

Slow and fast pathways in the human rod visual system: electrophysiology and psychophysics

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Under most conditions, increasing the intensity of a flickering light makes the flicker more conspicuous. For a light flickering at 15 times per second, however, increasing the intensity can cause the flicker to disappear before reappearing again at higher intensities [Vision Res. **29**, 1539 (1989)]. This flicker disappearance or null is also evident in human electrophysiological recordings at the same intensity levels. These results point to a duality within the rod visual pathway, in which flicker signals travel through a slow and a fast pathway and then recombine at a later stage. At 15 Hz the slow rod flicker signals are delayed by half a cycle relative to the fast signals. Thus, when the two signals are recombined, they destructively interfere and diminish the perception of flicker. The dual-pathway interpretation is supported by both electroretinographic and psychophysical evidence showing a phase difference of half a cycle between 15-Hz rod signals just below and just above the null region. These effects are apparent not only in the normal observer but also in an achromat observer who lacks functioning cone vision.

1. INTRODUCTION

At low scotopic adaptation levels, the delay between the transmission of rod and cone signals is large.¹⁻⁶ As the adaptation level is increased, however, the delay abruptly decreases by approximately one half.¹ This quickening of the rod signal seems to be due to a change from the transmission of rod signals through the familiar, slow rod pathway at low intensities to transmission through a faster, less sensitive pathway at higher intensities.¹ Evidence for the transition comes from graphs of flicker sensitivity versus intensity, which can be distinctly double branched⁷⁻⁹ even though detection on both branches is mediated by rods alone,⁷⁻¹⁰ and from measurements of the relative delay between rod and cone signals, which reveal a clear transition from a slow to a fast rod signal as the intensity level is increased.¹

The delay between the slow and the fast rod signals is between 30 and 35 ms.¹ Since this corresponds to approximately half the period of 15-Hz flicker, slow and fast rod signals at 15 Hz will be 180° out of phase. Consequently, destructive interference may cause some 15-Hz scotopic lights to appear to flicker much less saliently than would be expected if there were only a single rod signal. Moreover, if the slow and the fast rod signals are

similar in magnitude, their recombination may result in a flicker signal that falls below the threshold of the more distal stages of the visual system and give rise to a perceptual flicker null (i.e., the light will no longer appear to flicker). At other frequencies, when the signals are less than 180° out of phase, less cancellation should occur and less reduction in flicker salience should ensue (at 8 Hz, for instance, the signals are only approximately 90° out of phase,¹ and no cancellation should take place).

Figure 1 illustrates the self-cancellation or nulling of rod signals at 15 Hz. Consistent with this model, we have found a range of retinal illuminances for the normal observer within which 15-Hz rod flicker appears invisible, despite being well above the conventional flicker threshold (see Fig. 2 below and Ref. 1). Counterintuitively, increasing the flicker amplitude of the suprathreshold stimulus causes the flicker percept to diminish or disappear before reappearing again at higher intensities.

We now report a correlation between the psychophysical data and electrophysiological data. At 15 Hz increasing flicker amplitude causes the amplitude of the Ganzfeld electroretinogram (ERG) to fall to a minimum at retinal illuminances corresponding to the perceptual null and then to increase again at luminances above the null. Also in agreement with psychophysical measurements,¹ our

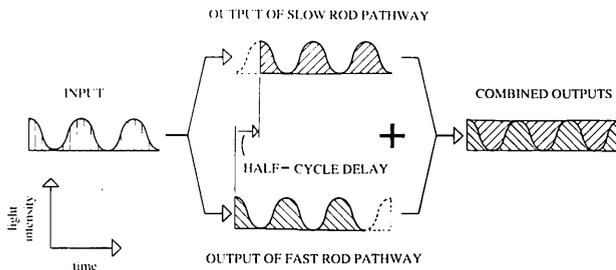


Fig. 1. Self-cancellation of 15-Hz rod flicker. The flicker signal produced by a single stimulus (INPUT) travels through either a slow or a fast pathway. At 15 Hz the signal emerging from the slow pathway is delayed by half a cycle relative to the signal emerging from the fast pathway. If the outputs from the two pathways are of equal amplitude, they will cancel each other and produce a steady, nonflickering signal when recombined. Thus the light will appear null to later stages of the visual system. To explain the restricted range of luminances within which the null is found (see Figs. 2 and 3), we assume that the luminance dependencies of the slow and fast signals differ, such that the former predominates at luminances below the null and the latter at luminances above the null, the two being approximately equal at luminances within the null. (The higher sinusoidal harmonics of 15-Hz square-wave flicker have frequencies higher than the rod visual system can follow⁸ and are not shown here.)

electroretinographic results show a phase difference of half a cycle (i.e., 180°) between the 15-Hz rod signals at retinal illuminances just below and just above the null region and thus a rapid reversal in phase as the null region is traversed.

