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# PHASE SHIFT IN THE PERCEPTION OF SINUSOIDALLY MODULATED LIGHT AT LOW LUMINANCES

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## *Summary*

Latency effects in the perception of light stimuli were investigated with sinusoidally modulated light. It appears that there is for low frequencies an increasing phase lag – rather than an increasing delay – with decreasing luminance. A model is proposed which in principle may explain the phenomena observed.

## *Introduction*

The perception of a light stimulus will always lag with respect to the stimulus itself. We cannot study this time lag as such, since the moment of perception is inaccessible to direct experimentation. But we can study it as a differential effect. An example of such a differential effect is the Pulfrich effect, in which the only apparently elliptical movements of the pendulum convincingly demonstrate the existence of differences in visual latency with differences in luminance. The stimulus conditions are however complex, as movements of the pendulum include spatial as well as temporal parameters. A simpler experimental procedure can be found, following the profitable track, indicated by De Lange<sup>1</sup> some ten years ago, by using sinusoidally modulated light. Differential effects of latency appear then as phase shifts, in De Lange's own experiment as a function of  $\Delta\lambda$ . Two years ago Walraven and Leebeek<sup>2</sup> reported at the flicker symposium in Amsterdam more on this phase shift between sinusoidally alternating light stimuli of different wavelength.

Following De Lange's procedure, the two stimuli were mixed (Fig. 1) with such intensities and difference in phase that flicker was eliminated as much as possible. The difference in phase on the stimulus side thus determined was interpreted as a compensation for their perceptual difference in latency. For details we refer to the original publication. In order to find an optimum experimental condition, they made a quick reconnaissance through the luminance range and found (Fig. 2) that the phase shift between the two colored stimuli steadily increased with decreasing luminance until the moment experimentation had to be stopped because the field became too dark.

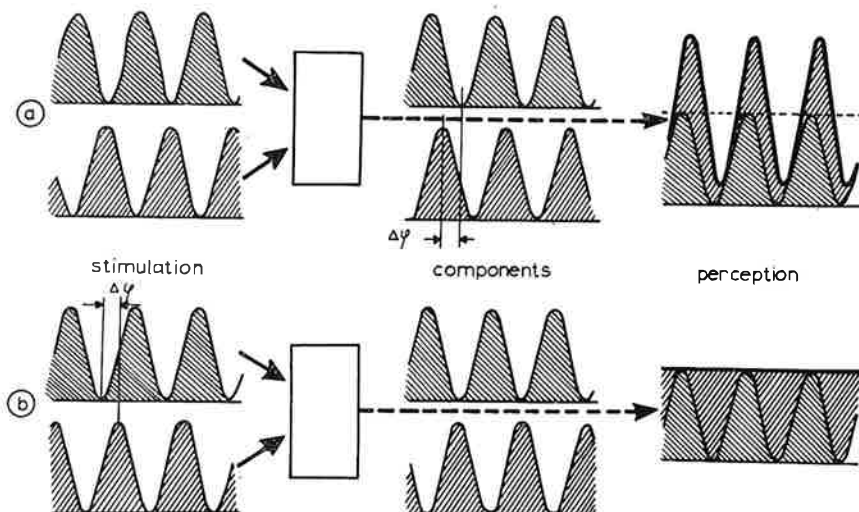


Fig. 1. The upper part shows how mixing of stimuli of different wavelength, which are offered in phase to the eye can produce luminance flicker because of a phase shift in the retina-cortex system. The lower part illustrates how we can compensate for this phase shift by a physical shift on the stimulus side.

