INTERMITTENT STIMULATION BY LIGHT

II. THE MEASUREMENT OF CRITICAL FUSION FREQUENCY FOR THE HUMAN EYE

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I

Critical Frequency

A field which is illuminated intermittently at a sufficiently high frequency produces a visual sensation similar to that of a field which is illuminated continuously. The frequency of interruptions at which this fusion of visual impressions takes place is called the critical frequency of flicker. Under controlled conditions the determination of this critical fusion frequency may be made with considerable accuracy.

A large body of work has been done in an effort to describe the precise value of the critical frequency under a variety of circumstances. These measurements will be described and evaluated in the next paper of this series. Here it is enough to state that the influence of the various factors on critical frequency is not wholly clear at present, especially in those aspects whose theoretical significance is most interesting. We have therefore undertaken an investigation of this problem, the results of which are to be presented in this group of papers. This paper is concerned with apparatus and methods, both of which it is necessary to describe in detail because of their significant bearing on the character of the measurements obtained previously and at present.

The apparatus was designed to present to the observer a small field of light periodically interrupted and surrounded by a much larger field continuously illuminated, but otherwise the same as the interrupted field. The various parts of the apparatus are then concerned

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with controlling and recording the position, intensity, spectral composition, and frequency of interruption of the visual field in their relation to the determination of the critical frequency of flicker by specific portions of the observer's eye.

II

Optical System

The arrangement of the apparatus is shown diagrammatically in Fig. 1. The source of light is a concentrated filament, 500 watt, projection Mazda lamp, running on 110 volts and 4.2 amperes direct current furnished by storage cells. The lamp is placed in a rectangular lamp house which possesses a circular opening 30 mm. in diameter in each of two adjacent walls. The openings are covered with ground glass, and serve now as two secondary sources of illumination.

The light from one is deflected 90° in its path, by a totally reflecting prism, and focussed by a lens into the plane of a rotating, sectored wheel with four 45° sectors removed. The diverging light then passes through a hole in the silvering of a photometer cube, immediately after which it is focussed by a lens on to the exit pupil. Between this last lens and the exit pupil there are (*a*) places for filters, of which we used both neutral and monochromatic, (*b*) a neutral, balanced, Eastman Kodak gelatine wedge, and (*c*) a very thin slip of glass, tilted so as to reflect a red fixation point into the eye looking through the exit pupil.

The light from the other ground glass of the lamp house passes through an identical optical system and eventually impinges on the photometer cube, where it is reflected from the silvered diagonal face, through the lens, filters, wedge, and glass slip, on to the exit pupil. All light paths, prisms, sector wheel, etc., are enclosed in blackened tubing or in blackened housing to reduce stray light to a minimum.

The exit pupil is a circular opening 1.8 mm. in diameter, and constitutes the artificial pupil through which all the observations are made. An eye looking into the exit pupil sees the photometer cube through the wedge, balancer, filters, and lens, and sees it bounded by the circular edge of the lens. The visual field is thus a circular area 10° in diameter with a circular hole in it, 2° in diameter. The hole in the silvering on the diagonal of the cube is actually an ellipse, so made that in front view it appears circular. The larger circular field surrounding this opening is illuminated with continuous light; the smaller, central observation field is illuminated with intermittent light whose frequency depends on the rate at which the sector wheel rotates.