2. METHODS

A. Subjects

A normal trichromat (author LTS) and an achromat (author KN) served as the main observers in this study. The normal observer is slightly myopic (-2 D) with normal color vision as indicated by conventional acuity and color-vision tests. During the experiment he wore no corrective spectacles. The achromat observer displays all the classic symptoms of typical, complete achromatopsia (see Ref. 11 for a full description). No evidence has been found for cone function in his dark adaptation, fundal reflectometry, spectral sensitivity, threshold, spatial and temporal sensitivity, and directional sensitivity to light (for a summary, see Ref. 12). He is hyperopic and during the experiments wore a $+9.0$ -D convex lens. This lens magnified the retinal image so that the effective visual angles for him were $1.22\times$ larger than those stated in Subsection 2.B.1.

B. Apparatus and Stimuli

1. Psychophysical Measurements

In our psychophysical experiments we used a three-channel Maxwellian view, optical system (see also Refs. 13 and 14) to produce the flickering test stimuli and steady background and bleaching fields. All three channels originated from a 100-W tungsten-iodine lamp run at constant current. One channel provided the flickering, 6° -diameter test light. Its wavelength was shaped by a grating monochromator (Jobin-Yvon V-10) into a triangular profile peaking at 500 nm and having a half-bandwidth of 4 nm. A second channel provided the 16° -diameter adapting

field. It was rendered monochromatic by an interference filter (Schott, Mainz) having peak transmittance at 640 nm and a half-bandwidth of 5.5 nm. The luminances in the three channels were attenuated by neutral-density filters and wedges; the latter were controlled by stepping motors (Berger, Lahr). The quantal-flux densities of the light beams were measured at the plane of the observer's pupil with a calibrated radiometer-photometer (United Detector Technology, Model 80X Opto-meter).

Fixation was 14° temporal and was aided by a small red fixation cross. To maintain rod detection over an extended range of background intensities for the normal observer, we used a 500-nm test field and a 640-nm background field (see Refs. 1 and 15). The 500-nm test field was flickered at 100% contrast with the use of a frequency generator (Wavetek) connected to an electromagnetic shutter. Flicker was square wave. The shutter had rise and fall times of less than 0.1 ms.

2. Electroretinogram Measurements

The test flashes for the scotopic ERG measurements were generated by a commercially produced Ganzfeld stimulator (Nicolet). Stimulus and recording conditions were all exactly in accordance with the International Society for Clinical Electrophysiology of Vision's ERG standard.¹⁶ The subject, positioned with the aid of a headrest, stared into the center of a Ganzfeld bowl. The bowl was homogeneously illuminated by white flashes produced by a xenon discharge lamp (correlated color temperature 6000 K). Each flash was triggered by a computer (Nicolet Compact Four), which was also used for the ERG recordings. The duration of the flashes were 100 ns. For flicker produced at a given frequency, the flash was repeated the required number of times per second. The flicker produced by this device was full field at 100% contrast. The flash luminance could be controlled over a limited range by the computer and also by the insertion of neutral-density filters (Kodak, Wratten) into a filter holder. Special care had to be taken to block all the stray light that leaked into the apparatus from both external and internal sources.

The mean luminances were measured by a Gossen photometer with CIE V_λ characteristics, converted to photopic trolands (phot. Td) and then to scotopic trolands (scot. Td) according to the formulas given by Wyszecki and Stiles.¹⁷ Luminances were also checked by monitoring the amplitude of output of the xenon discharge lamp by a silicon photodiode and an oscilloscope.

C. Procedure

Before beginning an experiment, the subjects dark adapted for between 30 and 45 min, depending on the adaptation level to be used.

1. Psychophysical Measurements

For the normal observer (subject LTS), rod isolation for detection of the 500-nm test light was further improved by offsetting the light's entry point 3 mm nasally from the pupillary center (since oblique entry light is much less effective for cones than for rods^{18,19}). (This was not necessary for the achromat observer KN.) To effect this, we dilated the pupil by the application of a solution of 0.5% tropicamide (Mydraticum, Roche) 30 min before the start of the experiment.