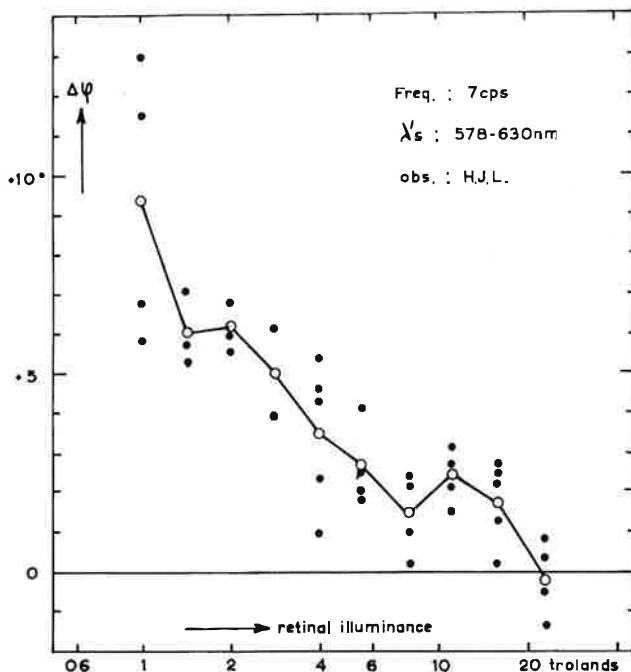


Fig. 2. Phase shift as a function of retinal illuminance for the wavelength combination and frequency indicated. Each dot is an experimental point. The line drawn connects average values (open circles).

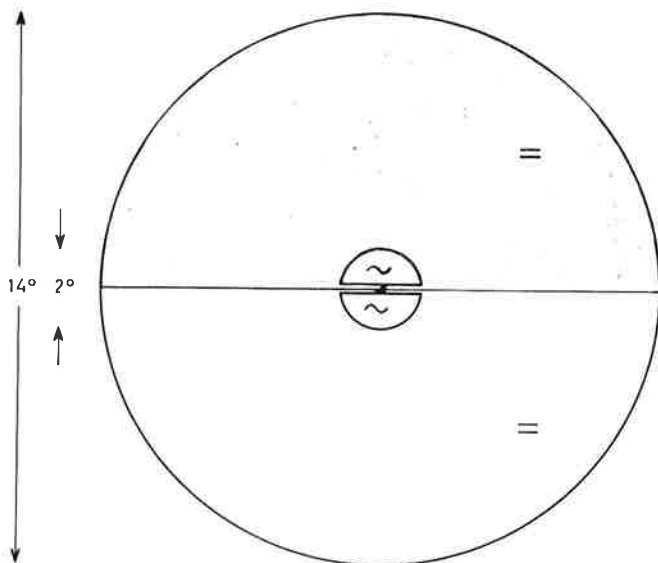


Fig. 3. The field of view in the experiments where two flickering fields of different luminance were subjectively matched in phase. Either the upper or the lower half was covered with a 10% transmitting filter.

Later experiments, directed in particular on this luminance effect confirmed this trend. In these experiments two luminance levels were compared directly by giving them simultaneously in the upper and lower half of the foveal field, respectively (Fig. 3). The observer had to match both flickering half fields in phase.

The two half fields had a luminance ratio of 1 : 10 in all experimental conditions, but the general level could be varied. Again it was found that there is a phase difference in the perception of the two flickering half fields and that this phase shift steadily increases with decreasing luminance.

In Fig. 4 we have plotted these various phase shifts as straight strips, which were put in line in the best possible way to form a cumulative graph. This implies the – most obvious – assumption that phase shifts are additive. That these phase shifts increase with decreasing luminance is interesting, though not surprising if one is familiar with the Pulfrich phenomenon<sup>3</sup>. More surprising is the fact that the phase shifts in Fig. 4 are independent of the flicker frequency in the experimental range, and their size. Between 0.25 and 1.72 cps the experimental data hardly differed and the cumulative phase shift between the brightest and faintest flicker field turned out to be about 32°. This phase shift corresponds to about 0.3 sec latency difference at 0.25 cps. Both the magnitude of this time and the independence of the phase shift with respect to the frequency make us believe that we do not deal here with a real

