cdot}04 \pm 0{\cdot}42$ msec ($n = 9$). All repeat determinations were made using the same turntable speed (33·3 rpm), neutral-density filter (1·5 OD), and illumination.

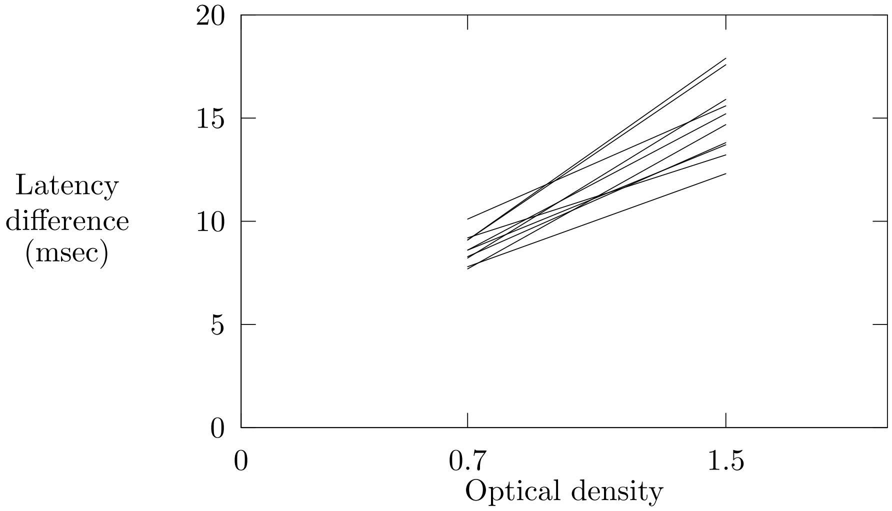

Figure 2: Influence of optical density on visual latency difference in 10 subjects ($\Omega = 33{\cdot}3$ rpm). For data see Table 2.

3.2 Influence of angular velocity on latency difference

The latency difference data is presented in terms of turntable speed (Figure 3) and in terms of mean (rms) angular velocity at the eye (Figure 4).

The mean angular velocity at the eye (deg/sec) of the rotating rod was determined as the root mean square (rms) angular velocity, and shown in Tables 4 and 5. This was calculated from the turntable speed and the mean viewing distance at transition, using the formula for the instantaneous angular velocity described in Appendix 2.

3.2.1 0·7 **OD filter**

These results (see Table 4 & Figures 3 and 4) indicate that with the exception of one subject (RWDN), both the latency difference and the viewing distance at transition associated with the slower turntable speed (33·3 rpm), were greater than those associated with the faster turntable speed (44·7 rpm).

The mean (±SEM) within-subject difference in Δt ($1{\cdot}2 \pm 0{\cdot}21$ msec; $n = 10$) is significant ($P < 0{\cdot}001$). In this group, the mean (±SEM) latency difference determination at 33·3 rpm ($8{\cdot}7 \pm 0{\cdot}23$ msec; $n = 10$) is significantly different ($P < 0{\cdot}001$) from that determined at 44·7 rpm ($7{\cdot}5 \pm 0{\cdot}21$ msec; $n = 10$).

3.2.2 1·5 **OD filter**

These results (see Table 5 & Figures 3 and 4) indicate that for each subject, both the latency difference and the viewing distance at transition associated with the slower turntable speed (16·6 rpm), were greater than those associated with the faster turntable speed (33·3 rpm).

