Monocular Light Exclusion for a Period of Days Reduces Directional Sensitivity of the Human Retina

Abstract. *Single eyes of young adult observers were occluded for as long as 10 days. Directional sensitivity of the retina (the Stiles-Crawford effect of the first kind) under photopic conditions was dramatically reduced at every retinal location tested in all subjects. The maximum effect was observed within 3 to 5 days, and recovery took place at approximately the same rate after termination of patching.*

Retinal photoreceptors align approximately with the center of the exit pupil of the eye (*1-4*). Some alignment is present near term in the fetus (*3, 4*). The retinal pigment epithelium (RPE) plays a role in maintaining this alignment (*5-7*), although the nature of the interaction is not clearly understood. The standing potential of the eye could be a factor influencing receptor alignment. However, normal receptor orientation can be maintained at several points across the retina when the light-induced portion of the standing potential is extinguished (*6*). Receptor alignment recovers after physiological stress to the retina [that is, marked accommodation (*8*) and eye movements (*9*)] and after pathology [for example, neurosensory retinal detachments (*5-7*)]. Corrective action can occur locally (5° separation of points in the visual field) (*7*). We now provide further evidence that alignment is active.

The receptors of an eye with a displaced pupil were recently reported to be approximately aligned with the displaced pupil center (*10*). This finding suggested that light could be an important factor mediating postnatal receptor alignment (*1-3, 11, 12*). Unfortunately, a number of complications in the eye studied (*10*) make interpretation difficult. The means by which the retinal receptor detects a less-than-optimal alignment and the corrective mechanism or mechanisms are as yet undefined (*13*).

The retinal receptor is a light guide or waveguide (*14*). A characteristic feature of such fiber optics elements is the presence of a limiting aperture and resultant directionality. Receptor directionality in a given sampling area can be inferred from measures of the Stiles-Crawford (S-C) effect (*15*). Varying the point of entry of a light beam in the pupil of the eye alters the angle of incidence at which light strikes the retina (*16*). The peak of the S-C function defines the most probable central alignment tendency for a sampled receptor population. By defining the directionality of the sampled receptor population one has some hint as to distributive quality. One of the simplest formulas for evaluating the directional sensitivity of the retina is that suggested by Stiles (*15*):

$$\rho = \frac{\log_{10}\eta_{\max} - \log_{10}\eta}{r^2}$$

where η is a measure of visual sensitivity to a beam entering a given point in the entrance pupil of the eye, $\eta_{\max}$ is the maximum of sensitivity, ρ is a constant descriptive of the individual distribution