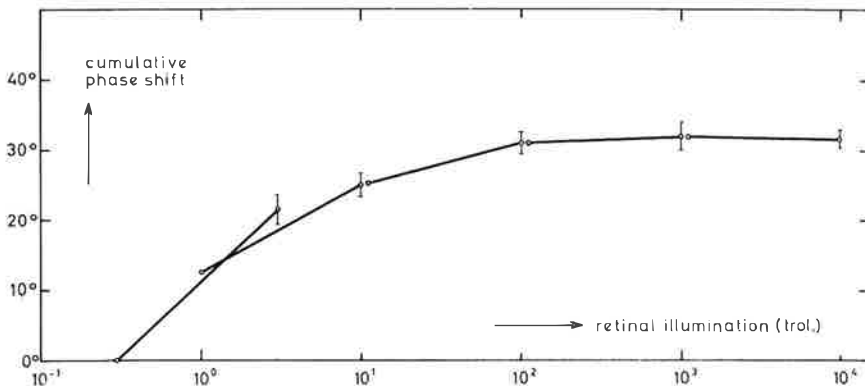


Fig. 4. The cumulative phase shift as a function of retinal illumination. Each straight part represents the phase shift measured over one log unit difference in retinal illumination. The various strips were arranged in line in the best possible way to form the cumulative curve. The vertical bars indicate the spread in the slope for any separate strip within the frequency domain 0.25–1.72 cps.

effect of latency or transport time but rather with a genuine phase shift. Physically, these things are completely different – though they may be mathematically equivalent.

We will now try to describe a model which in principle may account for the experimental findings presented. We consider this model as a first approach rather than as a final description. Much experimental and theoretical work has to be done to allow further refinements.

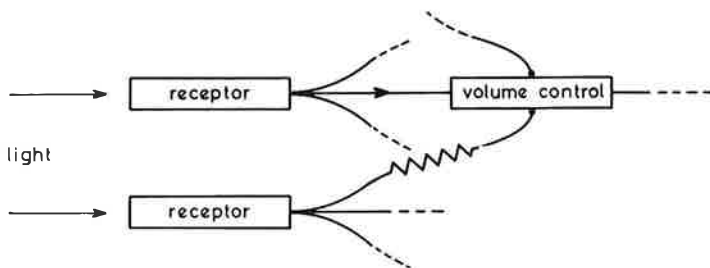


Fig. 5. Schematic representation of the model. For details see text.

#### *A simple model for phase shift vs. luminance*

We will start from a simple scheme (Fig. 5).

Light with intensity  $I$  is converted to a nervous signal in the receptors on a proportional basis. The output signal may also be indicated as ' $I$ ' therefore. Directly behind the receptors is a volume control unit which limits an indefinite growth of  $I$ . This volume control is assumed to be performed by

inhibitive lateral connections from neighbouring receptors. As a result the output signal  $N$  is

$$N = I \times V$$

in which  $V$  stands for volume control.

$V$  is assumed to be out of action ( $V = 1$ ) at low luminance levels. In that situation the nervous output  $N$  is the untransformed input signal  $I$ . Evidently, the high frequency filtering as described by De Lange is not incorporated in the scheme. In our opinion this filtering is a diffusing process inherent to nervous transmission which should be localized mainly behind this volume control mechanism. In view of the limited scope of this paper – the discussion of perceptual phase shifts – we will leave this more efferent filtering out of consideration.

Let us now try to become more specific about  $V$ . If  $I$  is a sinusoidally modulated stimulus

$$I = I_0 (1 + m \cos \omega t),$$

we may assume, as an obvious choice in first approximation, that the temporal variation in  $V$  is also sinusoidal. For low frequencies we may expect that  $V$  is in counterphase with  $I$ , but at higher frequencies it will lag with respect to  $I$ , so that we have to introduce a phase shift  $\varphi$  in the formula:

$$V = V_0 [1 - m T \cos (\omega t - \varphi)]$$

$T$ , which stands for transmission, determines to which degree  $V$  will follow the variation in  $I$  and this will understandably be dependent upon  $I_0$  and upon  $\omega$ . We will assume

$$T = T_\omega \cdot T_I$$

which means that we consider  $T_\omega$  and  $T_I$  as independent processes, acting in series.

As to  $T_\omega$  we will assume that it is determined by the same kind of filtering of the nervous signal as we thought responsible for the De Lange attenuation. We will assume therefore as a first and most simple choice that  $T_\omega$  is identical to the low luminance De Lange attenuation characteristic (Fig. 6). The same process will make that  $V$  will increasingly lag with respect to  $I$  with increasing flicker frequency. To this phase lag  $\varphi_\omega$  we will return later.

About  $T_I$  we can presume that it is characterized by a typical low luminance, near threshold behaviour and by a typical high luminance behaviour – quite similar to the behaviour of the foveal contrast threshold. The foveal contrast threshold vs luminance curve is well known to consist of two branches, connected by a short and smooth transition.