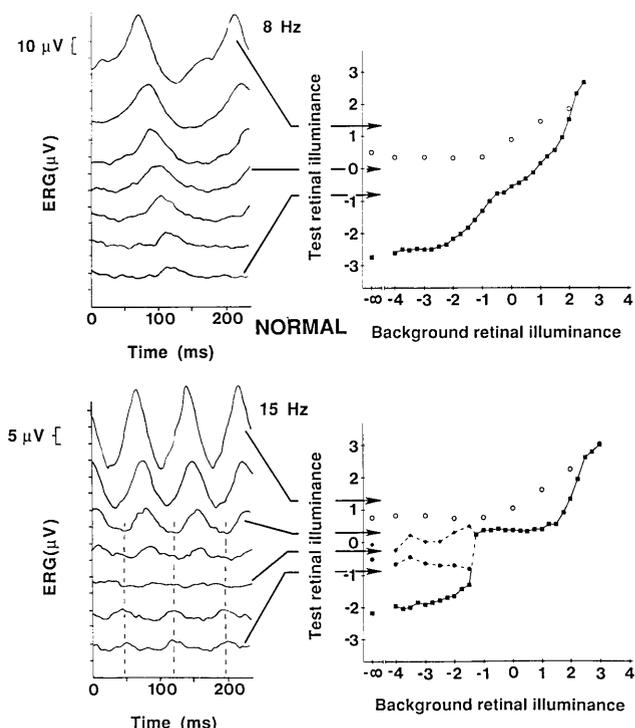


Fig. 2. Right-hand side: 8-Hz (upper panel) and 15-Hz (lower panel) flicker detectability data for a normal observer LTS plotted as the logarithm of the background retinal illuminance (scot. Td). The squares represent conventional rod flicker thresholds measured as a function of background retinal illuminance. The open circles are cone thresholds measured during the cone phase of recovery following a $7.7 \log_{10}$ phot. Td s (3100-K) bleach. At both 8 and 15 Hz, there is a break in the curve at approximately $0.0 \log_{10}$ scot. Td. In the lower panel (15 Hz) the dashed lines delimit a region within which 15-Hz flicker was invisible. Data points designating the lower and upper limits of this nulled region are indicated by filled circles and diamonds, respectively. No nulled region was found at 8 Hz. Psychophysical data points are averaged from six settings made during each of two experimental sessions. The test retinal illuminances refer to the amplitudes of the flickering stimuli (the mean illuminances would be $0.3 \log_{10}$ unit lower). Left-hand side: 8-Hz (upper panel) and 15-Hz (lower panel) Ganzfeld electroretinogram recordings for the same normal observer, LTS. In each panel the flicker intensity increases upward in steps of approximately $0.3 \log_{10}$ unit. The arrows point to the retinal illuminances in the flicker detectability diagram for which the mean scotopic retinal illuminances (discounting the red background) correspond to the mean ERG flicker retinal illuminances. There was no background present in the ERG experiment. At 15 Hz the ERG response decreases as the retinal illuminance corresponding to the perceptual null is approached and then increases after the null. Across the null the ERG response reverses in phase (as indicated by the dashed lines). In contrast, at 8 Hz neither a null nor a phase reversal is found with increasing stimulus amplitude. The vertical scale in microvolts is indicated in each ERG panel. Note that the vertical scale for the 8-Hz ERG recordings is half that for the 15-Hz records.

Thresholds at 8 and 15 Hz, and the lower and upper limits of the 15-Hz nulled region, were determined by the method of adjustment. To make a threshold setting, the observer varied the retinal illuminance of the target until the target flicker was just visible. The direction from which the observer approached the threshold was alternated. After completing the flicker threshold settings at several background retinal illuminances, the observer determined, in a separate run, the limits of the null. The subject increased the retinal illuminance of the supra-

threshold rod stimulus until the sensation of flicker vanished (this was possible at 15 Hz but not at 8 Hz). This setting, repeated several times, defined the lower limit of the null region. The upper limit of the null region (i.e., the retinal illuminance level of the suprathreshold rod stimulus at which the sensation is seen once again) was similarly defined. All settings were repeated six times. Cone flicker thresholds for the normal observer were determined during the plateau terminating the cone phase of recovery from a white (3100-K) bleach of $7.7 \log_{10}$ phot. Tds.

The achromat observer KN experienced slightly more difficulty in setting the limits of the null in the psychophysical experiment than the normal observer because he had to ignore the effect of involuntary eye movements (horizontal pendular nystagmus²⁰), which tended to revive the sensation of flicker and so disturb the null. This disturbance of the null is most likely due to the movement of the test field onto a relatively unadapted portion of the retina, but it may also reflect some habituation to the flickering stimuli. Despite his nystagmus, KN's settings were reliable and proved to be stable over sessions separated by many months. Normal subjects were given no special instructions, except to fixate the center of the test field.

2. Electroretinogram Measurements

To make the electrophysiological recordings, we dilated the subject's pupils with 0.5% tropicamide, and fiber electrodes (DTL) were placed on the conjunctiva of each eye near the corneal border. Reference electrodes (Ag-AgCl) were placed over both temporal bones, and a ground electrode was attached to the earlobe. The impedance of the electrodes was always less than 20 kW. The ERG responses to the flashes were recorded and stored by means of a Nicolet Compact Four computer supplied with artifact rejection for amplitudes larger than 100 mV. The records were filtered to remove responses that were too low or too high in frequency and averaged 100 times. Single records are reproduced in the figures below.

3. RESULTS

A. Psychophysical Data

The right-hand panels of Fig. 2 show 8-Hz (upper right) and 15-Hz (lower right) psychophysical results for the normal observer LTS. These results have been confirmed in four other normal observers. In each panel the squares represent a conventional rod flicker threshold curve (that is, at each retinal illuminance of the red background a square marks the retinal illuminance of the green target required for the flicker to be just visible). The open circles are cone flicker thresholds measured during the period following a rod-and-cone bleach when cone sensitivity has recovered but rod sensitivity has not.

At 8 Hz the target retinal illuminance required for flicker to be seen increases with background retinal illuminance. There is a small inflection at a background intensity just below $0.0 \log_{10}$ scot. Td (a consistent feature in 8-Hz data for other normal subjects^{1,9} and for the typical, complete achromat²¹). Although it is small, this inflection suggests that 8-Hz flicker detection is not mediated by a simple, unitary mechanism—otherwise the

curve would be expected to be continuous in shape. Since this inflection occurs more than $1.5 \log_{10}$ units below cone threshold in the normal observer and since it is also found in the achromat, it cannot simply reflect a transition from rod to cone vision.

