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Inferred Positive Phototropic Activity in Human Photoreceptors

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INFERRED POSITIVE PHOTOTROPIC ACTIVITY IN HUMAN PHOTORECEPTORS†

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CONTENTS

The Stiles–Crawford (S.–C.) function, a measure of the directional sensitivity of the retina, was used to infer the alignment characteristics of the sampled retinal elements. One assumes that the peak of the photopic S.–C. function reflects the central alignment tendency of retinal elements sampled, and that the shape of the function reflects, among other factors, distributive qualities.

Here two tests were performed to determine whether the function sampled reflected positive phototropic activity. The natural eye pupil was dilated and artificial pupils were substituted having specified eccentricity from the centre of the natural pupil. This was achieved with a displaced iris contact lens. After a series of complex experiments, it was finally shown that the peaks of the S.–C. function shifted towards the displaced aperture of the contact lens. As a second test, individuals were occluded uniocularly with a black patch for periods of time up to 10 days. This caused remarkable flattening of the measured S.–C. function. That flattening occurred in determinations

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of both photopic and scotopic S.–C. functions. Comparable effects were not seen in the second eye or if a diffuser was substituted for the black patch.

Change and recovery in both experiments occurred within 3–5 days.

On the basis of these experiments it is inferred that there is an active mechanism behaving in a positive phototropic manner present in the human retina.

Introduction

In 1933, the directional sensitivity of human photoreceptors was first reported in *Proc. Roy. Soc.* by Stiles & Crawford (1933) (figure 1). In the years since this discovery, it has become evident that the peak of this psychophysical function reflects the central orientational tendency of the set of receptors (and associated structures) whose response is sampled, and that the shape of the function provides information about the degree and distribution of orientation within the sample tested.

It is inferred that these properties are mediated in substantial measure by retinal photoreceptor fibre optics elements acting as waveguides that have limiting apertures (see, for example, Enoch 1972). The Stiles–Crawford (S.–C.) function (of the first kind) is also influenced by some pre-retinal optical properties (yellow pigment in the eye lens, eye lens fluorescence), as as well as several added retinal factors, including orientated photolabile pigment in the disk membranes of photoreceptors, self screening by receptor pigments, dark pigment in the layers backing the photoreceptors, and reflecting surfaces behind the receptors in some species. Psychophysically determined measures of directional sensitivity are influenced by these factors and optical and neural interactions with other receptors and neural units, as well as dispersion in alignments between individual receptors and groups of receptors.

The results reported here support a hypothesis that human photoreceptors (and associated structures) are positively phototropic, i.e., there is active alignment towards the pupillary aperture in response to light. Two specific tests of this hypothesis have been conducted. (*a*) If the pupillary aperture is displaced, and enough light is provided over a period of days, the peak of the S.–C. function will be shown to shift towards the displaced aperture. The peak returns to its original location within a few days of removal of the displaced aperture. (*b*) When light is removed (occlusion of one eye with a black patch for a period of days), there is a gross flattening of the S.–C. function, far in excess of any previously recorded physiological change in these functions. (This change approaches that seen in various retinal pathologies affecting alignment.) Recovery follows after a few days of light exposure and is dependent upon the amount of that light. The results of these studies are clear, but not simple (Enoch *et al.* 1979*a*, *b*; Enoch *et al.* 1980; Birch *et al.* 1980; Enoch & Birch 1980).

Previous research has yielded results that suggest an active alignment mechanism. S.–C. functions have exhibited a stability not often found in psychophysical functions (Stiles 1939; Enoch 1956; Safir & Hyams 1969; Bedell & Enoch 1979). The system can recover from physiological transients (Richards 1969; Enoch 1975) and from major alterations due to pathological processes (see, for example: Fankhauser & Enoch 1962; Enoch *et al.* 1973; Fitzgerald *et al.* 1980*a*). These corrections can be local in nature, and may even occur under superficial retinal traction bands (see, for example, Campos *et al.* 1978). The peak of the directional sensitivity function approximates the centre of the pupillary aperture rather than the centre of the eye (Laties 1968; Enoch 1972; Webb 1972). This alignment tendency may be already present in some form before birth (Laties & Enoch 1971). The pigment epithelial layer of the retina apparently plays some necessary role in the maintenance of proper directional sensitivity (Fitzgerald

et al. 1980*b*). On the basis of limited evidence, neither the light nor dark component of the standing potential of the eye (electroculogram, eog.) seems to be the mechanism controlling alignment (Fitzgerald *et al* 1980*b*; Bedell & Enoch 1980; Enoch *et al.* 1979*b*, 1980).

In some, but certainly not all, cases of pathological pupillary displacement, the S.–C. function peak has been found to be displaced towards the pupillary aperture (Dunnewold 1964; Bonds & MacLeod 1978). While such studies of pathologically induced displacement (trauma, congenital, etc.) are valuable, there is alway some uncertainty as to independence of changes in the pupil and retina. However, the finding of codisplacement of pupil and S.–C. function peak demonstrates the need to test for evidence of positive phototropism of the response system of the normal eye.