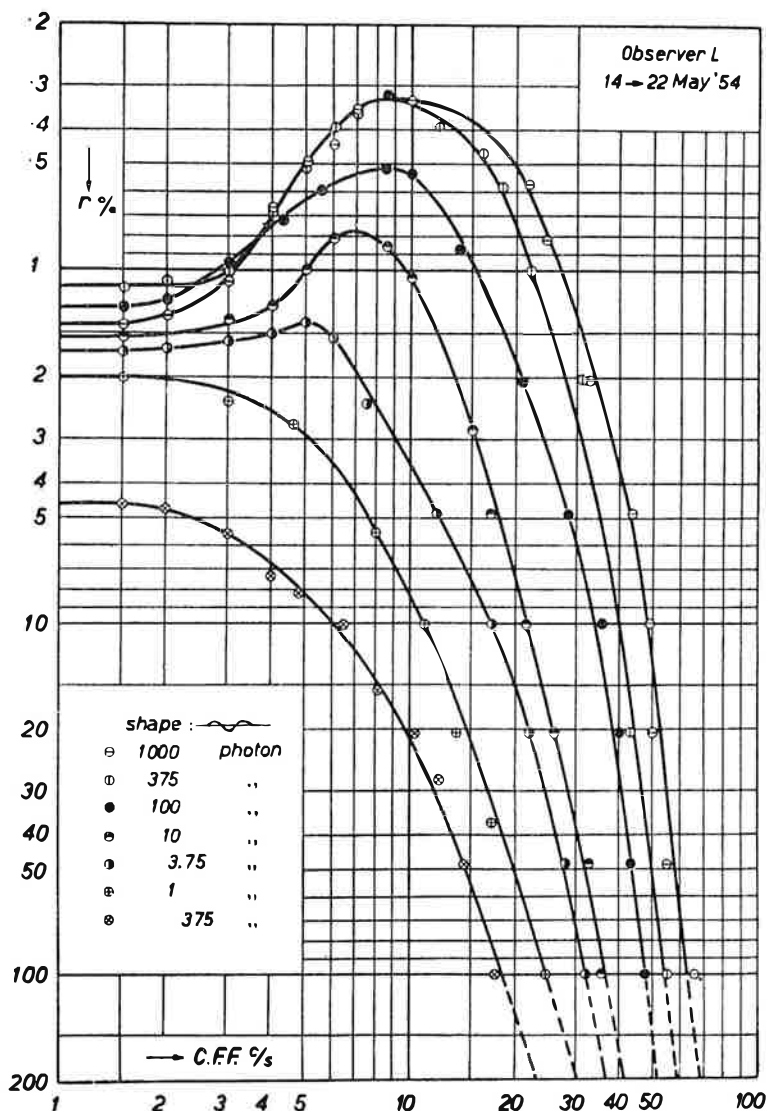


Fig. 6. The modulation depth vs. frequency plots for just perceptible flicker according to de Lange<sup>1, 4</sup> (with kind permission).

When we indicate the 'transition point' by  $I = 1$  per definition we can discern the 'absolute threshold' branch for  $I \ll 1$  and the 'Weber-branch' for  $I \gg 1$ . For  $I \ll 1$  it is a natural choice to assume that the volume control is inactive, that is  $T_1 \ll 1$ . With growing stimulus strength,  $V$  will increasingly counteract  $I$ , but of course never overcompensate it. An increasing



stimulus will always lead to an increasing neural signal and sensation. We therefore expect that, with  $I \rightarrow \infty$ ,  $T_I \rightarrow 1$ .\*

These requirements

$$T_I \ll 1 \text{ for } I \ll 1 \text{ and } T_I \rightarrow 1 \text{ for } I \rightarrow \infty$$

are most easily met by defining

$$T_I = \frac{I}{1 + I}.$$

It will be clear that the actual course of  $T_I$  vs  $I$  might show considerable deviations from this formula, in particular in the region around  $I = 1$ . At the moment we have not sufficient data to be more precise, however.