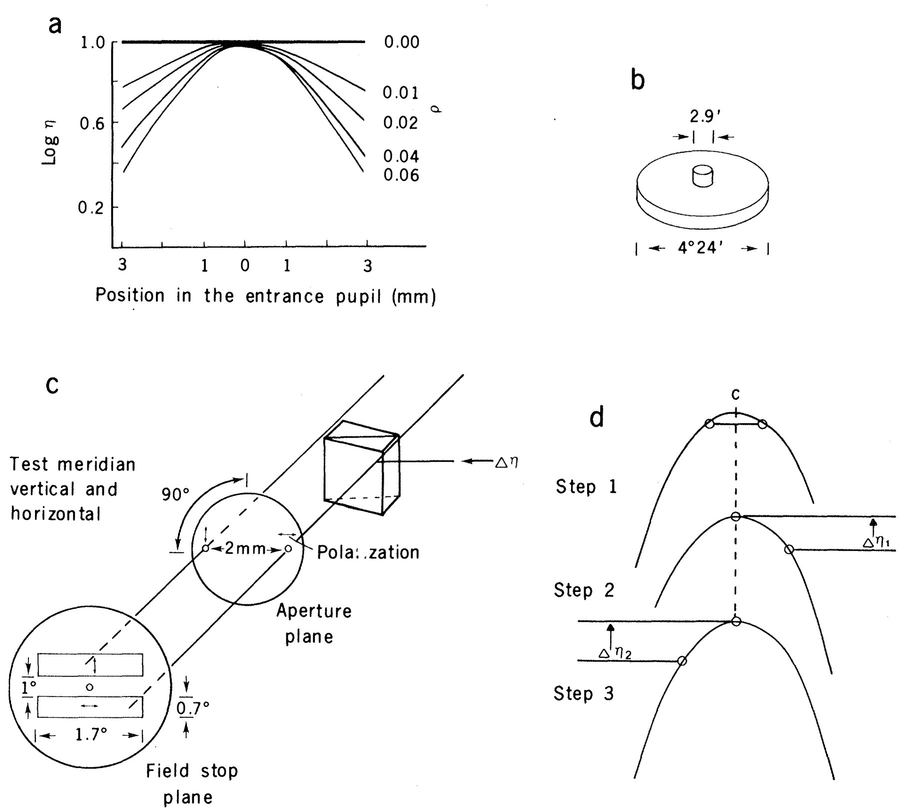

Fig. 1. (a) The variation of log η with position in the entrance pupil for several representative values of ρ. (b) Observed stimulus pattern (orange, 620-nm peak) used for the standard determination of the S-C function. The small (2.9′) test flash (150 msec presented once per second) was always centered in the pupil. The beam from the background field (4°24′, 3.04 log photopic trolands) was shifted across the pupil in a stepwise fashion. The task of the observer was to adjust the luminance of the centered test spot until it just disappeared. Increment-threshold functions determined both before and on the last day of patching confirmed that all testing was within the Weber region (*27*). (c) Schematic representation of the modified S-C apparatus. Two rectangles were located just above and below a fixation point in the field stop plane. (This fixation point was removed for testing at other retinal loci.) They were illuminated by a pair of pinholes in the aperture plane. The aperture plane was imaged through the use of unit magnification in the entrance pupil of the eye. Polaroids restricted the light from each aperture to a single rectangle. The determination of horizontal S-C function peaks and ρ_2 required horizontally aligned apertures. For determinations in the vertical meridian, the pinholes in the aperture plane were aligned vertically. $\Delta\eta$ indicates the additional light path that was added for ρ_2 determinations. Such addition could be made in either light path. (d) Technique used for the rapid assessment of the S-C peak and ρ_2. Step 1: The two apertures were translated in tandem stepwise across the entrance pupil of the eye. When the apertures were symmetrically disposed around the point in the entrance pupil corresponding to the S-C function peak (*c*), the rectangles they illuminated appeared equal in brightness. The peak was taken as the midpoint of the line connecting these two symmetrically disposed apertures (*17*). Step 2: The apertures were translated until one of the apertures lay at the position in the entrance pupil corresponding to the previously determined S-C peak. The rectangle illuminated by this aperture then appeared the brighter of the two. The dimmer rectangle was illuminated by the aperture located 2 mm from the peak. The amount of light that had to be added to the latter ($\Delta\eta_1$) in order to produce a brightness match was used to derive ρ_2. Step 3: The value of $\Delta\eta_2$ was determined from the other side of the S-C function. The mean of $\Delta\eta_1$ and $\Delta\eta_2$ was used to determine ρ_2. These three steps constituted a single determination of the S-C peak and ρ_2 in one meridian. The entire sequence was then repeated in the second meridian.

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(Fig. 1a), and r is the displacement in the entrance pupil of the eye from the peak of sensitivity (that is, from the measured η_{max}).

In this study subjects wore black eye patches for 7 or 10 days; we measured the directional sensitivity of the retina before, during, and after occlusion. The patch was designed to exclude all light but to leave the pressure and temperature of the eye unaltered. Patching one eye for a period of days changed the directional sensitivity of the retina at all retinal loci tested from fixation to 20° eccentricity. A variety of other functional changes were noticed but will not be described here. These included an increase in overall sensitivity, some perceived hue and saturation changes, and modest alterations in retinal resolution.

The method used for the standard determination of the S-C functions has been described in detail elsewhere (*11*) (Fig. 1b). All testing was at background levels at least 3 log units above cone threshold.

A second technique was developed for a rapid assessment of the S-C peak and ρ. This technique minimally compromises the experiment. Both the location of the peak and an estimate of ρ could be obtained from a given retinal locus by use of the second method with less than 5 minutes of light exposure per day. The apparatus is presented schematically in Fig. 1c, and the method is outlined in Fig. 1d (*17*).