The mean (±SEM) within-subject difference in Δt ($6{\cdot}4 \pm 0{\cdot}35$ msec; $n = 11$) is significant ($P < 0{\cdot}001$). In this group the mean (±SEM) latency difference

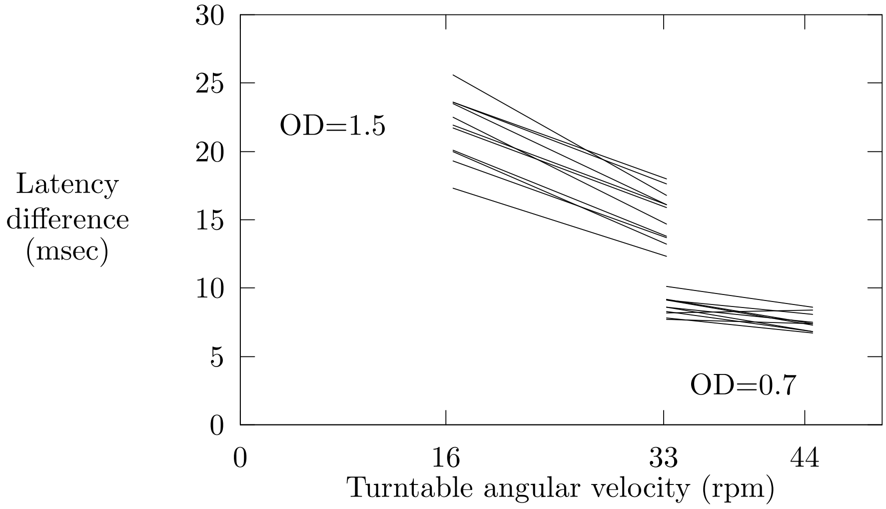

Figure 3: Influence of turntable speed on visual latency difference in 11 subjects. For data see Tables 4 & 5.

determination at 33·3 rpm (15·3 ± 0·57 msec; $n = 11$) is significantly different ($P < 0{\cdot}001$) from that determined at 16·6 rpm (21·7 ± 0·72 msec; $n = 11$).

4 Discussion

4.1 Variation of latency difference with optical density

This study indicates that the variation of latency difference with filter density (see Figure 2) for the given illumination using the rotating Pulfrich effect, is in close agreement with both (a) the data of Prestrude & Baker (1968) using concentric rotating lines with similar filters and illumination, and (b) the data of Standing *et al.* (1968) using similar filters and a vertical rod. These results therefore further validate the use of the rotating Pulfrich technique (Nickalls, 1986a) for the measurement of visual latency differences.

In addition the present study also indicates that latency difference determinations, made using the rotating Pulfrich technique for the 1·5 OD/33·3 rpm combination under identical circumstances, are reproducible over many months (see Table 3).

4.2 Variation of latency difference with angular velocity

The major finding of this study is that for the inter-ocular luminance differences used, visual latency difference was found to vary significantly with both turntable speed and mean (rms) angular velocity at the eye.

When using the 1·5 OD filter, there was a significant inverse relationship between latency difference and both turntable speed and mean (rms) angular velocity at the eye (see Figures 3 and 4). Similarly, the data obtained using the

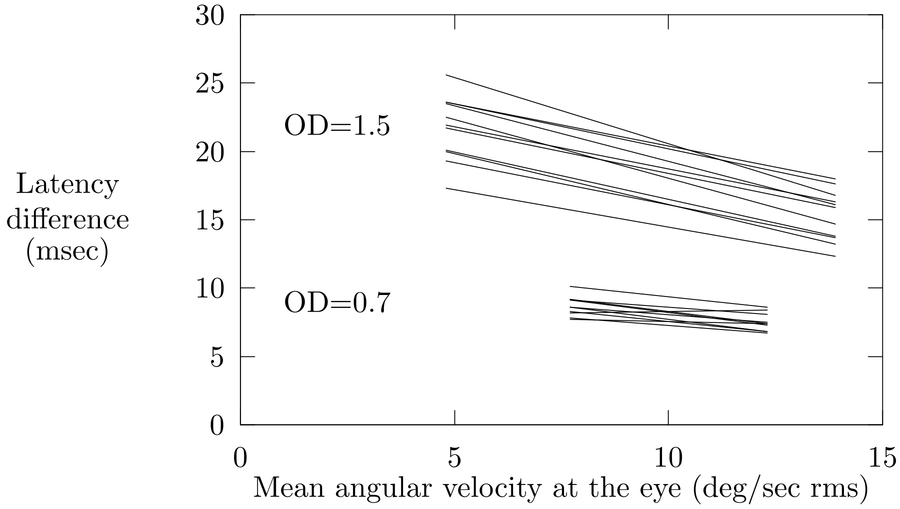

Figure 4: Influence of angular velocity at the eye on visual latency difference in 11 subjects. For data see Tables 4 & 5.