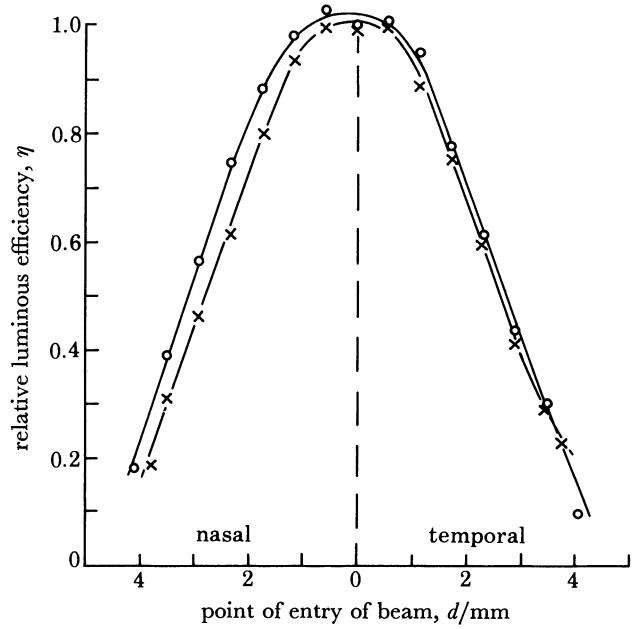

FIGURE 1. These data were obtained by Stiles & Crawford (1933). The horizontal traverses of subject W.S.S. are shown. The circles represent the original measurement and the crosses are replications made 6 weeks after the initial data set. Relative luminous efficiency (or sensitivity) is plotted on the ordinate and the point of entry of the test beam in the entrance pupil of the eye (in millimetres) is plotted on the abscissa.

Numerous individuals including the authors have suggested that the system is active and phototropic (see, for example, discussions in Enoch (1972, 1976), Enoch & Horowitz (1975), Enoch *et al.* (1979*a*), Bonds & MacLeod (1978), Laties (1969), and Laties & Burnside (1979). Earlier findings of great stability of S.–C. functions, alignment of receptors with a point approximating the centre of the pupil, recoveries from physiological and pathological insults, and findings in patients with displaced pupils lead to the development of the experimental hypothesis.

APPARATUS AND METHODS

Apparatus

Directional sensitivity and retinal resolution were measured in a three-channel Maxwellian view optical system. The apparatus has been described in detail previously (Enoch & Hope 1972). Two channels, both originating from a 6 V 18 V tungsten ribbon filament source (similar to C.I.E. Illuminant A), were used for the S.–C. determinations. One channel produced a

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flashing (150 ms duration, once per second) test spot (0.36° diameter, 605 nm); the second channel produced a steady background (4.4° diameter, 605 nm). The pupil entry position of the test beam was always the geometric centre of the pupil, while the entry position of the background beam was variable. The field stops in both channels could be translated in the x, y, and z dimensions. Translation in the z dimension (Badal optometer) was used to minimize blur at the retina; x–y translation was used to centre the background with respect to the test spot at each pupil entry position.

A third channel, originating from a helium–neon gas laser, was used to assess visual resolution interferometrically.

For both S.–C. and interferometric measurements, the subject was held rigidly in place through a bite bar–head rest assembly that could be translated through x, y and z axes. The pupil was illuminated with infrared light and was carefully monitored through an infrared image converter. Continuous adjustments during testing prevented changes in pupil position of over 0.1 mm.

Two collimated fixation devices were available for testing loci in the visual field (and retina) eccentric to fixation.

Procedure and data analysis

Standard S.–C. determinations† were made with an increment–threshold procedure, with the task of the observer being to set the intensity of the flashing test spot to threshold. Thus, the effect of the background upon the threshold of the test beam was determined for each pupil entry position of the background.

The technique depends upon the Weber relationship; that is, the results are only valid when $\Delta I/I = C$ (see Enoch & Hope 1972, appendix 2). Increment thresholds were routinely determined at a number of background intensities to establish that the subjects were functioning on the linear part of the increment threshold curve during all phases of these experiments.

Mean thresholds and standard deviations were obtained from a number of pupil entry positions to determine each S.–C. function. The central portion of the photopic S.–C. function can be fitted by Stiles's equation (Stiles 1937):

$$\rho = \frac{\log_{10} \eta_{\max} - \log_{10} \eta}{r^2}, \tag{1}$$

where η is a measure of sensitivity at a given pupil entry position, r is a measure of the distance in the entrance pupil of the eye from the location of the peak of sensitivity ($\eta_{\max}$), and ρ is a constant reflecting the directionality of a given data set.

The design of some of the experiments reported here precluded the use of standard technique. As will become clear, it was necessary to assess the location of the S.–C. peak, directionality and sensitivity at a large number of retinal loci. As well as requiring an inordinate amount of time, use of the standard technique would have exposed the subject to many hours of light and may have seriously comprised these experiments. To avoid this difficulty, we used a rapid technique for determining the peak location of the S.–C. function (Enoch 1959; Blank *et al.* 1975). For this technique, only one channel of the apparatus was required. Two rectangles in the field stop plane were illuminated by a pair of pin holes in the aperture plane of the instrument. Crossed polaroids limited the light from each aperture to one of two rectangles in the field stop plane (figure 2). The two beams entered the pupil at a fixed separation of 2 mm and could be moved

† Standard here implies 'customary, as used in this laboratory'.