Finally we have to discuss the phase lag  $\varphi_\omega$  of  $V$  with respect to  $I$ . We have some indications on the  $\varphi$  vs  $\omega$  relation. In the first place we have Veringa's<sup>7</sup> and Brindley's<sup>8</sup> data from the study of interference between photic and electric stimulation of the retina. The phase effects found in that type of experiments may be different from ours, but certainly they have some relation. Roughly their phase vs. frequency relation is linear, in Veringa's acceptable reasoning even proportional. One may expect proportionality if the cause of the phase shift is a latency, but even a diffusion concept as developed by Veringa<sup>9</sup> predicts a proportional course of  $\varphi$  with  $\omega$  for not too high frequencies. We will therefore postulate that

$$\varphi = \tau \cdot \omega$$

in which  $\tau$  represents a characteristic time of the lateral transmission line.

Now we have specified  $T$  and  $\varphi$  in the definition of  $V$ , we can oversee the final describing formula.

$$\begin{aligned} N &= I_0 [1 + m \cos \omega t]. V_0 [1 - m \frac{I_0}{1 + I_0} T_\omega \cos \omega (t - \tau)] = \\ &= I_0 V_0 [\{1 - \frac{1}{2} m^2 \frac{I_0}{1 + I_0} T_\omega \cos \omega \tau\} + m \{\cos \omega t - \frac{I_0}{1 + I_0} T_\omega \cos \omega (t - \tau)\} \\ &- \frac{1}{2} m^2 \frac{I_0}{1 + I_0} T_\omega \cos 2\omega (t - \frac{1}{2} \tau)] \end{aligned}$$

At higher intensities  $I_0 \gg 1$ , this formula shows the presence of an extra modulation component, due to variations in  $V$ ; and it shows, for not too small values of  $m$  in addition, the presence of an extra *DC* component and the appearance of the first harmonic.

\* A similar description as given here for visual flicker holds for the flicker ERG, with the difference that  $T_I$  may exceed 1 for the ERG. It is the right place here to mention our fruitful discussions with drs. Troelstra and Schweitzer of our institute and to refer to their work<sup>5, 6</sup> on this subject.

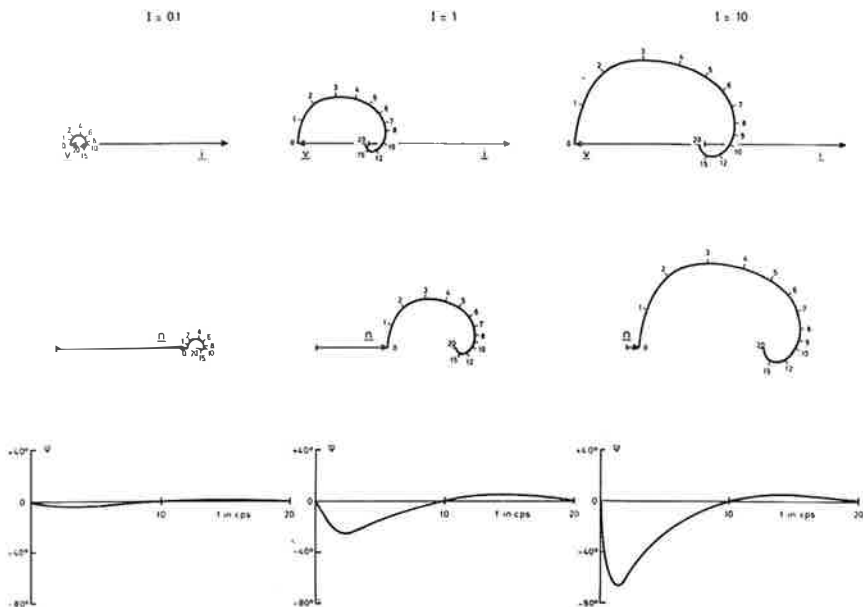


Fig. 7. The construction of the phase lag  $\psi$  of the AC neural output  $n$  with respect to the AC input  $i$ .

The upper line gives, for three intensity values, the behaviour of the volume control component  $v$  with respect to  $i$ .

The middle line gives their vectorial summation to  $n$ .

The lower line gives the phase lag  $\psi$  of  $n$  with respect to  $i$ , as it can be read from the vectorial diagram above.