At 15 Hz, the data are more clearly incompatible with detection by a unitary mechanism: Not only is the threshold curve distinctly double branched but adjacent to it lies a region (shown here enclosed by dashed lines) within which the 15-Hz flicker is completely invisible to the observer. We attribute the double branch and the disappearance of flicker to a duality within the rod visual pathway. These features are found at 15 Hz because it is the frequency at which the signals transmitted through the two pathways emerge out of phase and so destructively interfere. At other frequencies the two signals do not emerge out of phase. At 8 Hz, for example, the two differ in phase by less than a quarter-cycle (see Ref. 1 and see Fig. 4 below).

We should note that there is not a simple correspondence between the two branches in the 15-Hz threshold data and the two rod pathways. According to our model, much of the double-branched curve reflects an interaction between the slow and the fast rod flicker signals; for instance, the steeply ascending portion of the curve and the early portion of the upper branch reflect cancellation between the two signals. In addition, the disappearance of the lower threshold and the lower limit of the null above $-1.0 \log_{10}$ scot. Td does not imply that the slow rod signal is absent at these levels. Rather, it means that the slower rod signal is canceled by the faster signal, so that it no longer exceeds threshold.

As did other researchers,^{1,9} we use the traditional threshold-versus-intensity format in which to display our psychophysical 8- and 15-Hz rod flicker detection data; in other words we plot the scotopic luminance of the flickering green test light as a function of the luminance of the red background field. It should be noted, however, that, because the null near 15 Hz is significantly above the scotopic flicker threshold, the test lights used to produce it are themselves moderately intense scotopic adapting stimuli. To the extent that the rods adapt independently of the cones, the red background field should have little effect on either the upper or the lower limits of the null until its scotopic luminance exceeds the mean luminance of the test lights.

B. Electroretinographic Data

The left-hand panels of Fig. 2 show ERG results obtained at 8 Hz (upper left) and 15 Hz (lower left) for the same normal observer, LTS. The correspondence between the mean scotopic ERG retinal illuminances and the mean psychophysical retinal illuminances (discounting the red background) is indicated by the arrows. The lowest flashes (for which we show ERG traces in Fig. 2) were approximately $-0.9 \log_{10}$ scot. Td, which is approximately $1.8 \log_{10}$ units above the absolute threshold for seeing Ganzfeld 15-Hz flicker in the ERG apparatus ($-2.75 \log_{10}$ scot. Td). The flashes were increased in steps of approximately $0.3 \log_{10}$ unit, as indicated by the position of arrows along the ordinate of the right-hand figures.

The 8-Hz ERG data, like the psychophysical data, are comparatively uncomplicated. As the flicker amplitude

increases, the ERG responses speed up (the peaks move leftward) and grow progressively in strength. There is no evidence of a null in these data at 8 Hz. Once again, this is not the case at 15 Hz: As flicker amplitude increases, the amplitude of the ERG declines until a minimum is reached at a retinal illuminance associated with the perceptual null and then increases above the null. (The retinal illuminance corresponding to the center of the psychophysical null and to the diminution of the ERG response at 15 Hz is approximately $-0.3 \log_{10}$ scot. Td.) Furthermore, as the retinal illuminance associated with null is crossed, there is an abrupt reversal in the phase of the ERG response (i.e., the peaks become troughs and vice versa). This reversal is in accord with our self-cancellation model, which predicts a phase difference of half a cycle between the slow 15-Hz rod signals that predominate below the null and the fast 15-Hz rod signals that predominate above it. These results have been confirmed in two other normal subjects. (Our observers tend to differ slightly as to the best frequency for eliciting the null in the psychophysical and ERG data, but the optimal frequency is always in the range 14–16 Hz.)

In the electrophysiological experiments Ganzfeld flicker was used, whereas in the psychophysical experiments smaller flickering fields were used. Nevertheless, for both conditions, the subject reported a clear region of nulled or reduced flicker at 15 Hz. With the Ganzfeld, though, the null was less uniform and could be disturbed more easily by eye movements. In the ERG experiment we asked the normal subject to rate the magnitude of the perceived flicker. The ratings for 15-Hz flicker, in ascending order of the stimulus retinal illuminances shown in the left-hand panel of Fig. 2, were as follows: 5, 4, 0, 2, 4, 6, and 8, with flicker at the lowest ERG retinal illuminance being defined as 5. These perceptual ratings correlate roughly with the change in the amplitude of the ERG recordings. Importantly, they show that a reduction in the perceived flicker or a flicker null can be obtained with white full-field flicker just as it can with a green, 6° test field and at comparable retinal illuminances. But the ratings correspond only approximately to the amplitudes of the ERG records: For instance, the observer tended to give higher phenomenological flicker ratings to the two flash levels below the perceptual null than to the two above the perceptual null, though the latter have greater peak amplitudes. This discrepancy, however, may reflect the fact that different pathways predominate below and above the null.