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in tandem stepwise across either the horizontal or vertical meridian of the pupil. For each position of the apertures, the task of the subject was to indicate (forced choice) which of the two rectangles appeared brightest. When the apertures were symmetrically disposed around the point in the entrance pupil corresponding to maximum sensitivity (η_{max}, see figure 1), the rectangles that they illuminated appeared equal in brightness. The S.–C. peak was taken as the midpoint of the two apertures. Strictly speaking, this technique is only valid when the S.–C. function is symmetric around the peak, and sufficiently uniform within the field areas sampled. However, the degree of asymmetry encountered in most of the experiments reported here would have little effect on the derived values of η_{max}. The locations of secondary peaks (when present) can also be determined by this procedure.

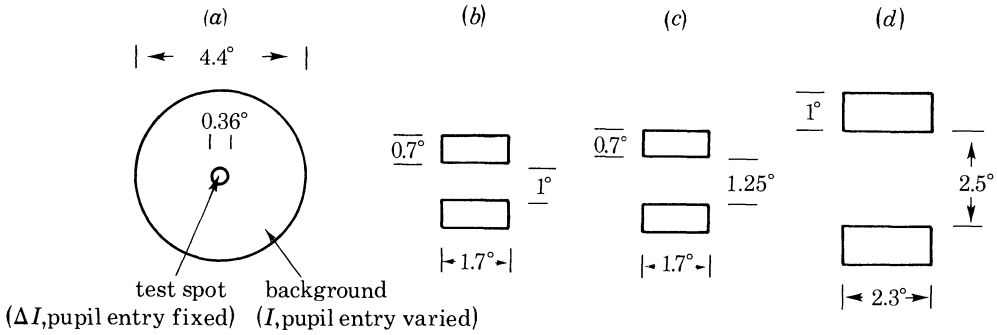

FIGURE 2. This figure shows all target arrays used during testing. (*a*) Regular array, all field positions. (*b*)–(*d*) Rapid peak-finding arrays: (*b*) fixation; (*c*) 5, 10°(*d*) 15, 20°. For the standard determinations of the S.–C. function, array (*a*) was used. Note that the test spot samples an area different to that used when the rapid technique was applied (displays (*b*)–(*d*)). Added fixation points were provided during the standard test. Different displays were used with the rapid technique because of the relative difficulty of the task for more peripheral test loci. At 15° and 20° from fixation, the entire display was flashed for 150 ms, once per second, to prevent local adaptation. Increasing separation of the two half-fields made judgements slightly easier for more peripheral retinal test loci.

The sizes (in degrees of visual angle) of all the stimuli used for S.–C. testing are shown in figure 2. Note in particular, that the retinal loci tested by the rapid peak-firing arrays are not identical to the loci tested by the regular array. At each eccentricity, (e.g. 5° nasal visual field (n.v.f.), temporal retina), the standard array falls on a locus midway between the areas tested by the rapid peak-finding array. It should be evident, therefore, that the two techniques could yield different values of η_{max} if highly localized changes in alignment were to occur. These are field stop displays.

Special lenses and pharmaceutical agents used

Soft contact lenses were chosen for comfort, and special experimental lenses were manufactured by Titmus-Eurocon A.G., Aschaffenburg, F.R.G. A painted-iris contact lens was combined with a double slab-off scleral lens portion (Weicon-T), which is designed to limit contact lens rotation in astigmatic corrections.

Cycloplegic and mydriatic drugs were employed for chronic dilation of the natural pupil during special contact lens wear and/or measurement: two drops of homatropine hydrobromide ophthalmic solution (20 mg/ml), twice a day, and before testing, one drop of cyclopentolate hydrochloride (10 mg/ml) and one drop of phenylepherine hydrochloride (100 mg/ml, non-viscous). Added instillations of the latter two agents were made if pupil dilation during testing was not adequate.

Three special lenses were fitted to author J.M.E.'s right eye.

TABLE 1. SPECIAL PAINTED-IRIS SOFT CONTACT LENSES

lens	diameter of pupil aperture (mm)	displacement of pupil centre† (mm)
1	2	2.0
2	1	0.0
3	3	2.5

† The aperture was displaced temporally on the right eye at all times.

The transmission of the black-painted portion of the contact lens, the photopic luminosity function of the eye (V_λ), and the pass bands of the two filters used during the test are shown in figure 3. The transmission of the black portion of the lens was less than 0.001 % at wavelengths shorter than *ca.* 700 nm as measured on a Beckman ACTA III spectrometer. When the wearer glanced at the sun (or other intense light source), a slightly doubled deep-red image of the sun was visible to him. This transmission may be regarded as negligible under ordinary viewing conditions. The apertures settled slightly off the horizontal meridian (lens 1, slightly low; lens 3, slightly high). The position of each lens was remarkably stable with time.