The symbol ρ_2 is used to distinguish the estimate obtained with the rapid as-

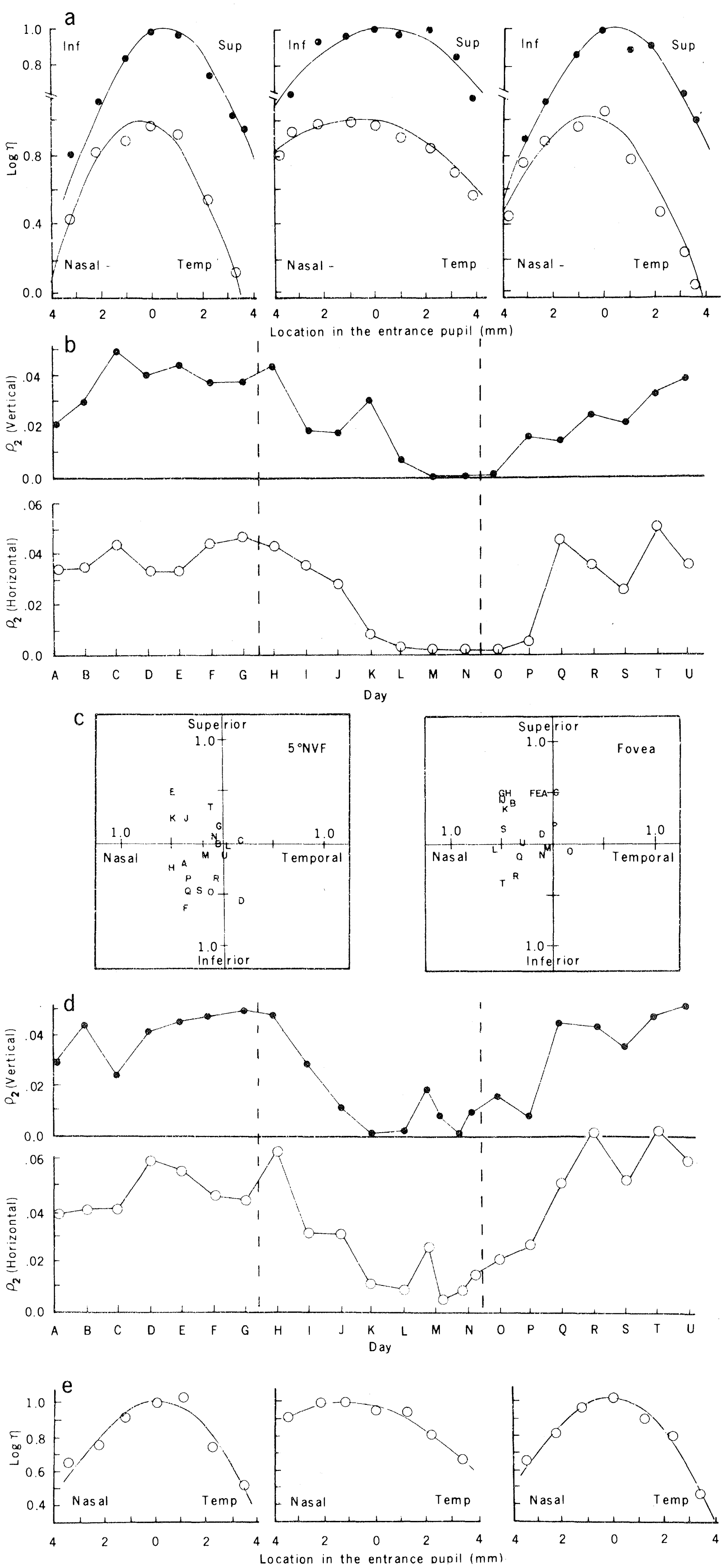

Fig. 2. Results from observers D.B. (a to d) and J.T. (e). ●, vertical meridian; ○, horizontal meridian. (a) Full S-C functions determined according to the standard technique 5° from fixation in the nasal visual field (*NVF*) before patching (left), after seven days of occlusion (middle), and following recovery (right). (b) Daily results according to the rapid technique at 5° in the nasal visual field. The period of occlusion is indicated by vertical lines. (c) Daily S-C peak locations derived by the rapid technique. Each point designated by a letter is the combined mean S-C function peak value for both horizontal and vertical sweeps of the apertures (Fig. 1c) in the entrance pupil on a given day. The letters correspond to the sequence of days indicated in (b). Peak locations for the tests conducted at 5° in the nasal field are shown on the left. On the right are the S-C peak locations for comparable daily assessments at the point of fixation. The value 1.0 in the figures corresponds to 1 mm in the entrance pupil of the eye. (d) Results from the rapid technique at the point of fixation. The method of plotting daily values of ρ_2 is the same as in (b). (e) Full S-C functions obtained with the standard technique from the point of fixation before patching (left), after 10 days of occlusion (middle), and after recovery (right).

sessment technique from that determined from the complete S-C function. Although the two estimates covary, they are not identical. There are important differences in both the retinal extent of the stimuli and the psychophysical methods used.

