Critical Fusion Frequency of Flicker and the Electrical Excitability of the Retina

By

Eietsu Suzuki and Yutaka Ooba

From the Physiological Laboratory of Prof. K. Motokawa, Tohoku University, Sendai

(Received for publication, May 23, 1955)

INTRODUCTION

When the eye is exposed to intermittent light a sensation of flicker is produced, which, however, disappears at a certain critical frequency of intermittence, and this is known as the critical fusion frequency (CFF). The dependence of CFF on the intensity of illumination has extensively been investigated by a number of workers\(^1\text{-}^{13}\). If the CFF is plotted as ordinates against the logarithm of intensity as abscissae a S-shaped curve is generally obtained at the fovea, but outside the fovea the relation is represented by two such curves which are interpreted as representing cone- and rod-functions respectively (Porter\(^5\), Hecht and Verrijp\(^14\text{-}^{15}\)). The linear portion of the S-shaped curve which is limited to the middle range of intensities is called sometimes "Ferry-Porter law."

The question as to whether the CFF is determined at the retinal level or at higher centers is not yet settled, although a number of experiments has been made, taking various kinds of phenomena such as ERG, action potentials of the optic nerve, of the optic radiation, and cortical potentials as the index.\(^16\text{-}^{21}\)

It is to be noted that the CFF is a relatively simple function of intensities, and that it is utilized as a measure of luminosity. Motokawa\(^22\) and Motokawa and Iwama\(^23\) showed that the increase of electrical excitability of the retina following an illumination may be represented by a S-shaped curve very similar to the curve for CFF, when plotted against the logarithm of intensities of pre-illuminating light. This fact suggests that there may exist some simple relation between the CFF and the \(\zeta\)-value which is a quantitative expression of Motokawa's phenomenon. In the present experiment both kinds of quantities were measured on one and the same subjects under one and the same experimental conditions in order to compare their dependence on a variety of factors such as, intensity, retinal location, etc.
EXPERIMENTAL

Method

The method is described in detail in a previous paper, so that only the principle of the method will be mentioned here. The CFF was measured by a flicker apparatus in which flickering light was produced by means of a rotating sector of light-dark ratio 1:1. The rate of flicker was measured by a well-calibrated electric tachometer attached to the apparatus. After a preliminary dark adaptation for about 20 minutes, the experiment was carried out without any background illumination. An opaque glass disc of 1 cm. in diameter was illuminated from behind by intermittent white light and viewed from a distance of 30 cm., so that the angle subtended by the disc at the eye was 2°.

The electrical sensitivity was determined following an illumination with fused light. The increase in sensitivity caused by the illumination was quantitatively expressed by ζ which is defined by the formula: \( ζ = 100 \frac{(E-E_0)}{E_0} \), where E and E₀ denote electrical sensitivity measured with and without illumination. The electrical stimulus used was a single constant current pulse of 100 msec. in duration. A comparing procedure of Motokawa was used when the subject told that a sensation of phosphene was uncertain.

RESULTS

The ζ-time curve obtained at the fovea for fused white light of 52.5 lux is illustrated in the inset of Fig. 1. In this inset, percentage increases in electrical excitability of the eye over resting level are plotted as ordinates against times in seconds after termination of pre-illumination as abscissas. In this experiment, the velocity of the rotating sector was fixed just above the CFF and the left eye was exposed to white light for 2 seconds. The CFF in this case was 46 cycles per second (cps). As can be seen in this inset, the ζ-time curve has its crest at 2 sec., which will be called “the white process” (W-process).

In the first place, we studied the dependence of the magnitudes of the W-process and of the CFF upon the intensities of illumination. The data are shown in Fig. 1. In this figure, the magnitudes of the W-process or ζ and the CFF are represented by a broken and a continuous line, respectively. As can be seen in this figure, the CFF is related linearly to the logarithm of intensities over the range used (from -4 to +4 log units). The range of the CFF in this case was approximately between 100 and 6 cps. It is apparent that the Ferry-Porter law holds good within the intensity range used in our experiment. The same is true of the magnitude of the W-process. According to the analysis by Motokawa, the W-process
Fig. 1. Inset: Excitability curve obtained at fovea with pre-illuminating white light of 52.5 lux. The duration of pre-illumination used was 2 sec. Ordinates: ζ or percentage increases of electrical excitability over resting level. Abscissas: Time in second after end of pre-illumination. FW: Fused intermittent white light.