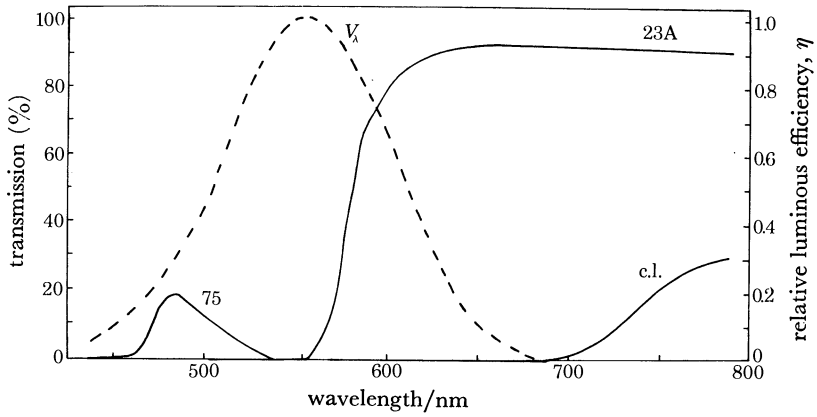

FIGURE 3. The transmission curves are presented for the painted portion of the contact lens, and the two test filters employed during testing (Kodak Wratten 23A and 75). Superimposed is the photopic relative luminous efficiency (V_λ) curve of the human eye. The contact lens (c.l.) allowed virtually no transmission below about 700 nm.

Most testing was conducted with a red-orange Eastman Kodak Wratten 23A filter (see methods). A second blue-green filter (75) was employed for limited testing. The intent, at this time, was to establish that changes recorded were not solely occurring at the long wavelength portion of the spectrum. Obviously, many interesting questions pertaining to independence of receptor mechanisms, relative efficiency, action spectrum and identity of responses, etc. remain to be tested.

For the monocular occlusion experiments, dense black patches (Bernell Corporation, South Bend, Indiana, U.S.A.) were used. These were supplemented by tape etc. and were worn 24 h per day. No light was visible through these occluders. Care was taken not to put any pressure on the eye. Patches were raised by a black plastic foam support layer from the orbital rim.

The diffuser was made by sanding both sides of a clear plastic patch (also available from Bernell) with fine grain carborundum sandpaper. The diffuser reduced light transmission by less than 0.2 lg unit, and allowed transmission of only very low spatial frequencies, e.g. a hand moving across the field was visible as a shadow. The diffuser did not meaningfully alter light level or pupillary aperture. However, there was some alteration of the distribution of energy within the aperture, and there was a resultant general veiling glare. In these experiments generally only one drop each of cyclopentolate hydrochloride (10 mg/ml) and phenylepherine hydrochloride (100 mg/ml) were administered each day before the S.–C. (and other) testing.

Results

Monocular occlusion experiments

Our findings may be summarized as follows. The normal S.–C. function becomes remarkably flattened within a few days of monocular light occlusion (dark patching) in normal human adults, with the effect reaching its peak between 3 and 5 days (Enoch *et al.* 1979*a*, *b*; 1980). Both photopic and scotopic functions are affected; comparable changes are noted in males and females, and a population with an age range of 20–50 years has been tested to date (Enoch *et al.* 1979*a*, *b*; 1980). Parallel modest alterations in perceived hue and saturation, modest reductions in resolution (in some cases) and contrast sensitivity functions, and increases in absolute sensitivity are recorded (Birch *et al.* 1980). The peak of the S.–C. function is either not altered or altered only slightly, generally with a modest nasal bias (Enoch *et al.* 1979*a*). Rate of recovery following patching is to some degree dependent upon light exposure and is complete within 3–5 days after removal of the occluder (Enoch *et al.* 1979*a*, *b*; 1980). Examples of these findings are presented in figure 4. Data of subject D.B., age 29, male, Caucasian, are shown for fixation, 5 and 20° in the nasal visual field (n.v.f.). In the first column of figure 4, pre-occlusion data are presented; in the second column are presented S.–C. data recorded after one week of continuous patching; and in the third column are data determined 5–7 days after the termination of occlusion. The constant ρ was determined for the central portion of the function by a least squares method.

At all loci tested (figure 4), a marked reduction in directionality (here estimated by ρ) occurred with occlusion. One example of test–retest data is presented. Note also that before occlusion ρ is greater at 5° n.v.f. than at fixation or at 20° n.v.f. This has been confirmed experimentally several times previously (Westheimer 1967; Enoch & Hope 1973; Bedell & Enoch 1979; Bedell 1980). These results show that the changes following occlusion are not unique to the fovea. Parallel scotopic changes in the S.–C. function have been reported elsewhere (Birch *et al.* 1980).

Figure 5 shows S.–C. functions measured at fixation in three added observers: M.E.B., age 48, female, Caucasian; J.T., age 24, male, Mongolian; and M.D.B., age 27, male, Caucasian, with keratoconus, a degenerative thinning of the cornea, with a peaking outward or coning of the residual corneal tissue (corrected by a contact lens; maintenance of centration of the lens presented some problem during testing). Data are comparable with those of D.B. (figure 4). In figure 6, data on the contralateral (non-occluded) eye of M.E.B. are presented to show that comparable flattening of the S.–C. function did not occur in the control eye.