Round about  $\omega\tau = \pi$  both the *DC*-component and the modulation of the basic frequency reach a maximum, which we think to be associated with the Brücke-Bartley brightness enhancement and with the pseudo-resonance peak in the De Lange characteristics respectively. Since both phenomena occur at frequencies in the order of 10 cps we will assume

$$\tau = \frac{\pi}{2\pi \times 10} = 0.05 \text{ sec.}$$

In the present context a more precise determination is not important, so that this rough estimation will suffice.

When we ignore now the terms with  $m^2$ , which is allowed for  $m \ll 1$ , we get

$$N = I_o V_o \left[ 1 + m \left\{ \cos \omega t - \frac{I_o}{1 + I_o} T_\omega \cos \omega (t - \tau) \right\} \right]$$

The most easy way to study this behavior of  $N$  is to plot its dependence on  $\omega$  and  $I_o$  as vector diagrams (Fig. 7). The question is what the position is of the resultant  $n$  of the vectors

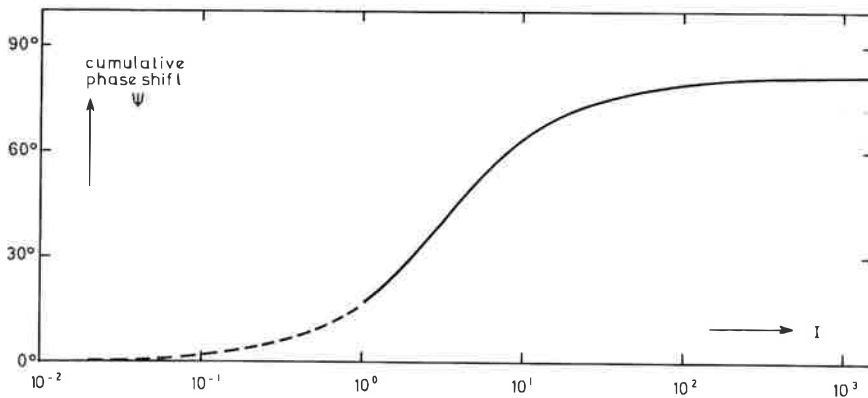


Fig. 8. The dependence of the phase lead of the nervous output  $n$  with respect to the stimulus input  $i$ . The right hand part of this figure should be compared with the experimental data of Fig. 4. The left hand part is interrupted as verification at these low luminances seems to be difficult.

$i$ , which symbolizes the stimulus part  $\cos \omega t$   
and

$v$ , which symbolizes the volume control component  $\frac{I_0}{1 + I_0} T_\omega \cos \omega (t - \tau)$ .

The upper line gives for three intensity values the behaviour of the volume control component  $v$  with respect to  $i$ . To recall the data on which this course is based:

- the De Lange low luminance attenuation characteristic (Fig. 6) governs the amplitude transmission of  $v$  as a function of  $\omega$ .
- the time  $\tau = 50$  msec, derived from the frequency at which pseudo-resonance effects occur, determines the rotation  $\phi$  of  $v$  with  $\omega$ .
- the volume control characteristic  $T = \frac{I}{1 + I}$  determines the length of  $v$  with respect to the length of  $i$ .

At low frequency  $v$  and  $i$  have opposite direction and the resultant  $n$  points to the right. But with increasing frequency,  $v$  starts lagging. At low intensities this has only small oscillating effect on the position of  $n$  but at high intensities, where  $v$  and  $i$  are almost equal  $n$  may show a large phase lead  $\psi$  with respect to  $i$  in particular for very low frequencies. In the limit this phase lead  $\psi$  becomes even  $90^\circ$ .

To find how this phase shift depends on the intensity  $I$  we have to compare points of equal frequency on the  $\psi$  vs frequency plots. In Fig. 8 we plotted  $\psi$  as a function of  $\log I$  for 1 cps. For  $I \ll 1$  phase shifts are small; for  $I \gg 1$  the limit situation is almost reached and the  $\psi$  vs  $I$  relation gets saturated. Below  $I = 1$  we have drawn an interrupted curve because we approach then the absolute threshold. Flicker phenomena can hardly be studied in that region

