Retinal Responses to Intermittent Light of Subfusional Frequencies

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INTRODUCTION

The phenomenon of flicker has hitherto been studied by various methods, for example, by the method of CFF, by ERG, by EEG and by other psychological methods.

Bartley1) reported that at some subfusional pulse frequencies the brightness of the pulses appears greater than the brightness of steady illumination of the same physical intensity. This enhancement was found maximal in the neighborhood of 10 pulses per second. This rate approximately coincides with the alpha rhythm, and this coincidence seemed to him not accidental because both photic stimulation of the retina and electric stimulation of the optic nerve were found maximally effective in producing responses at the optic cortex when delivered at the rate of the alpha rhythm. This finding seems to suggest that Bartley's effect occurs at the visual cortex, but cannot rule out the possibility that this phenomenon may occur at the retinal level.

The effect of light on the retina manifests itself in increases in electrical excitability of the eye following an illumination (Motokawa et al.2)). A percentage increase which is denoted by $\xi$ varies in proportion to the logarithm of the light intensity over a wide range of intensities just as does CFF (Suzuki and Ooba3)).

If Bartley's effect or enhancement of excitation at subfusional rates of flicker occurs at the retinal level, it is expected that a corresponding change should occur in Motokawa's effect. This notion was justified in the present investigation.

EXPERIMENTAL

Method

The method for determination of electrical excitability of the eye is
described in detail in previous papers, so that only points modified in the present experiment will be described. 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.

An opaque glass disc of 1 cm. in diameter was illuminated from behind by intermittent white or spectral light and was viewed from a distance of 40 cm., so that the visual angle subtended by the disc at the eye was $1^\circ 26^\prime$. The spectrum used was an equal-energy spectrum. The light intensity was controlled by a neutral wedge and by changing the distance from the light sources. Experiments were carried out at the fovea and in the periphery $50^\circ$ from the fovea.

After a preliminary dark adaptation of about 20 minutes the electrical excitability of the left eye was measured without pre-illumination and after exposure of the eye to the illuminated disc mentioned above for 2 seconds, if not otherwise stated. The test electric stimulus, a rectangular pulse of 0.1 second was delivered at different times after termination of the photic stimulus according to the wave-length of the pre-illuminating light.

Results

The $\zeta$-frequency curves obtained at the fovea for white lights of 525, 52.5, 5.25 and 0.52 lux are illustrated in Fig. 1. In this figure, percentage increases in electrical excitability of the eye over resting level ($\zeta$) are plotted as ordinates against frequencies of flickering white light used for pre-illumination as abscissas. The CFF for each intensity of white light is indicated with a vertical arrow. When such relatively high intensities as 525, 52.5 and 5.25 lux were used, the curves indicated two elevations having prominent maxima at about 7-10 and 20 cps. respectively, but at such a lower intensity as 0.52 lux a single maximum at about 15 cps. appeared.

Next, $\zeta$-frequency curves were obtained from other three subjects (Katayama, Aizawa and Kobata) under the same experimental conditions as stated above. The light intensity used was 5.25 lux. The data obtained are shown in Fig. 2. As can be seen in this figure, all curves show maxima at about 10 and 20 cps., although some individual differences can be seen about magnitudes and shape of the curves. Their CFF were found 40, 35 and 35 cps. respectively. These results are almost identical with those shown in Fig. 1.

Setting aside the maximum at about 20 cps., the phenomenon observed above coincides with Bartley’s observation that the brightness of flickering light is maximally enhanced at about 10 cps., because enhance-
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Fig. 1. Effects of subfusional intermittent lights of various intensities as a function of frequencies of flicker. Ordinates: \( \zeta \) or percentage increases of electrical excitability following exposure to intermittent light. Abscissas: frequencies of flicker in cps. Temporal sequences of procedure are shown in inset where W and S denote flickering white light and electric stimulus of 0.1 sec. in duration respectively. Curve at bottom refers to rod-process.

Fig. 2. \( f \)-frequency curves obtained from 3 subjects.

ment of electrical excitability means that the effect of the pre-illuminating light upon the retina was stronger at this rate than the other rates of flicker.

Similar measurements were carried out with red (650 m\( \mu \)), green
(530 m\(\mu\)) and blue (470 m\(\mu\)) lights from an equal energy spectrum. The results obtained from 2 subjects (Motokawa and Ooba) are shown in Fig. 3. In this figure, the curves for Motokawa are shown on the left side and those for Ooba on the right side. The time interval between the photic and the electric stimuli was 1, 2 and 3 seconds for red, green and blue lights respectively, because the maxima of the electrical excitability in the \(\zeta\)-time curves lie usually at 1, 2 and 3 sec. respectively.

![FOVEA](image)

**Fig. 3.** \(\zeta\)-frequency curves obtained from 2 subjects with various spectral lights at fovea. Curves marked by solid circles, empty circles and solid triangles were obtained with spectral lights of 650, 530 and 470 m\(\mu\) respectively.

when red, green and blue lights are used for pre-illumination. As can be seen in this figure, all curves show their maxima at about 10 and 20 cps., and the elevation at about 10 cps. is most conspicuous for red light and least prominent for blue light.

In the following experiment, spectral response curves were obtained by the method described in the previous paper. The curves for stationary lights R, G and B are marked by empty circles, empty triangles, and empty squares in Fig. 4. These three curves, R, G and B refer to the red, the
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Fig. 4. Response curves to steady spectral lights and to those flickering at 10 cps. R, G and B refer to responses of red, green and blue receptors to steady lights, and R', G' and B' represent corresponding responses to flickering lights. Scotopic response curves obtained at 50° from fovea are represented by broken curve marked by solid circles for stationary lights and by that marked by semicircles for flickering lights.

green and the blue receptors, respectively. When flickering spectral lights of 10 cps. were used instead of stationary lights, response curves R' (marked by crosses), G' (marked by solid triangles) and B' (marked by solid squares) were obtained. It is apparent from these results that the response curves for flickering lights are always higher than those for corresponding stationary lights. Enhancement brought about by flicker is found very marked, especially at the parts of longer wave-lengths.