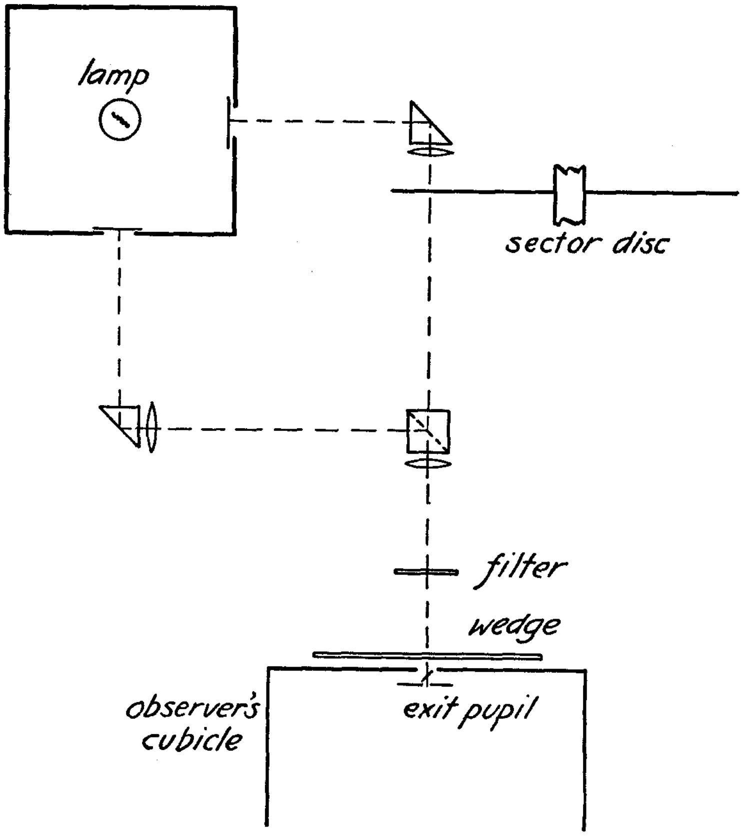

FIG. 1. A simplified, diagrammatic plan of the optical arrangements used in the measurements of critical frequency.

The filament of the Mazda lamp in the lamp house is in one plane. By rotating the lamp, one can vary the relative amount of light which falls on the two ground glass surfaces. This in turn controls the relative brightness of the inner, intermittently illuminated, test field, and the outer, continuously illuminated, surrounding field. In all our measurements we so adjusted the lamp that the brightness of the whole field was uniform; that is, that the brightness of the surrounding field was the same as the brightness of the test field when the sectored wheel was going well beyond the critical frequency of flicker, and the central field appeared continuously illuminated.

Our main reason for using the 10° surround of the same brightness as the experimental field is to be certain that the region surrounding the measuring area is in the same state of adaptation as the measuring area itself.[1] According to Lythgoe and Tansley (1929) the critical fusion frequency for most intensities becomes maximal when the surrounding field has the same brightness as the measuring field.

Fixation was provided for in several ways. In some of the measurements we used an ink spot on the lens in front of the cube. Later this was replaced by a luminous red fixation point reflected into the eye by a small cover-slip placed at an angle between the wedge and the exit pupil. The fixation point could then be adjusted for any desired visual angle by varying the tilt of the cover-slip. In the measurements made by C. D. V. on the field 20° off-center, a red fixation point was viewed through a prism by the *other*, non-measuring eye, and the binocular functioning of the two eyes was relied on to keep the working eye fixated.

The intensity of the light coming through the exit pupil is varied by means of two neutral, decimal, filters transmitting approximately

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[1] This point is frequently not appreciated, as, for example, in the recent work of Wilcox (1932). In this, the distance between two extremely small, illuminated stripes viewed *against an absolutely dark background* is used for measuring the relation of visual acuity to illumination. By this method Wilcox secures results which, at high illuminations of the stripes, do not resemble those obtained by previous workers; he therefore finds the theoretical treatment of such data inadequate.

Wilcox apparently does not realize that the term retinal illumination must bear some relation to the general light intensity prevailing on the retina in and around the area used for making the measurement. In Wilcox's case the total illuminated area of the two stripes occupies only 4.5 x 20 *minutes* of visual angle. Obviously one cannot know what the illumination on the retina is when, in the effort to resolve a small and very brightly illuminated test object, the eye moves here and there so that successive small retinal areas are now in very bright illumination and now in complete darkness. This is a problem in glare and not in visual acuity. Such a situation is here avoided by means of a comparatively large surround.