0·7 OD filter was also in keeping with this inverse relationship, with the mean latency difference at 33·3 rpm being significantly greater than that at 44·7 rpm.

4.3 Other relevant studies

The most relevant study in the literature appears to be that of Lit (1960a), who investigated the relationship between latency difference and angular velocity using a black vertical rod moving with constant linear horizontal velocity (range 1·5–31·8 deg/sec), at four separate binocular illuminance differences.

In this study Lit observed a significant non-linear inverse relationship between latency difference and target angular velocity at the eye for angular velocities less than about 20–25 deg/sec, which became progressively more pronounced as the binocular illuminance difference was increased. For any given difference in binocular illuminance, visual latency difference decreased progressively to a plateau as the angular velocity at the eye increased.

However, Lit gives no estimate of the precision of his observations. Furthermore, Lit determined the apparent displacement of the moving target using an adjustable pointer which was fixated by the subject, and in view of the difference between foveal and extra-foveal latency, this may have introduced some error (see Nickalls, 1986a).

Significantly, similar but rather more subjective evidence for an increase in visual latency as angular velocity decreases has also been described in association with a number of 'sensation-time' experiments; for example those by of Fröhlich (1923), Holz (1934) and others, which have been well summarised by Lit (1960a).

4.3.1 Hypothesis

The present study shows conclusively that there is a significant inverse relationship between visual latency difference and turntable angular velocity (and hence with

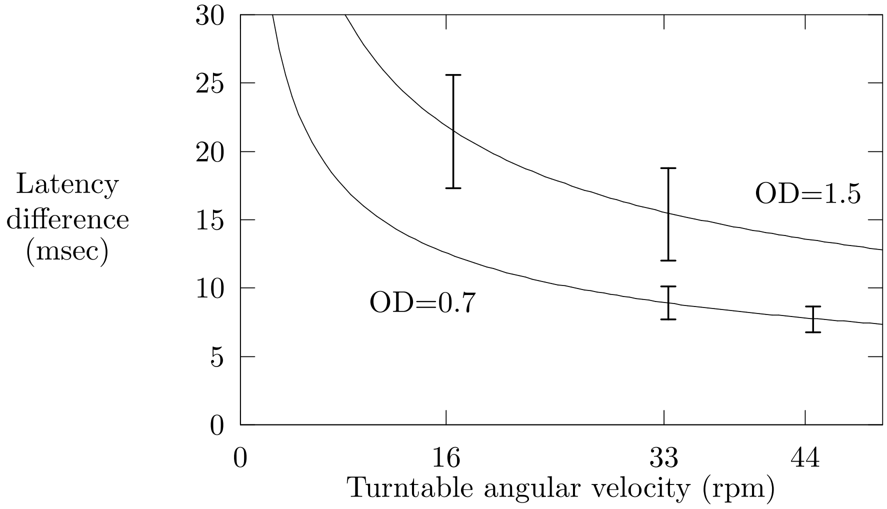

Figure 5: Hypothetical relationship between turntable angular velocity and visual latency difference. The bars indicate the range of data points given in Tables 4 and 5 and shown in Figure 3.

mean (rms) target angular velocity at the eye) within the parameter range studied. In view of these findings, and those of Lit (1960a), Fröhlich (1923) and Holz (1934), the author suggests the hypothesis that for a given inter-ocular illuminance difference there exists a continuous inverse relationship between visual latency difference and turntable angular velocity as shown in Figure 5.

The mechanism by which velocity influences visual latency difference is not clear. However, it has recently been shown that motion produces equivalent spatial blur which is velocity dependent (Pääkkönen & Morgan, 1994), and it is possible therefore, that there may be an association between smaller blur (slow velocity) and longer latency. Alternatively, this effect may be related to properties of the different motion sensor systems which process slow and fast velocities (see Hawken, Gegenfurtner & Tang, 1994).