C. Control for Cone Intrusion

Both the double branch and the null region found in the 15-Hz data occur at retinal illuminances that are below cone threshold (Fig. 2, lower-right-hand panel, open circles), suggesting that rods are principally responsible for those phenomena. Other psychophysical control experiments support this conclusion.^{1,8,9} Rod isolation for the full-field white flicker used in the ERG experiment is less secure, however. As a control we measured 15-Hz ERG responses in the normal trichromatic observer LTS before and after a rod bleach. These are shown in Fig. 3.

As in Fig. 2 (lower-left-hand panel), the left-hand panel in Fig. 3 shows 15-Hz ERG records made at a series of retinal illuminances, in this case separated by steps of

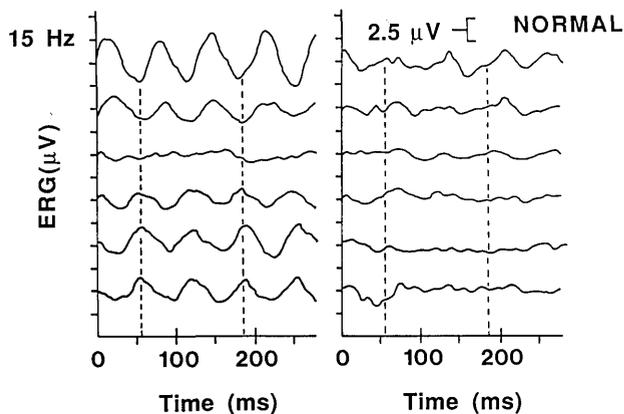


Fig. 3. Left-hand panel: 15-Hz ERG records for normal trichromat LTS before rod bleach. As before (Fig. 2, right-hand panel), there is a clear flicker null and a phase reversal. We attribute these phenomena to the rod system. Right-hand panel: ERG records made at the same retinal illuminances but during the cone plateau of dark adaptation (4–10 min) following a full-field, bright bleaching light (see the text for details). For this condition there are no responses at those retinal illuminances for which we find the phase reversal and null in the unbleached eye. In both panels the flicker intensity increases upward in steps of approximately $0.2 \log_{10}$ unit.

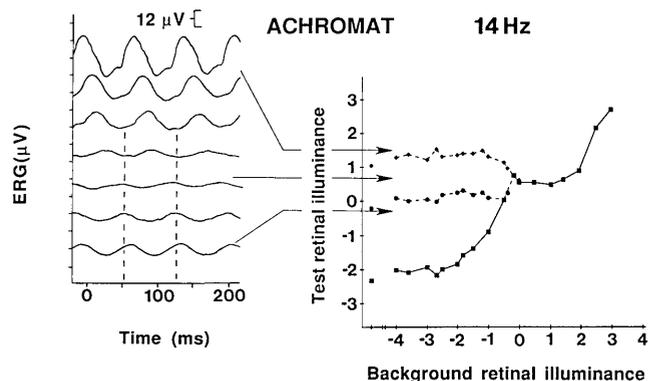


Fig. 4. Right-hand panel: 14-Hz flicker detectability data for a typical, complete achromat observer KN. Details are like those for Fig. 2. These data have many features in common with the data for the normal observer. The flicker threshold curve is double branched, and there is an adjoining region within which the flicker is invisible. The only important differences are that the nulled region and the transition from the lower branch to the upper branch are found at higher scotopic retinal illuminances for the achromat than for the normal observer. Left-hand panel: 14-Hz electroretinogram recordings for the achromat KN. Details are like those for Fig. 2, left-hand panel. For the achromat KN, as for the normal observer LTS (Fig. 2), the ERG signal reaches a minimum at retinal illuminances associated with the perceptual null and reverses in phase as the null is traversed. In accordance with the psychophysical results, the ERG null is found at higher retinal illuminances for the achromat than for the normal.

approximately $0.2 \log_{10}$ unit. In accord with the previous records the amplitude of the ERG declines to a minimum at a retinal illuminance at which the subject sees a perceptual flicker null and then increases in opposite phase above the null. The right-hand panel of Fig. 3 shows 15-Hz ERG measurements made at the same retinal illuminances as those shown in the left-hand panel but during the cone plateau (between 4 and 10 min) following the extinction of a bleaching light. We effected the bleaching by first exposing the observer for 5 min to the

brightest Ganzfeld illumination that could be produced by the ERG apparatus ($4.74 \log_{10}$ phot. Td), then by exposing him to 50 flashes ($7.0 \log_{10}$ phot. Td s) of a modified fundus camera (Olympus) superimposed upon the bright background ($5.5 \log_{10}$ phot. Td) used to focus the camera within the subject's eye. These extreme procedures were employed to provide a full-field bleach of the eye in order to prevent the ERG records measured during the cone plateau from being contaminated by rod flicker responses from unbleached peripheral areas of the visual field. Even so, the measures were only partially successful: A crescent-shaped upper-right portion of the visual field, partially obscured by the eyelid during the intense bleaching by the fundus camera, was less bleached than the rest of the eye and recovered its sensitivity much faster. Thus, even after only 4 min of dark adaptation, some scotopic flicker could be detected in this region at the highest retinal illuminance used.

This limitation notwithstanding, the ERG measurements show no correlated 15-Hz response until retinal illuminances are reached well above those for which the phase reversal and null are found in the left-hand panel.