1/100 and 1/10,000 of the light, and a neutral wedge with a transmission range of 1 to 1000. The combination of wedge and neutral filters enables us to cover easily and accurately a range of illumination between 1 and 50,000,000 units. The spectral composition of the field is varied by placing Wratten Monochromatic Filters, Nos. 70 to 76, in the path of the light. The filters and wedge are from the Eastman Kodak Company.

The wedge is mounted so as to be moved by a rack and pinion, and is so arranged that its position may be read easily to 0.1 mm. on an attached millimeter scale. We calibrated the wedge by measuring the transmitted illumination at 13 points along its length by means of a Macbeth illuminometer. The relation between log I transmitted and distance along the wedge is linear, as is to be expected from the construction of the wedge.

The apparent brightness seen by the eye looking through the exit pupil, was measured by matching it against a white surface placed so as to cut off part of the visual field furnished by the lens. The illumination on the white surface was given by a lamp which was moved until the white surface, when viewed through the exit pupil, matched the rest of the field. The photometric brightness on the white surface was then measured directly with the illuminometer after the exit pupil had been removed. The factor for converting units of photometric brightness (millilamberts) into units of retinal illumination (photons) is $\pi a/10$ where a is the pupil area, and $\pi = 3.142$. With the present apparatus, which has a pupil area of 2.54 sq. mm. the maximum retinal illumination available in the central test area when it is not interrupted is very nearly 6000 photons.

The "neutral" filters we calibrated with a Martens polarization photometer for white light, and for each of the monochromatic filters. We first calibrated a 1/10 filter. Then keeping the 1/10 filter in place we put the 1/100 filter in the path of the other beam of the photometer. The difference between the two filters is then of the order of 1/10, which is readable with good accuracy on the scale of the polarization photometer. In the same way we calibrated a 1/1000 filter against the 1/100, and finally the 1/10,000 against the 1/1000 filter. In the measurements we used only the 1/100 and the 1/10,000 filters. The monochromatic filters we calibrated with a Koenig-Martens spectrophotometer.

III

Control of Frequency

The sector wheel, which is made of cold-rolled steel, is solidly mounted on an axle which rests in a special iron casting made to support and hold it. It can be actuated by either of two motors. For high speed its shaft is continuous with the shaft of a series-wound, high speed 1/8 horse power motor, while for low speeds it is driven by a 1/20 horse power, shunt-wound motor through a reducing gear and belt. The speed of the motors may be varied by means of rheostats in series with their power supply. The motors run on 110 volts, direct current supplied from storage cells.

There are two reasons for having two motors. One is that a single motor, unless it is run in connection with a variety of pulleys and wheels, cannot by variations in current supply be made to negotiate easily and smoothly the entire extent of frequencies which we desired. The other reason is that at low speeds we often wished to set a flicker frequency and to adjust the intensity of light until the flicker either just disappeared or just became visible. This requires the motor to remain quite steady, which can be accomplished by the shunt-wound motor. At higher frequencies we usually wished to set the intensity and to vary the speed of flicker. For this purpose it is desirable to have a motor which responds rapidly to change in power supply; this is accomplished by the series-wound motor.

It is of interest to determine the sharpness of cut-off and reappearance of the light by means of the sectored wheel. By clamping a long pointer perpendicularly to the long axis of the shaft of the sectored disc, we were able accurately to determine the angle through which the disc has to move in order for the visual field to pass from complete extinction to full intensity. This turns out to be nearly 3° of arc, and shows that the cut-off and reappearance of the illumination may be considered as practically rectangular.

For this work we wished to cover a rather large range of speeds for the rotation of the sector disc; in particular we wished to record the very slow speeds. We could find no commercially available tachometer which possessed both the desired range and the necessary accuracy. We therefore adopted the procedure of timing a given number of revolutions of the disc. In the beginning this was done by permanently connecting the shaft of the sectored disc with a revolution counter which made an audible contact every 100 revolutions through a relay system. The audible contacts were then timed with a stop-watch. This was for the faster speeds. For the slow speeds, the rotation of the shaft itself was directly observed, and 10 revolutions were timed with a stop-watch. Later the entire arrangement was made automatic by means of an electrical circuit a description of which follows.