In figure 7, data from two subjects, L.T., age 34, male, Caucasian, and B.B., age 25, female,

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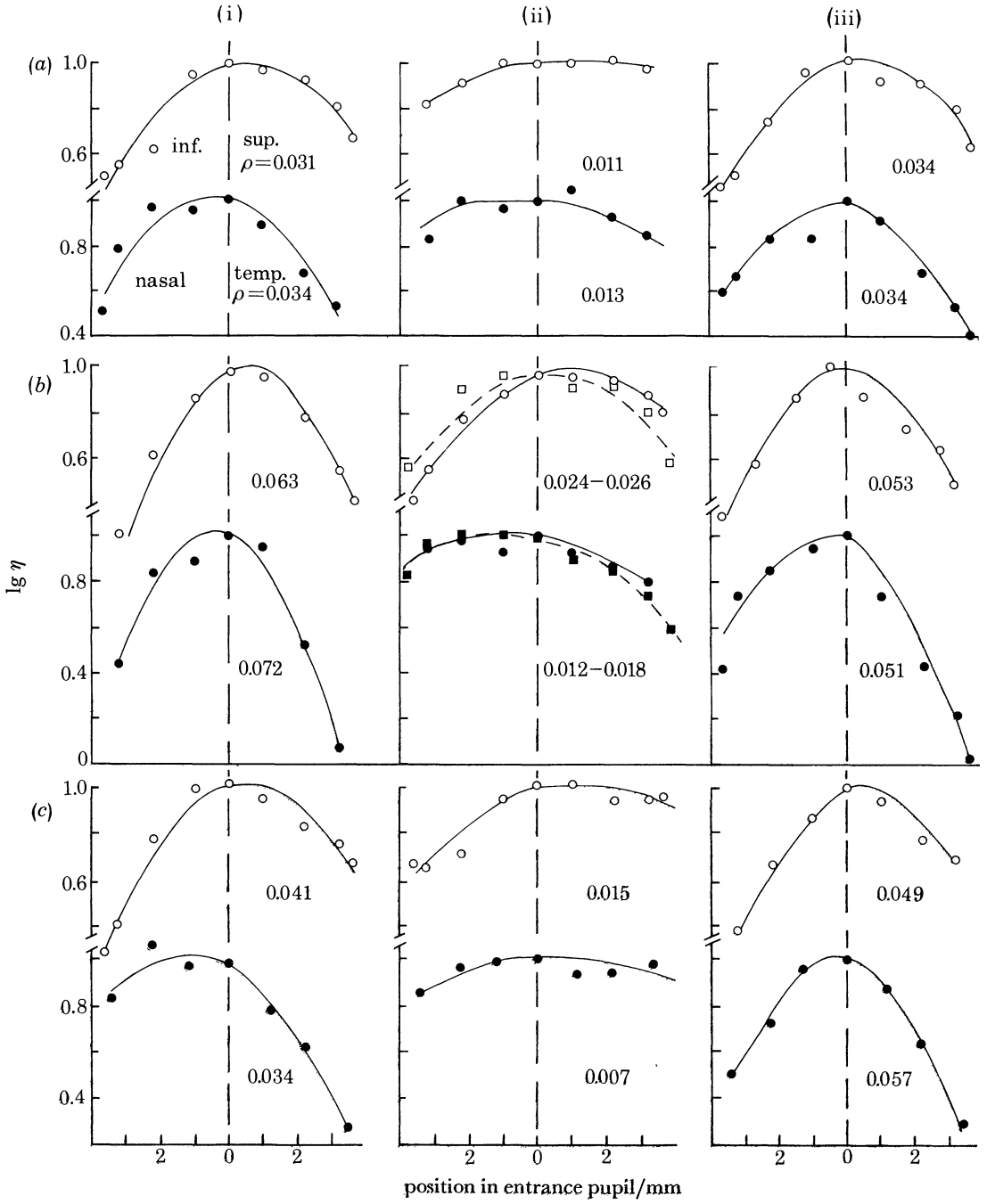

FIGURE 4. Sample data obtained with subject D.B. (left eye, o.s.) at (*a*) the point of fixation (presumed fovea) and at (*b*) 5° and (*c*) 20° n.v.f. Sample test–retest data are plotted ((ii), (*b*)). All data in column (i) were obtained before uniocular occlusion. The data shown in the column (ii) were obtained at the end of the seventh day of uniocular occlusion, and the data in column (iii) show functional recovery 5–7 days after removal of the black occluder. These photopic S.–C. functions were measured in the horizontal and vertical pupillary meridians (temp. temporal; inf, inferior; sup., superior). Note that all data used for computation of ρ were limited to 3 mm from the peak.

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Caucasian, are presented. They both wore the diffuser over the test eye rather than the dark patch. Wearing the diffuser had little effect on the S.–C. function. Thus, the changes recorded with the dark patch must be due to loss of light and not to loss of pattern information.