At the highest level, there may be a weak 15-Hz flicker response, but it is irregular and reduced in amplitude compared with the response measured before the rod bleach. These signals may derive either from partially bleached rods (see above) or from cones. Whatever their origin, the signals cannot be the primary basis of the fast rod pathway. In the unbleached eye the fast rod signals at this level must be strong enough first to nullify the slow rod signals and then to produce the large signals found in the normal ERG response.

D. Achromat Data

A second, important control for the possible effects of cone contamination in the data of the normal observer is provided in Fig. 4, which shows 14-Hz flicker detectability data (right-hand panel) and 14-Hz ERG recordings (left-hand panel) from an achromat observer, KN, who has been consistently shown to lack functioning cone vision.^{10,12,13,20} The results for this observer also provide a critical test of the validity of the self-cancellation model in a visual system that transmits only rod signals.

The psychophysical results for the achromat are similar to those for the normal observer. Like the normal observer, the achromat exhibits a clearly double-branched flicker threshold curve with an adjoining region of flicker invisibility (for KN, 14 Hz is better than 15 Hz for eliciting the null; see Subsection 3.E). Also like the normal observer, the achromat's ERG responses (at 14 Hz) decrease to a minimum at a retinal illuminance corresponding to the psychophysical null (his phenomenological report of reduced flicker magnitude also coincides) and then increase with the opposite phase above the null. The similarities between the achromat and the normal observer indicate that self-cancellation is a property of the rod visual system and does not depend on functioning cones.

E. Phase Lags between the Slow and Fast Rod Pathways

In the normal observer it is possible to compare the speeds of the slow and the fast rod signals by measuring the speed of rod signals relative to cone signals. Such psychophysical data are shown as open circles in the right-hand

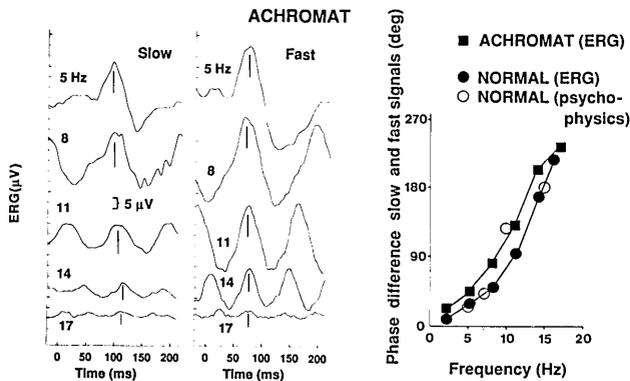


Fig. 5. Left-hand panel: ERG recordings for the achromat KN made at a retinal illuminance below his perceptual null (left recordings) and at a retinal illuminance above the null (right recordings) at frequencies ranging from 5 to 17 Hz. The vertical line in each trace is an estimate of the peak in the ERG record corresponding to the flash that occurred at time zero. For the slow pathway there is a delay of 90–115 ms between the flash and the ERG response; for the fast pathway the delay is 70–80 ms. Right-hand panel: Squares are the phase differences in degrees between the slow and fast rod signals for the achromat KN estimated from the ERG records shown in the left-hand panel. The filled circles are similar data for the normal subject, also estimated from ERG recordings (not shown). The open circles are phase differences between the slow and fast rod signals for the normal subject estimated psychophysically. These were obtained by subtracting the rod-cone phase differences measured just below the null (at a time-averaged retinal illuminance of $-0.43 \log_{10}$ scot. Td) from those measured just above the null (at $0.45 \log_{10}$ scot. Td). (See Fig. 6 of Ref. 1.)

panel of Fig. 5, in which the phase difference between the slow and fast rod signals in degrees is plotted as a function of frequency. These data were obtained by a flicker cancellation technique, in which the observer is presented with rod and cone stimuli flickering at the same frequency and is asked to adjust their relative phase and retinal illuminance to cancel the perception of flicker (for more details, see Ref. 1). If rods and cones were equally fast (i.e., if there were no delay between their signals), flicker cancellation would be best when the rod and cone stimuli were physically out of phase. Since the rods are actually slower than cones, the rod stimulus must be advanced relative to the out-of-phase cone stimulus to achieve the null.

As predicted by our self-cancellation model, the phase difference measured psychophysically grows monotonically with frequency and reaches approximately 180° between the slow and fast signals at 15 Hz.

If, as we believe, the slow and fast rod signals are differentiated in the ERG recordings, an electrophysiological estimate of the phase differences between the slow and the fast rod signals should be similar to the psychophysical estimate. Such estimates can be obtained for both the achromat and the normal observer from the relative delay between the slow and fast rod ERG responses. The left-hand panel of Fig. 5 shows ERG recordings for achromat KN made below the null (left-hand records) and above the null (right-hand records). In each recording the vertical line is an estimate of the time taken (the delay) for the response to the flicker pulse at time zero to appear in the ERG. Since the delay of either the slow or the fast rod responses is roughly constant with temporal frequency, the position of the peak corresponding to the pulse at time zero is roughly the same for all temporal frequencies.