IV

Automatic Timing

The system developed for automatically timing the rotational frequency of the sector disc consists essentially of three parts. The first is a small-angle contact on the shaft of the disc; this contact gives rise to one electrical impulse per revolution of the disc. The second part is an adding relay, through the primary circuit of which these impulses pass; the adding relay has a commutator on its face so arranged that its secondary circuit can be opened for a variable number of primary impulses. The third part is a Cenco impulse counter (Klopsteg, 1929) running on 60 cycle current; this impulse counter is used as a time-measuring device and is controlled through a polar relay by the secondary circuit of the adding relay. By this means the time occupied by a selected number of revolutions of the disc is automatically recorded in units of 1/120 of a second.

The range of flicker frequency covered in these experiments is from 2 to 60 per second. Since the sector disc gives 4 flicker cycles per revolution, the range of rotational frequency to be measured lies between $\frac{1}{4}$ and 15 revolutions per second. Since the inherent accuracy of the time-measuring system is 1/120 of a second, the shortest timing interval has to be about one second to achieve an accuracy of better than 1 per cent. This means that at the highest speeds of rotation 15 revolutions of the sector disc must be timed, whereas at the lowest speeds only 1 revolution is sufficient. It is therefore necessary to arrange for a change at will of the number of revolutions to be timed.

In Fig. 2, which shows diagrammatically the arrangement of the timing system, the particular device for selecting the number of revolutions to be timed is the adding relay *AR*. It is similar to the Cenco interval timer, but sturdier, and has been modified by replacing its pointer and scale with a contact arm and commutator, *C*. The contact arm moves 1/100 of the circumference with each impulse through its coils. A hard rubber ring, containing fifty brass segments imbedded radially in it, forms the circumference against which travels the hardened steel roller at the end of the arm. The fifty segments are divided into three circuits. One contains every odd fifth; the second, every even fifth; and the third, all the other segments. Thus by joining all the three circuits together we get a contact every two impulses through the electromagnet; by joining only the first two, we get a contact every ten impulses; and by using either of the first two

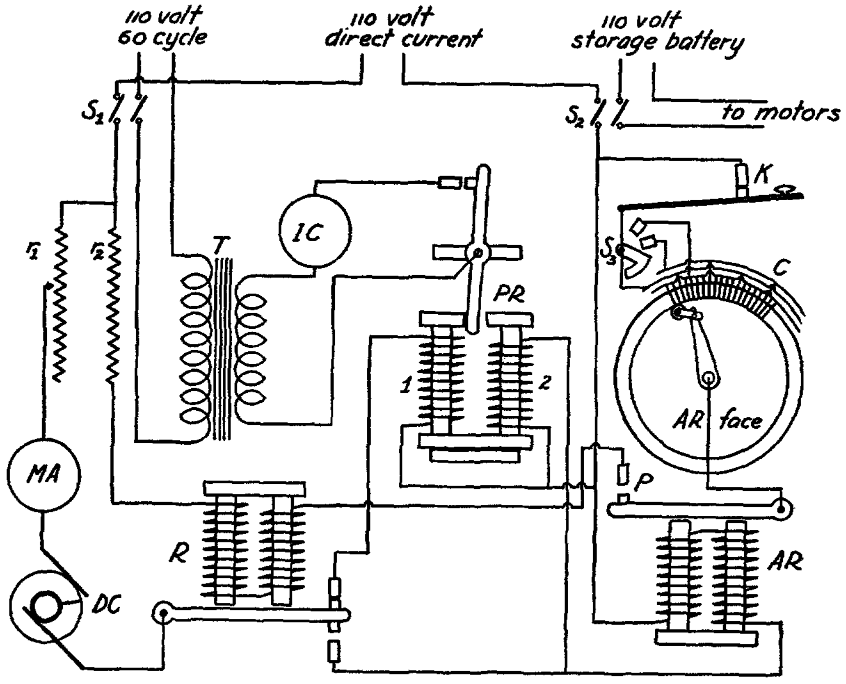

FIG. 2. Diagram of wiring and construction of the apparatus made to record automatically the speed of the sectored disc used to interrupt the light for critical frequency measurements. A complete description is in the text.

alone we get a contact every twenty impulses. The function of these contacts is to actuate an ordinary relay, *R*, which makes the electrical impulses generated by the sector disc control the opening or closing of the timing circuit through the polar relay *PR*. An additional contact *P* is put on the armature of the adding relay *AR*, to prevent arcing at the commutator *C*.