The dependence of magnitude of W-process (broken line) and of CFF (full line) obtained at fovea upon logarithm of light intensity. Ordinates: ζ or percentage increases of electrical excitability over resting level and CFF in cps.

having its crest at 2 sec. represents the excitation of cones. From the similarity concerning the dependence on intensities both CFF and W-process must be concerned with the cone-process at the fovea.

In the second place, a similar experiment was carried out in the peripheral retina. ζ-time curves obtained at 20° periphery are illustrated in Fig. 2. The pre-illuminating light used was varied, and the frequency of flicker was kept just above the CFF for each intensity. When such a high intensity as 525 lux was used, the curve indicated a single elevation at 2 sec., but at lower intensities two elevations having distinct maxima at 1.5 and 3 sec. appeared. This type of ζ-time curve is obtained from the periphery when the subject perceives a weak colorless sensation, irrespective of the wave-length of light. This process was designated “a twin-process” by Oikawa and interpreted as concerning colorless sensations together with the so-called rod-process to be mentioned below.

We studied the dependence of the magnitudes of the two elevations
Fig. 2. Excitability curves obtained at periphery 20° for pre-illuminating white light of 2 sec. at various intensities of light. Number of each curve indicates the intensity of pre-illuminating white light in lux.

mentioned above upon the intensities of light in comparison with the CFF. The results are shown in Fig. 3. In this figure, the broken line and the full line indicate the magnitudes of the elevations at 1.5 and 3 seconds respectively, and the dotted line the CFF. As can be seen in this figure, the CFF gradually increases in the range of low intensities, but the rate of increase becomes steeper at about 0.1 lux and remains constant

Fig. 3. The dependence of magnitudes of ζ at 1.5 sec. (broken line), ζ at 3 sec. (full line) and rod-process (chain line) and of CFF (dotted line) obtained at periphery 20° upon logarithm of light intensities.
The CFF-log intensity curve apparently consists of two portions, as shown by previous investigators. As will be shown later, a similar change in the rate of increase occurs more earlier at 50° than at 20°. With regard to the \( \xi \)-log intensity curves for the magnitudes of the two elevations a similar tendency can be observed, too.

The chain curve at the bottom in Fig. 3 refers to the relation between the magnitude of the so-called rod-process and the light intensity. It was shown by Motokawa and Ebe\(^{26}\) and by Oikawa\(^{27}\) that a \( \xi \)-time curve shows a maximum at 4.5 seconds from the onset of illumination, and further Motokawa \textit{et al.}\(^{28}\) showed that the magnitude of this elevation varies with the wave-lengths of spectral lights just as the scotopic visibility curve. Therefore the process having a maximum at 4.5 seconds from the onset of illumination is called "a rod-process". When test light lasting 0.5 seconds as in the following experiment is used the rod-process is expected to appear having a crest at 4 sec. from the end of illumination. In Fig. 4 (c) the rod-process is shown together with the twin-process mentioned.

---

Fig. 4. Excitability curves obtained at periphery 20° with pre-illuminating white light of 5250, 525 and 0.1 lux. The duration of pre-illumination used was 0.5 sec. Broken lines represent rod-process.
above. At higher intensities of illumination the rod-process is generally masked by the W-process, but with special precautions, the masked rod-process may be disclosed, utilizing apparent thresholds\(^{29}\) caused by rod-excitation. The broken curves shown in Fig. 4 (a) and (b) represent the rod-process thus disclosed. As is shown with the chain line in Fig. 3, the magnitude of the rod-process increases with increasing log intensity and reaches a maximum at about 50 lux, beyond which a further increase in intensity caused a decrease of the rod-process. The maximum \(\zeta\)-value at this intensity is about 20. The fact that the magnitude of the rod-process decreases above a certain intensity, i.e. about 50 lux, may be due to an inhibitory action of cones upon rods, as was shown by Oikawa and Kurosawa.\(^ {30}\)

The behavior of the rod-process was observed at 50° from the fovea. The results are illustrated in Fig. 5. As can be seen in this figure, the

![Fig. 5. (a) Excitability curves obtained at periphery 50° for pre-illuminating white light of 0.5 sec. in duration. Light intensities used was 525 and 0.1 lux respectively. (b) The dependence of magnitude of rod-process (broken line) and of CFF (full line) obtained at periphery 50° upon logarithm of light intensities.](image-url)
curves for 525 and 0.1 lux are different in height, but they show three elevations having distinct maxima at 1.5, 3 and, 4 sec. respectively. With such a high intensity as 525 lux no such curve could be obtained at 20°, where a curve having a single maximum at 2 sec. was obtained, instead. Another difference is that the magnitude of the rod-process is decidedly greater at 50° than at 20° when the intensity of illumination is high. In consequence, as is shown in Fig. 5 (b), the magnitude of the rod-process obtained at 50° increases with increasing intensities and shows no such decline as observed at 20° over the range of intensities used. The CFF-log intensity curve consists of two clearly different portions (the full curve), while the magnitude of the rod-process is represented by a single smooth curve.