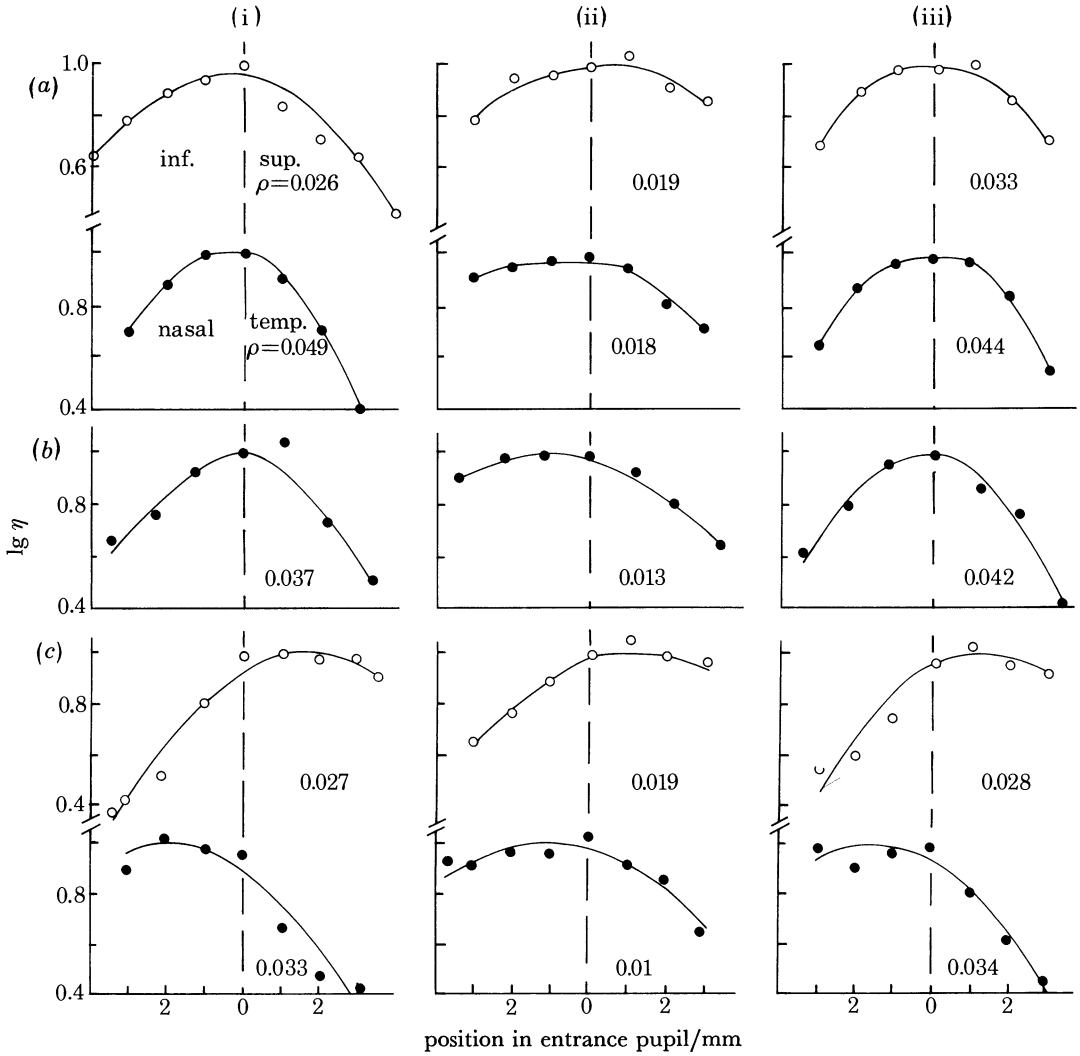

FIGURE 5. Data obtained at fixation on three added observers, (*a*) M.E.B., (*b*) J.T., and (*c*) M.D.B. They may be compared with data in figure 4 (subject D.B.) at fixation. Horizontal and vertical photopic S.–C. functions are displayed. Computed ρ values are shown. Column (i), data obtained before uniocular occlusion; (ii) data obtained after 7 days uniocular occlusion; column (iii) data obtained 5–7 days after removal of the occluder.

In summary, removal of light caused a marked reduction in directional sensitivity with little shift in the peak of the S.–C. function. Restoration of light resulted in recovery. Rate of change (Enoch *et al.* 1979*a*, *b*; 1980) was measured in days. Thus, we assume that the system will show no meaningful dispersal at night or during modest periods of time in a dark environment. Response is to a general, long-term alteration in the luminous environment and is apparently dose-dependent. Since both photopic and scotopic vision are affected, one infers that both rods and cones are involved. Several parallel visual changes are noted (see discussion).

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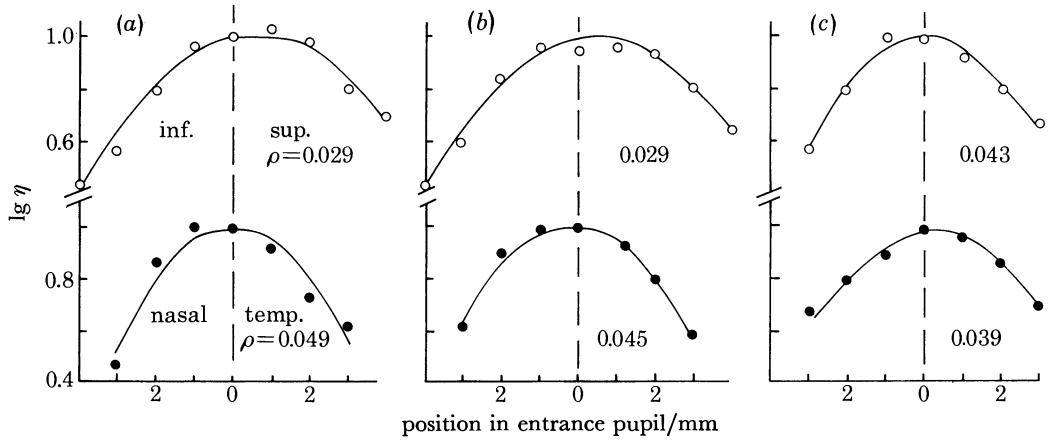

FIGURE 6. Data for the non-patched right (o.d.) eye of observer M.E.B. (figure 5). Data were obtained (*a*) before left eye occlusion, (*b*) at the same time that the left eye had been occluded for a full week, and (*c*) 5–7 days after removal of the occluder from the left eye. It is obvious that no meaningful concurrent change had occurred in the non-occluded eye.