The difference in the delay between the slow response (left-hand side) and the fast response (right-hand side) is plotted as a phase difference in degrees by the squares in the right-hand panel of Fig. 5. The filled circles represent similar data for the normal subject, also estimated from ERG recordings (not shown). For the normal observer the phase differences between the slow and the fast rod signals obtained electrophysiologically agree well with the phase differences determined psychophysically. Further, the estimate obtained electrophysiologically for the achromat is comparable with the psychophysical and electrophysiological estimates for the normal observer.

4. DISCUSSION

In summary, the flicker detectability data and the ERG recordings for both the normal observer and the achromat provide strong support for a duality in the rod visual system, in which rod signals are transmitted through either a slow, sensitive pathway predominating in dim light or a fast, less sensitive one predominating in brighter light. Near 15 Hz, both observers exhibit a region of flicker self-cancellation well above conventional threshold. This null seems to be the result of destructive interference between slow and fast rod signals that are out of phase with each other close to 15 Hz. The cancellation is found not only psychophysically but also in the ERG. Accompanying the null is a rapid change of phase. This phase reversal suggests that cancellation is indeed the cause of the null: When the two signals are exactly equal in strength and in opposite phase there will be complete cancellation, but, if there is any imbalance in the strengths of the two signals, the result will have the phase of whichever is the stronger signal. In short, there will be a rapid phase transition of 180° as the 15-Hz fast rod signal equals and then exceeds the strength of the slow signal, and the transition will be accompanied by a flicker null.

A. Comparison of Normal and Achromat

One interesting difference between the results for the achromat and those for the normal observer, but one that seems not to be central to our model, is that the achromat's null occurs at a higher intensity (compare Figs. 2 and 4). This difference is unlikely to be the result of the normal observer's cones detecting the target and producing tiny, subthreshold flicker signals because the cone signals would actually be in phase with the slow rod signals at 15 Hz^{1,3} and out of phase with the fast rod signals. Thus their effect would be to add to the slow rod signals and cancel the fast ones, so that both the upper and the lower limits of the null in the normal observer would be raised—quite the reverse of what we found.

The displacement of the null might instead be caused by a change in the relative strengths of the slow and fast rod signals between the normal observer and the achromat. If the quickness of the fast rod signals occurs because they, but not the slow signals, are transmitted partly through a pathway that is ostensibly a cone pathway (one of the possibilities suggested in Ref. 1), then a deficiency of cone pathways in the achromat might weaken the fast rod signals and so elevate the null. Histological studies of the retinas of totally color-blind observers²²⁻²⁵ (not all of whom may have been typical, complete achromats) differ

greatly in their results (for a discussion, see Sharpe and Nordby,¹¹ p. 273). Each study divulged the presence of morphologically intact cones or conelike structures in the enucleated retinas, even though little or no evidence was found for cone function in previous clinical and psychophysical investigations of the subject's vision. In the first histological investigation²² cones were found to be scarce and malformed in the fovea but to be normally distributed and normally shaped in the periphery. However, in the three subsequent studies^{23–25} the cone numbers in the totally color-blind eye were found to be vastly fewer than those found in the normal retina. It is conceivable, therefore, that there are some cones in the eye of our achromat observer that are structurally malformed or functionally impaired or too few in number to provide an independent visual signal but that suffice to leave intact a vestigial cone system. Although it is unable to contribute to vision *per se*, this system might provide a weakened pathway for the fast rod signals.

Another difference between the data for the normal observer and for the achromat is that the phase difference between the slow and the fast rod signals grows a little more quickly for the achromat than for the normal observer (Fig. 5, left-hand panel). One consequence of this effect is that the slow and fast rod signals are out of phase at a lower frequency than those for the normal observer, a result that is consistent with the need to use 14 Hz rather than 15 Hz to improve the null for the achromat. These differences in phase delay between the achromat and the normal observer may also be related to the need to use higher-illumination levels to produce flicker self-cancellation in the achromat. The phase delay between the achromat's slow and fast rod signals measured in the region of his null would be expected to be larger if, for example, light adaptation differentially speeds up the fast rod signals.

B. Other Considerations

When we describe the rod visual system as being dually organized into slow and fast pathways, we are referring in the first instance to the delay of the two rod responses (see Fig. 5, above), rather than to the shapes of the temporal-frequency response of the rods. Conner⁹ and Sharpe *et al.*¹ measured the shapes of the rod temporal-frequency responses of the slow and the fast rod pathways. At luminances well below the 15-Hz null region, for which we assume that the slow pathway predominates, the frequency response is low pass. Similarly, the frequency responses measured just below and just above the null region are also low pass in shape, but presumably in this region neither reflects the exclusive activity of a single pathway. At higher-luminance levels, for which we assume that the fast pathway predominates, the frequency response becomes bandpass and slightly more extended to higher frequencies. Thus, in addition to the large difference in response delay between the rod pathways, there is evidence for a change in the shape of the temporal-frequency response.

One other aspect of the results shown in Fig. 5 should be mentioned. It is that the phase difference between the slow and fast rod signals falls toward 0° as the frequency is reduced. This result argues against a model for the null in which the cancellation is between a signal and a

phase-reversed version of the same signal because such a model predicts a phase difference of 180° at all frequencies, not just at 15 Hz as we find.