Acknowledgements

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Table 2: Comparison of latency difference determinations in 10 subjects ($\Omega = 33{\cdot}3$ rpm) using two different neutral density filters. The mean within-subject difference in Δt is significant ($P < 0{\cdot}001$). Each determination is the mean of 10 sequential measurements. $*$ indicates pooled data from two separate determinations. This data is shown in Figure 2.

Subject	IPD	$OD = 1{\cdot}5$ $\Omega = 33{\cdot}3$ rpm		$OD = 0{\cdot}7$ $\Omega = 33{\cdot}3$ rpm	
	(mm)	d_T (cm) mean ± SEM (range)	Δt (msec) mean ± SEM (range)	d_T (cm) mean ± SEM (range)	Δt (msec) mean ± SEM (range)
PO	60·9	142·8 ± 2·3 (125·5–160·7)$*$	12·3 ± 0·21 (10·8–14·0)$*$	228·1 ± 6·2 (197·4–260·6)	7·8 ± 0·21 (6·7–8·9)
RWDN	66·4	119·9 ± 1·0 (112·1–130·1)$*$	15·9 ± 0·14 (14·5–17·1)$*$	234·9 ± 3·5 (206·2–261·4)$*$	8·2 ± 0·12 (7·4–9·3)$*$
EAN	61·3	120·5 ± 2·5 (99·6–135·8)$*$	14·7 ± 0·31 (13·1–17·5)$*$	229·0 ± 3·3 (210·1–244·4)	7·7 ± 0·11 (7·2–8·4)
RC	68·0	111·4 ± 1·9 (96·1–128·3)$*$	17·6 ± 0·30 (15·1–20·3)$*$	214·1 ± 3·6 (195·3–239·1)	9·1 ± 0·15 (8·2–10·0)
SM	61·9	130·3 ± 2·0 (106·4–151·9)$*$	13·7 ± 0·22 (11·7–16·7)$*$	210·2 ± 10·1 (171·0–263·7)	8·6 ± 0·41 (6·7–10·3)
MC	61·2	129·2 ± 3·3 (109·0–162·4)$*$	13·8 ± 0·33 (10·9–16·2)$*$	219·0 ± 12·6 (168·1–261·8)	8·3 ± 0·50 (6·7–10·5)
IJ	57·9	115·0 ± 2·7 (104·7–134·6)	15·2 ± 0·34 (12·9–16·6)	205·9 ± 9·1 (168·0–245·5)	8·6 ± 0·37 (7·1–10·4)
AM	64·0	121·5 ± 4·5 (105·5–153·5)	15·6 ± 0·52 (12·2–17·7)	190·4 ± 11·4 (143·4–246·8)	10·1 ± 0·61 (7·5–13·0)
PN	63·5	100·2 ± 1·0 (97·1–107·6)	17·9 ± 0·16 (16·8–18·5)	198·9 ± 5·0 (169·8–219·6)	9·1 ± 0·23 (8·2–10·6)
MK	64·4	141·4 ± 5·8 (123·5–185·3)	13·2 ± 0·48 (9·9–14·9)	202·5 ± 8·2 (169·8–244·2)	9·2 ± 0·36 (7·5–10·9)
	n	10	10	10	10
	mean	123·2	15·0	213·3	8·7
	SEM	4·16	0·58	4·60	0·23

Table 3: Repeat determinations of latency difference in 9 subjects ($OD = 1{\cdot}5$; $\Omega = 33{\cdot}3$ rpm). The mean within-subject difference in Δt is not significant (P> 0·1). Each determination is the mean of 10 sequential measurements.