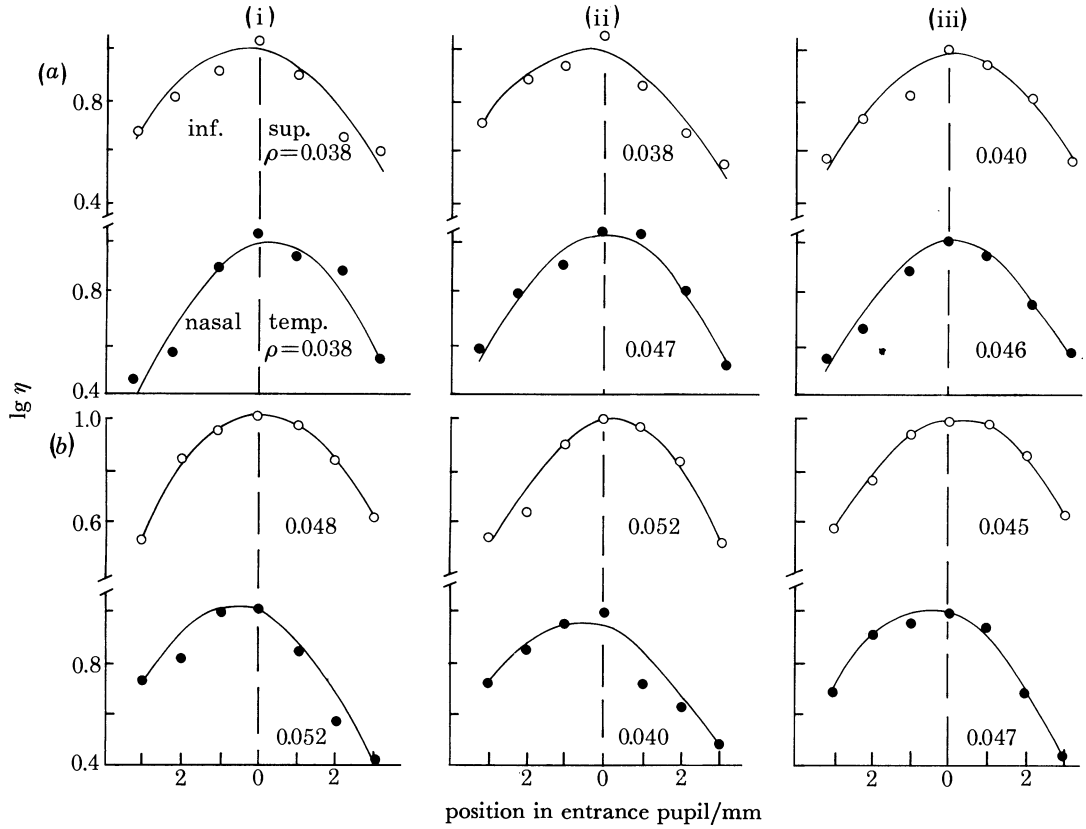

FIGURE 7. S.–C. data for two normal observers ((*a*) L. T. and (*b*) B. B.), who wore a diffuser over one eye, rather than a black occluder: (i) before wearing diffuser; (ii) wearing diffuser; (iii) after wearing diffuser. S.–C. data obtained in both the horizontal and vertical meridians are shown and ρ values are indicated. Seven days of wear of the diffuser did not meaningfully alter measured S.–C. functions.

Displacement of the aperture of the eye through use of special contact lenses

If the mechanisms subserving directional sensitivity are positively phototropic, then displacement of the pupillary aperture should result in an alteration in the peak of the S.–C. function towards the new source of radiant energy. Such an alteration was obtained, but achievement of success† was complex and revealed the presence of added competing mechanisms in the eye studied (J.M.E., right eye). This portion of the experiment was divided into three phases.

The original design called for wearing lens 1 (table 1) with its aperture displaced temporally, and then repeating the experiment using a nasal displacement of the aperture. The symmetry of lens design provided two stable lens positions, 180° different in orientation from each other. After the first seconds of lens wear, the lens settled and one could easily tell lens orientation. Orientation was periodically checked with a mirror carried for this purpose. For reasons that will become obvious, this original plan was not followed. The lens was worn only with temporal aperture displacement.

Phase I

In figure 8, day-by-day location of S.–C. peaks (rapid technique) in the horizontal meridian are presented. Two test points are reported, fixation and 5° nasal visual field (n.v.f., projects onto temporal retina). Parallel data were obtained in the vertical pupillary meridian at the same time, but generally these experiments showed no meaningful alterations in alignment (none were anticipated). These data are not presented, except where exceptions to the latter statement were found (see, for example, end of phase II).