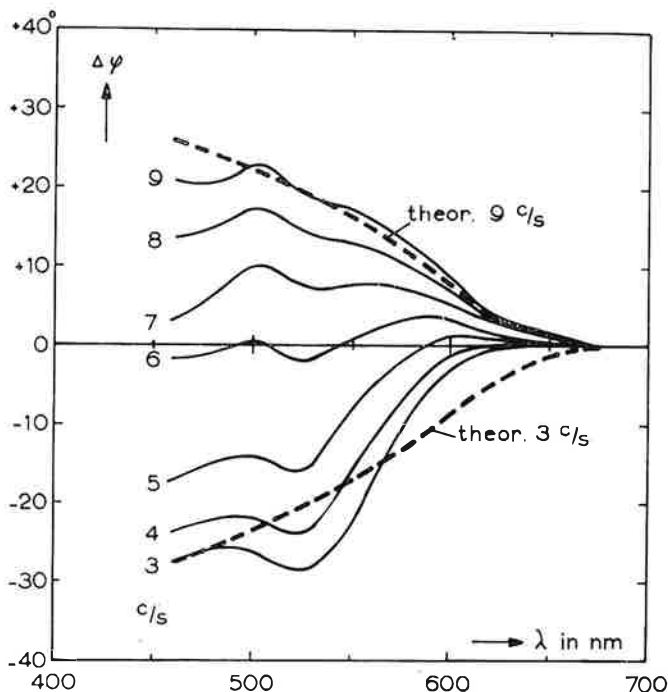


Fig. 9. The phase shift with respect to 675 nm with the frequency as parameter, constructed as a cumulative graph from many  $\Delta\phi$  vs  $\Delta\lambda$  experiments. The theoretical curves show how well these curves can be described with the phase vs frequency relation of Fig. 10.

because the contrast sensitivity is so low that we should need a high modulation depth  $m$  of the stimulus with as a result that the stimulus might be sub-threshold during part of the duty cycle. We must therefore expect, on the basis of this model, that phase effects tend to steadily increase with decreasing light level. And this is exactly which was found in Fig. 4. At other frequencies we would have found other  $\psi$  vs  $I$  curves in principle. But it is evident from the  $\psi$  vs  $\omega$  curves at the bottom of Fig. 7 that in the low frequency domain, around the minima, the results are only slightly dependent on frequency. The width of the span in  $\omega$ , for which this holds good, depends upon the assumptions about  $T_f$ . In the future we hope to do more experimental and theoretical work to further elucidate this point.

#### *Application to phase shifts in colour flicker*

In the introduction we already mentioned the experiments of Walraven and Leebeek on phase shifts in colour flicker. We return now to these experiments and first summarize their main results.

They determined, in small wavelength steps, the phase difference in the

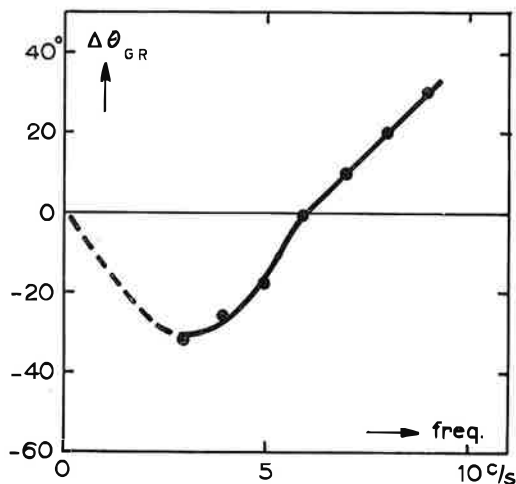


Fig. 10. The phase shift vs frequency relation between the red and the green system as determined from all experiments with various wavelength combinations. The interrupted part represents a theoretically induced extrapolation.

perception by measuring the physical difference in phase on the stimulus side required for a subjective adjustment on minimum flicker. By plotting these  $\Delta\phi$  vs  $\Delta\lambda$  data in a cumulative way, just like we did in our Fig. 4 they obtained  $\Delta\phi$  vs  $\lambda$  curves with the frequency as parameter (Fig. 9).

In analysing their data they found that all experimental data could in good approximation be reduced to one basic phase vs frequency relation between the two participating colour mediating systems: the red and the green one (Fig. 10). The blue system could be neglected in the wavelength domain studied.