The complete system may be understood by first following the circuit through the contact *DC* on the sector disc shaft. Beginning at the 110 volt direct current supply, one side of the line comes through one pole of the switch, S_1, the variable resistance r_1, the milliameter *MA*, and the contact *DC* to the armature of the relay *R*. From there it can go through either one of two windings on the polar relay *PR* depending on whether there is current flowing through the coils of relay *R* or not.

If there is a current through the coils of *R*, then the circuit from *DC* will go into coil 1 of *PR* and out through switch S_2 to the other side of the line. Starting with the armature of the *PR* in an open position, impulses passing through coil 1 have no effect since only an impulse through coil 2 can close it.

When, however, there is no current through the coils of relay *R*, the circuit from *DC* divides into two parallel paths. One is through coil 2 of the polar relay *PR*, causing its armature circuit to be closed and thus starting the Cenco impulse counter, *IC*, recording the impulses of the sixty cycle current. The other path of the circuit from *DC* is through the coils of the adding relay *AR*, which records the number of impulses generated by the contact *DC* by moving its arm one division per impulse as already described.

The commutator circuit of *AR* is in series with the coils of *R* and its power supply. Thus the impulses generated by *DC* control the current in the coils of *R*, which in turn controls the recording of time by the Cenco impulse counter by means of *PR*. Switch S_3 may be set to record the time interval between 3, 11, or 21 consecutive impulses, which then corresponds to the time for 2, 10, or 20 complete rotations of the sector disc.

Due to the fact that the duration of the contact through *DC* varies with rotational speed, it is necessary to use a variable resistance, r_1, and a milliameter, *MA*, in series with it to regulate the current. The milliameter is a moving iron type of 750 milliampere range chosen because of its sluggish response. The resistance is adjusted so that the milliameter reads between 150 and 200 milliamperes. This value was found to be the optimum for all speeds of the sectored disc. The fixed resistance, r_2, merely acts as a current-limiting device for R.

To operate the system, switch S_2 is closed first, thus starting the motors which actuate the sector disc. The observer adjusts the speed of the motor to an approximately correct value and signals the recorder. The recorder then closes S_1 and adjusts r_1 to the correct value indicated by MA. The circuit through R is now closed, and therefore the impulses generated by DC pass through coil 1 of PR, leaving the Cenco counter circuit open. The observer, after adjusting the speed to the critical value, signals the recorder who then initiates a measurement. This is accomplished by opening the circuit through R by means of key K. As soon as the key is opened, the armature of relay R is pulled away by its spring and the next impulse from DC does two things at once. It goes through coil 2 of PR which closes the Cenco counter circuit and moves the arm of AR one division. After this happens, K is released since the commutator circuit is now open. The following impulses from DC have no further effect on the timing circuit, but they continue to move the arm of AR one division per impulse until it reaches the next "live" segment. Immediately after the last impulse passes, the armature of AR closes the circuit through R and the following impulse from DC passes through coil 1 of PR which opens the Cenco counter circuit. Thus the Cenco counter gives directly the time in 1/120 of a second that has elapsed during the rotations corresponding in number to the steps between two adjacent "live" segments in the armature C.

The whole system was checked for errors in time introduced by the various relays by causing a powerful double-throw snap switch to operate another Cenco interval timer simultaneously with the complete train of relays. In about two-thirds of the trials, the whole system was 1/120 of a second slower than the check counter, while in the rest of the trials no difference between the two counters was apparent.