C. Rod–Cone Interactions in Flicker

There is a considerable body of literature on rod–cone interactions affecting both cone and rod flicker detection (see, for example, Refs. 26–29). However, there seems to be no need to invoke any of the reported effects to explain our data, which to a first approximation can be explained as a simple cancellation between two rod signals. In an earlier paper,¹ we discussed some evidence for small non-linear interactions between the two rod signals.

A comparable perceptual null or loss of flicker perception has been demonstrated for suprathreshold mesopic flicker at 7–8 Hz.^{4,6} However, we can explain that null by assuming a cancellation between what we refer to as slow rod signals and cone signals, which are close to out of phase near such frequencies.^{3–6} As discussed above, the perceptual null near 15 Hz, however, cannot be so explained.

D. Mammalian Rod Pathways

In the cat—the mammalian species for which we have the most detailed information—there are at least two major pathways by which rod signals can travel through the retina from the rods to the ganglion cells (see, for example, Refs. 30–32 and Ref. 33 for a recent review). The main pathway is from rods to rod bipolars, to AII amacrine cells, and then to either ON cone bipolars and ON ganglion cells or to OFF ganglion cells. The secondary pathway relies on direct gap junctions between rods and cones through which rod signals have access to cone bipolars and thence to ON and OFF ganglion cells.³⁴ In the tiger salamander it has been shown that the electrical coupling between rods and cones can be strengthened by light.³⁵

Much less is known about the cellular pathways of the primate retina, but recent evidence suggests that, for the primate as for the cat, there is always a direct feed between the cone bipolars and ganglion cells, whereas there is much more amacrine influence and (or) intervention between the rod bipolars and ganglion cells.^{36,37} And, of the 25 amacrine-cell types described so far in the primate,^{38,39} the A6 can be identified with the AII amacrine of the cat.^{39–42} Nevertheless, there may be important differences between the microcircuitry of the cat and the primate retina. For one thing, gap junctions between rod and cone photoreceptors may not be so well developed in primates as they are in lower vertebrates.⁴³ For another, the situation is complicated by the synaptic wiring associated with the primate's highly developed sense of color vision.

E. Site of the Flicker Null

The low-luminance scotopic ERG records shown here are likely to be predominantly b-wave responses (see, for example, Refs. 44–47). The origin of the b wave has been known for some time to be after the receptors⁴⁸ but before the ganglion cells.⁴⁹ Much evidence suggests that its source is the glial (Müller) cells^{50,51} and that it is determined predominantly by activity in the depolarizing (ON) bipolar cells.^{52,53} If so, in order for the slow and the fast

rods signals both to be evident in the b wave of the ERG, the two signals must be segregated at or before the bipolar cell level.

Where then does the cancellation take place? One attractive possibility is that it occurs at the depolarizing (ON) cone bipolars, one of the points at which the two anatomical pathways conveying rod signals in the mammalian eye converge. At the scotopic levels at which the 15-Hz null is found, the cone bipolars might be driven by the rod signals traveling through the cone photoreceptors and the rod signals traveling through the rod bipolars and the AII amacrine cells. The most obvious problem with this model, however, is that the signal in the rod bipolar cell, although able to cancel the signal in the depolarizing ON cone bipolar, remains itself uncanceled. And, despite its being uncanceled, there is no trace of it in the b wave of the ERG, even though its (assumed) signal is clearly evident below the null. Another problem with this type of model is that the rod signal entering the cones should appear in both ON- and OFF-cone bipolars, so that the signal in the OFF-cone bipolars remains uncanceled too. To some extent, we can contend with these difficulties by arguing that the null in the b wave is the result of the electrical cancellation of signals in the separate rod and cone bipolars, whereas the perceptual null is due to neural cancellation at a later site, say, at the ganglion cell layer. But then one must additionally assume that the electrical cancellation at the bipolar-cell level coincides exactly with the physiological cancellation at the later stage.

There is a further objection, however, to the argument that the faster rod signals travel over the cone gap-junction pathway and that the locus of interaction between the slower and faster signals is the depolarizing cone bipolars. It concerns the typical, complete achromat observer; namely, how does the faster pathway originate in the achromat observer for whom there is no psychophysical evidence of postreceptoral cone vision and for whom the majority of the anatomical evidence²¹⁻²⁴ suggests that cone photoreceptors are altogether missing or reduced to at most 5-10% of their normal population (but see the discussion above)?

Thus attempting to correlate the psychophysically isolated slow and fast pathways with the electrophysiologically revealed rod bipolar and cone gap-junction pathways may turn out to be misdirected.⁵⁴ It seems possible that the interaction leading to the cancellation is taking place either at the rod bipolars themselves or before the bipolar cell level, possibly within the rod spherules, and that horizontal cells are implicated somehow. But wherever the site of cancellation, the prominence of the slow and the fast signals in ERG recordings does suggest that microelectrode recordings should easily reveal the neural substrate of the two signals.

5. CONCLUSION

Contrary to the traditional view that the human nighttime rod visual system is a relatively uncomplicated, unitary process, we report electrophysiological and perceptual evidence for a duality of organization. In addition to the familiar, slow rod signal, a faster signal becomes prominent at higher intensities.

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