$OD = 1{\cdot}5$, $\Omega = 33{\cdot}3$ rpm					
Subject	IPD (mm)	Δt_1 msec (first test)	Δt_2 msec (second test)	Time interval (days)	Difference (msec)
		mean ± SEM (range)	mean ± SEM (range)		$\Delta t_1 - \Delta t_2$
PO	60·9	12·9 ± 0·25 (11·6–14·0)	11·7 ± 0·21 (10·8–12·6)	206	+1·2
RWDN	66·4	16·1 ± 0·16 (15·5–17·1)	15·8 ± 0·23 (14·5–16·8)	197	+0·3
EAN	61·3	13·8 ± 0·19 (13·1–14·8)	15·6 ± 0·41 (13·5–17·5)	203	−1·8
RC	68·0	16·7 ± 0·28 (15·1–17·9)	18·5 ± 0·34 (16·7–20·3)	119	−1·8
SM	61·9	13·7 ± 0·21 (12·7–14·9)	13·7 ± 0·40 (11·7–16·7)	269	0·0
MC	61·2	14·6 ± 0·34 (12·8–16·2)	13·1 ± 0·47 (10·9–15·4)	439	+1·5
MH	57·9	16·6 ± 0·41 (14·3–18·8)	15·6 ± 0·23 (14·9–17·2)	175	+1·0
SY	64·0	15·8 ± 0·27 (14·4–17·1)	16·7 ± 0·13 (16·3–17·4)	27	−0·9
SR	63·5	17·2 ± 0·47 (15·5–19·8)	16·3 ± 0·32 (14·8–18·1)	1	+0·9
			n	9	9
			mean	182	0·04
			SEM	—	0·42

Table 4: Comparison of latency difference determinations in 10 subjects. The mean within-subject difference in Δt is significant ($P < 0{\cdot}001$). Each determination is the mean of 10 measurements ($\dagger n = 6$). $*$ indicates pooled data from two separate determinations.

Subject	IPD	$OD = 0{\cdot}7$ $\Omega = 33{\cdot}3$ rpm		$OD = 0{\cdot}7$ $\Omega = 44{\cdot}7$ rpm	
	(mm)	d_T (cm) mean ± SEM (range)	Δt (msec) mean ± SEM (range)	d_T (cm) mean ± SEM (range)	Δt (msec) mean ± SEM (range)
PO	60·9	228·1 ± 6·2 (197·4–260·6)	7·8 ± 0·22 (6·7–8·9)	195·3 ± 5·7 (171·0–224·0)	6·7 ± 0·19 (5·8–7·6)
RWDN	66·4	234·9 ± 3·5 (206·2–261·4)∗	8·2 ± 0·12 (7·4–9·3)∗	171·1 ± 2·4 (157·4–181·7)	8·4 ± 0·12 (7·9–9·1)
EAN	61·3	229·0 ± 3·3 (210·1–244·4)	7·7 ± 0·11 (7·2–8·4)	178·3 ± 2·8 (165·6–191·3)	7·4 ± 0·12 (6·9–7·9)
RC	68·0	214·1 ± 3·6 (195·3–239·1)	9·1 ± 0·15 (8·2–10·0)	180·5 ± 3·3 (163·0–195·5)	8·1 ± 0·15 (7·4–8·9)
SM	61·9	210·2 ± 10·1 (171·0–263·7)	8·6 ± 0·41 (6·7–10·3)	179·4 ± 14·2 (143·5–229·1)†	7·5 ± 0·57 (5·7–9·2)†
MC	61·2	219·0 ± 12·6 (168·1–261·8)	8·3 ± 0·50 (6·7–10·5)	198·2 ± 11·3 (150·1–234·1)	6·8 ± 0·42 (5·6–8·7)
IJ	60·3	205·9 ± 9·1 (168·0–245·5)	8·6 ± 0·38 (7·1–10·4)	193·0 ± 7·3 (155·5–224·4)	6·8 ± 0·27 (5·8–8·3)
AM	65·1	190·4 ± 11·4 (143·4–246·8)	10·1 ± 0·61 (7·5–13·0)	165·6 ± 8·0 (132·7–199·5)	8·6 ± 0·41 (7·0–10·5)
PN	62·7	198·9 ± 5·0 (169·8–219·6)	9·1 ± 0·23 (8·2–10·6)	182·7 ± 3·0 (171·9–199·6)	7·3 ± 0·12 (6·9–7·8)
MK	64·4	202·5 ± 8·2 (169·8–244·2)	9·2 ± 0·36 (7·5–10·9)	190·1 ± 10·1 (144·4–252·5)	7·4 ± 0·38 (5·4–9·5)
	n	10	10	10	10
	mean	213·3	8·7	183·4	7·5
	SEM	4·60	0·23	3·4	0·21
		Mean angular velocity at the eye = 7·9 deg/sec rms		Mean angular velocity at the eye = 12·3 deg/sec rms	