How good the approximation is can be judged from the discrepancies between the drawn and the interrupted line in Fig. 9. The interrupted lines represent the best fitting theoretical relations on the basis of the one fundamental phase relation of Fig. 10.

Below 3 cps the phase matching became so difficult that no experiments could be done. Yet we know that the curve of Fig. 10 has to pass through the origin – hence the interrupted extrapolation which was given a simple but rather arbitrary course.

In order to understand the behaviour, we have to introduce in our model wavelength-dependent parameters. The most obvious differences we can introduce are:

- a. A difference in time scale. We will assume that one system as a whole acts slower than the other – because, for instance, the nerve fibres have different thickness.

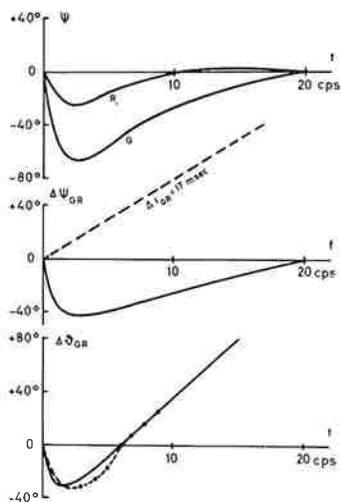


Fig. 11. A possible explanation of the experimental phase difference vs frequency relation for the red and green colour mediating systems, as shown in Fig. 5. For explanation see text.

- b. A difference in intensity scale. The 'breaking point'  $I = 1$  may correspond to different actual luminances for the red and the green systems.
- c. A difference in delay time. This is something other than the difference in time scale as mentioned before. We simply assume that somewhere in the nervous channel is a delay which is different for the two colour systems – because, for instance, the number of synapses is different.

In Fig. 11 we have applied a difference in time scale and a difference in intensity scale in the upper graph. To the difference-curve in the middle picture we have added a constant delay – with as a result the final phase difference vs frequency relation of the lower picture.

The assumptions made were that the time scale of the red system was two times the time scale of the green system, that the breakpoint of the green system was at a 10 times higher luminance than that of the red system; and that there is a delay difference of 17 msec. These assumptions were more or less arbitrary and other choices might do equally well. What is important, is that we have constructed a phase vs frequency plot which shows a remarkable similarity to the experimental relation of Fig. 10, here indicated as a dotted line. Concluding we can say that a simple model based on a slowly following volume control may well account for the essential features observed at the perceptual phase shift at low luminance flicker. But on the other hand, that much experimental and theoretical work has to be done before we will be able to speak of a satisfactory correspondence between theory and experiments.

## REFERENCES

- 1 DE LANGE, H. (1957): Attenuation characteristics and phase shift characteristics of the human fovea-cortex systems in relation to flicker fusion phenomena. *Thesis Delft*, see also ref. 4.
- 2 WALRAVEN, P. L. and LEEBEEK, H. J. (1964): Phase shift of alternating coloured stimuli. Proc. Flicker Symposium Amsterdam 1963. *Doc. Ophthalm.*, 18, 56.
- 3 ROUFS, J. A. J. (1963): Perception lag as a function of stimulus luminance. *Vision Res.*, 3, 81.
- 4 DE LANGE, H. (1958): Research into the dynamic nature of the human fovea-cortex systems with intermittent and modulated light. I. Attenuation characteristics with white and coloured light. *J. Opt. Soc. Amer.*, 48, 777.
- 5 TROELSTRA, A. (1964): Non-linear system in analysis electro-retinography. *Thesis Utrecht*.
- 6 TROELSTRA, A. and SCHWEITZER, N. M. J.: On the relationship between the single flash ERG and the ERG elicited by more complex stimuli. Flicker Symposium Amsterdam 1963. *Doc. Ophthalm.* 18, 114.
- 7 VERINGA, F. (1964): Electro-optical stimulation of the human retina as a research technique. Flicker Symposium Amsterdam 1963. *Doc. Ophthalm.*, 18, 72.
- 8 BRINDLEY, G. S. (1962): Beats produced by simultaneous stimulation of the human eye with intermittent light and intermittent or alternating electric current. *J. Physiol.*, 164, 157.
- 9 VERINGA, F. (1961): On the mechanisms underlying de Lange's results. *Proc. kon. ned. Akad. Wet.*, 64, 413.