The experimental results stated above are with respect to the cone-processes, and so in the following experiment the rod-process was measured at periphery 50°, in order to study the effect of flicker upon the rod-response. The ζ-value was measured at 3.5 sec. after exposure to flickering light for 1 second, because the rod-process shows its maximum 4.5 sec. after the onset of light, as was shown by Motokawa and Ebe6) and by Oikawa.7) The rod-response as a function of flicker rates is illustrated at the bottom in Fig. 1. As can be seen in this figure, the curve for the rod-process shows a single maximum at about 10 cps. and no second maximum as do the curves for the cone-processes.

Next, spectral response curves of the rod-process were obtained with steady spectral lights and with those flickering at a rate of 10 cps. at periphery 50°. The data are shown by broken curves in Fig. 4. The
curve marked by solid circles refers to the steady illumination, while the curve marked by semi-solid circles refers to the flickering lights. These two curves have their maxima at the same part of the spectrum (about 500 m\(\mu\)) as the scotopic visibility curve, and the curve for the flickering lights is higher only slightly. This finding indicates that the effect of flicker is much weaker upon the scotopic system than upon the photopic.

**DISCUSSION**

As to the effect of intermittent visual stimulation the interest of investigators has centered about the CFF, and researches on the effect of subfusional intermittent light are extremely scarce. This is because investigation of a transitional phenomenon is generally more difficult than a steady one. Bartley made his observers match the brightness produced by a series of light pulses to the brightness produced by a steady light, and found that the average physical intensity of the subfusional intermittent light was not so great as that of the continuous illumination equally effective in brightness. Based upon the fact that when the pulsation rate was in the neighborhood of 10 cps. enhancement was at its maximum, Bartley surmised that this effect might be correlated with the alpha rhythm of the brain.

The present investigation has shown that a similar enhancement occurs at about the same pulsation rate with regard to the electrical excitability of the eye following an illumination with intermittent light. Therefore, the present phenomenon seems to represent a physiological correlate of Bartley's effect. Both of these effects suggest that visual excitation is greater in the transition period than in the stationary state.

The evidence of this can be seen also in the discharge pattern of the optic nerve as was shown by Adrian and by Hartline. On the onset of a continuous illumination the impulse frequency rises rapidly, reaches a maximum, and declines slowly to reach a steady level which continues so long as the illumination lasts. Broca and Sulzer studied the brightness of a single flash of light in comparison of that of a steady light, and found that the brightness of a flash of a certain intermediate duration was much greater than that of the steady light of the same physical intensity. The time from the onset of illumination to the maximum of brightness seemed to depend upon the intensity and the wave-length of the light used. So far as Bartley's effect is concerned, the dark-light ratio had no effect upon the optimal frequency of the pulses, and in our phenomenon it did not seem that the intensity had any effect upon the optimal pulsation rate, unless it was too low.

Although Bartley emphasizes the correlation between his effect and the alpha rhythm, based upon the similarity of the optimal frequency...
for his effect to the alpha rhythm, some reservation seems to be necessary for this assumption. The reasons for this reservation are as follows:

1) The optimal frequency for Bartley's effect is, on an average, little lower than the alpha rhythm, and the same is true of our phenomenon.

2) A second enhancement is found at about 20 cps. in our phenomenon. This enhancement is usually not so great as that found at about 10 cps., but may be measured with greater ease and certainly in some subjects. It is apparent that this second optimal frequency has no connection with the alpha rhythm. We have yet no evidence that there is any steady rhythm of about 20 cps. in the human brain. On the contrary it is an established fact that the human eye shows the lowest threshold for electrical pulses or alternating currents of about 20 cps.\(^{11,13}\) Therefore, it seems more probable that photic activation caused by intermittent stimulation occurs at the retinal level.

According to Brazier\(^{14}\) and Van Buskirk et al.\(^{15}\) intermittent red light is more effective than other colored lights to evoke seizure waves in epileptic patients, and this fact is in line with our observation that intermittent spectral lights of longer wave-lengths are most effective to cause enhancement of electrical excitability of the eye.

**Summary**

The effect of intermittent lights of subfusional frequencies was investigated by the method of electrostimulation of the eye. The light-dark ratio of flickering light was always 1:1.

1. Increases of electrical sensitivity following an illumination with intermittent white light were usually greater below the CFF than above it. When the electrical sensitivity after an illumination was plotted against the rate of flicker of the illuminating light, the curve showed two prominent maxima at about 10 and 20 cps.

2. The same effect could be seen when monochromatic lights of various wave-lengths were used instead of white light.

3. At the flicker rate of 10 cps., the degree of enhancement of electrical excitability was found highest for red light, intermediate for green light, and lowest for blue light.

4. The rod-process received no such conspicuous enhancement as the cone-processes.

5. The above-mentioned effect was correlated with the psychological phenomenon described by Bartley that a light flickering at a subfusional rate looks brighter than a fused one. Based upon the wave-length dependence of this phenomenon a retinal mechanism was suggested for photic activation of seizure waves with intermittent stimulation.
7) Oikawa, T., ibid., 1953, 58, 69.
8) Adrian, E. D. & Matthews, R., J. Physiol., 1927, 63, 378.
12) Abe, Z., ibid., 1951, 54, 37.
15) Van Buskirk, C., Casby, J. U., Passouant, P. and Schwab, R. S., ibid., 1952, 4, 244.