V

Procedure

Before beginning work the subject became dark adapted by remaining in the dark room in which the measurements were made. For observations with the fovea, at least 15 minutes stay in the dark was given before operations were begun, which means about 25 minutes of dark adaptation before the first observation was recorded. Dark adaptation for the fovea is complete in much less time than this (Hecht, 1921). For measurements with the periphery of the eye at least three-quarters of an hour, and most often 1 hour of dark adaptation was given, before the first readings were made. This permitted complete dark adaptation. The measurements were always begun at the lowest illuminations, except in the special instances when only the higher frequencies of flicker were being investigated. Under these circumstances only a short period of adaptation was given.

The subject sat comfortably with his head in a chin-rest, and was optically separated from the rest of the dark room by a cubicle around his head. This cubicle was open at the back; but when necessary a cloth was thrown over it and over the shoulders of the observer to exclude all light except that which enters his eye through the observation pupil. Later, by proper screening of the light source and by encasing it in a metal housing, the last precaution became unnecessary even at the very lowest illuminations.

With each measurement the subject looked at the field for about a minute before beginning the setting. The manipulation preceding a decision required at least a minute, usually more, especially at the very low illuminations. Thus by the time the setting was made, the eye had been observing the field for at least 2 minutes, and usually for much longer. This insured the adaptation of the functional retinal region to the intensity under investigation (Lythgoe and Tansley, 1929).

The measurements were made in one of two ways, either by finding the intensity required for the extinction of a predetermined frequency of flicker, or by finding the frequency of flicker which would just be extinguished at a predetermined intensity of illumination. For the first method the motor was turned on and regulated until it ran at a chosen constant speed. The subject then got ready, and the light was turned on. The subject controlled the wedge which he now adjusted until the flicker in the center of the field disappeared. The speed of the sector disc was immediately recorded, as well as the position of the wedge. The position of the wedge was then changed, and after a moment's rest, the subject again set it so as to extinguish the flicker. The speed of the sectored disc and the position of the wedge were again recorded. When the required number of settings had been made for one frequency, the subject rested for about 5 minutes in the dark, while the motor was changed and regulated for a different frequency of flicker. The settings were then made as before, and the procedure repeated until the selected frequencies had been investigated. This method was used only for the lower intensities, particularly with C. D. V. as subject.

For the second method, the wedge and filters were set for a given illumination, and by moving a sliding rheostat, the subject adjusted the speed of the rotating sector disc until flicker just disappeared. The remainder of the procedure was the same as in the first method. The second method was always used at the higher illuminations; in the later measurements with S. H. as subject, it was most commonly used for the lower illuminations as well.

We could detect no difference in the results secured by the two methods, and we therefore used them to their best advantage. For example, as will become apparent in the following paper, the critical fusion frequency for certain parts of the retina remains constant or varies but slightly over a large range of intensities. Obviously here it is better to keep the illumination constant and to vary the motor speed.

In the early measurements, especially with C. D. V., we made at least 5 and often 10 and 15 settings for a given frequency of flicker. As the subject gained in experience, and we gained confidence in the measurements, this number was reduced until we were satisfied with two settings if they agreed with each other. We found no difference in accuracy when securing two readings only as opposed to ten or more. In fact, especially with S. H., we found fewer readings much more desirable, since a complete set of readings over the whole intensity range could be made at one sitting without any feeling of fatigue or strain.

VI

SUMMARY

An apparatus and a procedure are described to measure the critical frequency of flicker using different portions of the eye. The observer, looking through a pupil of fixed dimensions, views a field of 2° whose illumination is periodically interrupted and which is surrounded by a field of 10° whose illumination is continuous but otherwise identical with the interrupted field. Various parts of the apparatus are concerned with controlling and recording the retinal position of the field, its intensity, its spectral composition, and the frequency of interruption of its illumination. The procedure is so simplified and regulated that a complete set of readings over the whole intensity range of vision can be made at one sitting without fatigue or strain.

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