Sample results obtained with the rapid technique 5° from fixation are shown in Fig. 2b. The value of ρ_2 was determined for a number of days (designated by letters) before (A through G), during (H through N), and after patching (O through U). In both horizontal and vertical meridians, ρ_2 had decreased meaningfully by the third day of patching (J). It fluctuated near 0 for the remainder of the occlusion period and returned to normal 3 or 4 days after the patch was removed.

Full S-C functions were obtained before patching, on day 7 of patching, and after ρ_2 had returned to normal. Patching flattened the full S-C function, particularly in the central 4 to 6 mm of the entrance pupil (Fig. 2a). Although some directionality remained, the central flattening led to the low ρ_2 values (near 0.01) (Fig. 2b). Shifts in peak locations were minor (Fig. 2c), and at all times the peak lay within 1 mm of the pupil center (*18*). However, as ρ approaches 0, the location of the S-C peak becomes more difficult to define. The effective pupil center did not change during patching. Photographic records were made of the entrance pupil of the eye relative to the corneal reflex.

Similar overall results were obtained when testing was conducted at the point of fixation (Fig. 2, c and d). Directionality is normally lower in this region than in the parafovea (*19, 20*) (that is, ρ is lower, but the decline in ρ_2 is still obvious). Full functions from the point of fixation in a second observer are shown in Fig. 2e. Alignment was lost a little more rapidly in this subject, and recovery was a little slower. Otherwise, the changes were similar. This decrease in ρ during patching has now been replicated in several other observers with comparable results. Tests in individual observers were extended out to 20° from the fixation point. Apparently, the more eccentric the test, the greater the loss in directionality (the sample is somewhat limited). These changes are remarkable in an otherwise highly stable function (*20*).

The most reasonable explanation of the effect is that it is caused by light exclusion. Since we periodically tested the subjects without abolishing the effect, the elimination of light need not be total. The second eye was never patched during the period of monocular occlusion and showed no change in directional sensitivity. Thus, these data provide additional evidence that receptor directional properties reflect an active and local (here, one eye) process.

A subject recently exhibited relatively normal S-C functions in both eyes, but the peaks of these functions in one eye tended to align (across the retina) with a point just in front of the center of the retinal sphere; ρ was only modestly altered (*21*). This finding is counter to the one described here, in which shape—not peak—was altered. This contradiction implies that receptor alignment is influenced by more than one factor; the interactions of these factors must be understood before we can attempt an overall analysis of the mechanisms subserving alignment.

The receptors cannot disperse randomly because of physical packing. Groups of cells may align somewhat differently, however, and may change in alignment during patching. Alternatively, the outer segment disk structure may alter with patching. Changes in disk structure and elongation of receptors have been noted with aging (*22*) and with intense light exposure (*23*). Several studies have demonstrated increases in rhodopsin concentration, photoreceptor length, and visual sensitivity with prolonged light exclusion (*24*). Either group orientation dispersal or alterations in receptor disk structure would result in reduced directionality; a technique developed by O'Brien and Miller may allow us to distinguish between the two possibilities (*25*). In addition, the RPE, the interface between the RPE and the photoreceptors, or both may be altered by extended periods of patching. This could contribute to the changes found here and to the electrophysiological results found by others (*26*).

These data provide strong evidence that absorbed radiant energy plays an important role in maintaining receptor alignment and that receptor alignment is an active process. Even a modest period of occlusion (days) considerably alters some distributive factor. This is but a simple step in the evaluation of a complex response mechanism.

Patients are commonly patched as part of amblyopic training and as a therapeutic measure to protect the eye in disease or following surgery. We tested normal eyes in young adults; individuals with displaced pupils, natural or artificial, are yet to be studied. The parameters of these changes must be explored and clarified, mechanisms subserving alignment in receptors need to be better understood, and means of altering these factors must be considered.

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