Table 5: Comparison of latency difference determinations in 11 subjects. The mean within-subject difference in Δt is significant ($P < 0{\cdot}001$). Each determination is the mean of 10 measurements. $*$ indicates pooled data from two separate determinations.

Subject	IPD (mm)	$OD = 1{\cdot}5$ $\Omega = 16{\cdot}6$ rpm d_T (cm) mean ± SEM (range)	$OD = 1{\cdot}5$ $\Omega = 16{\cdot}6$ rpm Δt (msec) mean ± SEM (range)	$OD = 1{\cdot}5$ $\Omega = 33{\cdot}3$ rpm d_T (cm) mean ± SEM (range)	$OD = 1{\cdot}5$ $\Omega = 33{\cdot}3$ rpm Δt (msec) mean ± SEM (range)
PO	60·9	204·0 ± 7·1 (171·6–240·2)	17·3 ± 0·62 (14·5–20·3)	142·8 ± 2·3 (125·5–160·7)∗	12·3 ± 0·21 (10·8–14·0)∗
RWDN	66·4	179·4 ± 9·4 (143·2–221·2)	21·7 ± 1·10 (17·4–26·4)	119·9 ± 1·0 (112·1–130·1)∗	15·9 ± 0·14 (14·5–17·1)∗
EAN	61·3	156·4 ± 4·3 (135·9–182·8)	22·5 ± 0·62 (19·2–25·6)	120·5 ± 2·5 (99·6–135·8)∗	14·7 ± 0·31 (13·1–17·5)∗
RC	68·0	166·4 ± 4·8 (143·5–195·1)	23·6 ± 0·64 (20·2–27·1)	111·4 ± 1·9 (96·1–128·3)∗	17·6 ± 0·30 (15·1–20·3)∗
SM	61·9	188·8 ± 8·5 (152·3–238·2)	19·3 ± 0·85 (15·0–23·5)	130·3 ± 2·0 (106·4–151·9)∗	13·7 ± 0·22 (11·7–16·7)∗
MC	61·2	182·7 ± 10·8 (140·7–223·1)	20·1 ± 1·20 (15·8–25·3)	129·2 ± 3·3 (109·0–162·4)∗	13·8 ± 0·33 (10·9–16·2)∗
MH	57·9	142·2 ± 3·7 (120·3–156·1)	23·5 ± 0·68 (21·0–27·7)	103·6 ± 1·6 (88·7–116·0)∗	16·1 ± 0·26 (14·3–18·8)∗
SY	64·0	168·2 ± 3·0 (150·1–182·8)	21·9 ± 0·41 (20·0–24·7)	112·8 ± 1·3 (105·3–126·4)∗	16·3 ± 0·18 (14·4–17·4)∗
SR	63·5	146·8 ± 9·2 (113·2–199·5)	25·6 ± 1·52 (18·1–32·7)	109·4 ± 1·8 (92·4–123·4)∗	16·8 ± 0·30 (14·8–19·8)∗
MK	64·4	197·4 ± 16·7 (131·0–269·2)	20·0 ± 1·71 (13·8–27·9)	141·4 ± 5·8 (123·5–185·3)	13·2 ± 0·48 (9·9–14·9)
NGH	63·1	162·5 ± 12·7 (114·7–223·8)	23·6 ± 1·8 (16·3–31·3)	100·8 ± 1·4 (90·8–106·2)	18·0 ± 0·26 (17·1–20·0)
	n	11	11	11	11
	mean	172·3	21·7	120·2	15·3
	SEM	6·0	0·72	4·31	0·57
		Mean angular velocity at the eye = 4·9 deg/sec rms		Mean angular velocity at the eye = 14·1 deg/sec rms	