**Discussion**

Over the range of intensities of the light stimulus used, the CFF and the magnitude of the W-process increase hand in hand with the logarithm of illumination intensity, and the relation could be represented by a single straight line at the fovea. This fact may be so interpreted that the CFF and the W-process in terms of $\zeta$ refer to the function of the cones. However, when the peripheral area of 20° from the fovea was illuminated, a break in the curves occurred at about 0.1 lux. Von Kries$^{21-29}$, Hecht$^{33}$ and others interpreted this fact in such a way that the two portions of the CFF-log intensity curve represent the functions of the rods and the cones, respectively. As was shown by Simonson *et al.*, the break may be explained by an abrupt change in the number and type of excited elements. According to their explanation, the lack of such a break in animals with one type of receptor cells or in central areas smaller than 2°, which contain only cones, seems an excellent corroboration of Hecht’s duplicity theory. The fact that the break occurred at a higher intensity in the retinal area 50° from the center than in that 20° will be due to the higher degree of predominance of the rods over the cones.

For the interpretation of the $\zeta$-log intensity curves obtained in the periphery some knowledge of $\zeta$-values measured at 1.5 and 3 seconds from the end of illumination will be necessary. As shown by Motokawa$^{35}$, 1.5 and 3 seconds are the characteristic intervals of the yellow and the blue processes respectively. Therefore the $\zeta$-values measured in the range of high intensities, in which a photopic luminosity curve would be obtained, must be concerned with photopic vision.

On the other hand the twin-process which was discovered by Oikawa$^{25}$ shows two maxima at 1.5 and 3 seconds, and subserves colorless sensations like the rod-process. Since the spectral sensitivity of the twin-process coincides with the scotopic visibility curve, it must represent a scotopic
process. In view of these facts ζ-values measured in the lower range of intensities may be considered to concern scotopic vision. Therefore it is not surprising that our ζ-log intensity curves obtained from the retinal periphery should consist of two parts just as the CFF-log intensity curve. This fact is in turn further evidence that ζ-values measured at 1.5 and 3 seconds can refer to photopic vision under photopic conditions, but to scotopic vision under scotopic conditions.

In contrast to the double structure of the curves mentioned above, the curve for the rod-process is a smooth S- shaped curve, showing no break anywhere, as is illustrated in Fig. 5.

The decline of the magnitude of the rod-process at higher intensities at 20° from the center may be interpreted as due to inhibition exerted by simultaneous cone excitation, and the absence of such a decline at 50° may be interpreted in connection with the fact that the number of inhibitors or cones is smaller in this region of the retina.

**Summary**

Using the method of electrostimulation by Motokawa and a flicker apparatus the effect of light upon the electrical sensitivity of the eye was studied in comparison with the critical fusion frequency (CFF) at the fovea and in the retinal peripheries. The light-dark ratio of flicker was 1 :1, and the frequency of flicker was held just above the CFF in the measurement of electrical excitability.

1. At the fovea the CFF increased linearly with the log intensity of illumination. The increase in electrical excitability following illumination showed the same linear relation to the log intensity as the CFF.

2. At periphery 20° the CFF-log intensity curve consisted of two parts, belonging to scotopic and photopic vision. A similar double structure could be observed in ζ-log intensity curves where ζ denotes the magnitude of increase in electrical excitability measured at 1.5 or 3 seconds from the end of illumination.

3. After the method of Motokawa the rod-process was measured in isolation. The magnitude of the rod-process versus log intensity showed no double structure. The curve increased with rising intensities till about 2 log units, and then decreased at 20°.

4. At periphery 50° there was no such decline in the magnitude of the rod-process. The decline observed at 20° was attributed to the inhibitory effect of the cones upon the rods.

Prof. K. Motokawa furnished guidance and helpful criticism, for which we express here hearty thanks.
CFF and Electrical Excitability of Retina

References


4) Ferry, E. S., ibid., 1892, 44, series 3, 192.
9) Allen, F., Phil. Mag., 1919, 38, 81.
17) Adrian, E. D., ibid., 1926, 63, 378.
18) Adrian, E. D., ibid., 1927, 64, 279.
22) Motokawa, K., ibid., 1939, 12, 291.
32) von Kries, J., ibid., 1897, 15, 327.