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APPENDIX

***Appendix 1*: Latency difference**

The following relationship for the rotating Pulfrich effect, between the latency difference (Δt sec), the viewing distance (d_T cm) at which the 'transition' null-point is perceived, the value of half the separation of the rotation centers of the eyes (a cm), and the angular velocity of the turntable (ω deg/sec), was derived by Nickalls (1986a).

$$\Delta t = (2/\omega)\tan^{-1}(a/d_\mathrm{T})$$

However, in the present study the angular velocity of the turntable was calibrated in revolutions per minute (Ω rpm). Since 1 rpm $\equiv$ 6 deg/sec, then the above equation (where ω is in deg/sec) can be modified to become Equation 1 where Ω is in rpm, as follows.

$$\Delta t = (1/3\Omega)\tan^{-1}(a/d_\mathrm{T}).$$

***Appendix 2*: Target angular velocity at eye**[5]

Let the eyes be in the same plane as the rotating rod, and let the centre of rotation O lie in the subject's sagittal plane. Let the radius of rotation be r about the centre of rotation O. If O is a distance d from the eye ($d > r$), then it can be shown that the instantaneous angular velocity of the rod at the eye ($d\psi/dt$) is given by

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = \omega \left[\frac{r(d\cos\theta - r)}{r^2 + d^2 - 2rd\cos\theta} \right],$$

where the angle θ defines the instantaneous position of the rod about the centre of rotation O, and ω is the speed of rotation of the rod. The rod is at nearest approach to the eye when $\psi = \theta = 0$.

◇ ◇ ◇

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[5] Derivation:

> If the angle subtended by the rod at the eye is ψ, then we can write $\tan\psi = r\sin\theta/(d - r\cos\theta)$, and hence
>
> $$\frac{\mathrm{d}\psi}{\mathrm{d}\theta} = \frac{r(d\cos\theta - r)\cos^2\psi}{(d - r\cos\theta)^2}.$$
>
> But
>
> $$\cos\psi = \frac{d - r\cos\theta}{\sqrt{r^2 + d^2 - 2rd\cos\theta}},$$
>
> and so
>
> $$\frac{\mathrm{d}\psi}{\mathrm{d}\theta} = \frac{r(d\cos\theta - r)}{r^2 + d^2 - 2rd\cos\theta}.$$
>
> Finally,
>
> $$\frac{\mathrm{d}\psi}{\mathrm{d}t} = \left(\frac{\mathrm{d}\psi}{\mathrm{d}\theta}\right)\left(\frac{\mathrm{d}\theta}{\mathrm{d}t}\right) = \omega\left(\frac{\mathrm{d}\psi}{\mathrm{d}\theta}\right),$$
>
> and hence
>
> $$\frac{\mathrm{d}\psi}{\mathrm{d}t} = \frac{\omega r(d\cos\theta - r)}{r^2 + d^2 - 2rd\cos\theta}.$$
>
> As a check, it is clear that the maximum and minimum angular velocity of the rod at the eye is when the rod crosses the midline, i.e. when $\psi = \theta = 0, \pi$, in which case the above equation reduces to
>
> $$\frac{\mathrm{d}\psi}{\mathrm{d}t} = \frac{r\omega}{d \pm r},$$
>
> where the $+$ sign corresponds to when the rod is farthest from the eye (distance $d + r$), and the $-$ sign corresponding to when the rod is nearest to the eye (distance $d - r$). Rearranging this shows that the linear velocity of the rod at these points is simply $r\omega$, as expected.
>
> $$(d \pm r)\frac{\mathrm{d}\psi}{\mathrm{d}t} = r\omega = \text{linear velocity of rod.}$$