The contact lens (lens 1) was worn from midday on the fourth day to about midday on the seventeenth day of testing (for sleeping, a black patch was substituted). The presumed centre of the displaced-aperture painted-iris contact lens was 2.0 mm temporal (horizontal line, figure 8). We do not know exactly where that centrum was. The entire lens (corneal and scleral portions) was painted black. Photographs of the fine conjunctival vasculature lying on the sclera (white of the eye) were taken before and after lens insertion. However, the conjunctiva is so elastic, and the size of the vessels so variable, that simple overlay of photographs did not allow fine judgement of lens position. This lens aperture consistently settled slightly below (0.1–0.2 mm) the horizontal meridian. Total error was not substantial.

Somewhat similar experimental results were obtained at the fixation point and at 5° n.v.f. (figure 8). Both at fixation and at 5° n.v.f. the S.–C. peak during the pre-test period showed a modest nasal displacement. This is a common finding in S.–C. data determined on normal observers. By the fourth day after lens wear was initiated, there was a modest temporal shift of the peak. This shift is not very convincing here, but from analysis of phases II and III of the experiment it is probable that this slight temporal peak translation was real. This was followed shortly by a major nasal shift *away* from the displaced aperture at both test points.

Most data were obtained with a Kodak Wratten 23A (a red-orange filter). To show that response was not limited to long wave-length sensitive receptors, we tested occasionally with an Eastman Kodak Wratten 75 filter (blue-green pass band). At that time, we were not concerned with identity of response, which is an important question. Rather, we sought to establish

† This alteration could not occur if the pharmaceutical agents used to dilate the natural pupil blocked the phototropic response. The positive results obtained suggest that this was not a contaminating factor.

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that change was of the same general magnitude in both portions of the visual spectrum. On day 13, a secondary peak in sensitivity was noted on the S.–C. function measured at 5° n.v.f. This subpeak persisted until after lens removal.

The major nasal shifts, suggestive of a negative phototropism, were totally unexpected. Intensive additional trials were initiated. More points were tested, the second eye was examined, a thorough physical examination of the retinas was undertaken, etc. It was found that the nasal shift (bias) of the S.–C. peak was not limited to the two points followed intensively in figure 8, but rather extended over a zone from 5° t.v.f. (temporal visual field, nasal retina, towards the optic nerve head or blind spot) to 10° n.v.f. (figure 9).

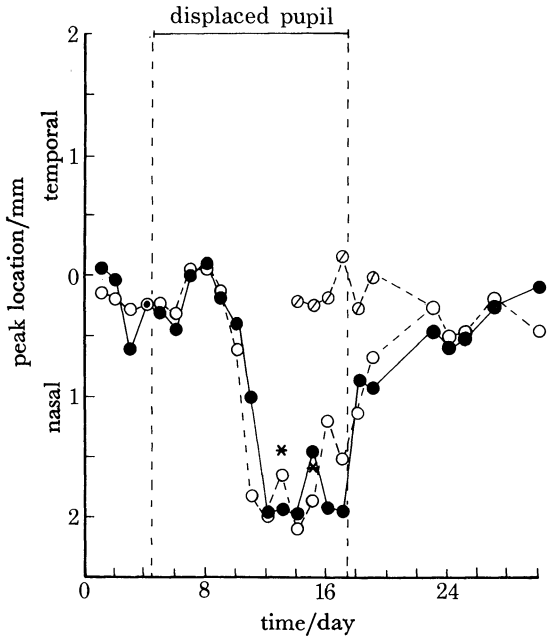

FIGURE 8. A day-by-day plot of peak location (rapid method) of the photopic S.–C. function in the horizontal meridian of observer J.M.E. Two test points were sampled in the right eye, fixation (●, 23A; ∗, 75) and 5° n.v.f. (○). Lens 1 (table 1) was worn from midday on the fourth day of testing (phase I). The centrum of the aperture of lens 1 was located at 2.0 mm temporal (top of figure). The period of wear of the displaced aperture contact lens is indicated by the two vertical dashed lines. Testing was conducted using both Kodak Wratten 23A filter and Kodak Wratten 75 filter. Towards the end of the test period a sub-peak (⊘) appeared at the 5° n.v.f. test locus.

Figure 9 needs to be explained. This a a plot of photopic S.–C. peaks in the horizontal meridian, by means of the rapid technique. A 1 mm displacement in the entrance pupil of the eye is equivalent to a 2.5° change in angle of incidence at the retina. Since shifts of the order of 1–2 mm are being considered here, if one plotted 1 mm = 2.5°, a true plot of angle would show only small changes and would be difficult for the reader to follow. Thus, angles have been multiplied by a factor of 8 for presentation, *i.e.* we plot 1 mm = 20°. A peak located at N.2.10 or 2.10 mm nasal would be plotted at an angle of $2.1 \times 20° = 42°$ from the vertical (bearing left). Temporal displacements of peak were plotted angled to the right. Both true findings and errors are multiplied by 8 by this technique. Clearly, the variance is low in the data presented in this and similar figures.

With cessation of wear of contact lens 1, there was prompt recovery (taking days) at fixation

and 5° n.v.f. (figures 8, 9), but there was *no* recovery at 5° t.v.f. Testing was extended to include 10° t.v.f. (near the temporal margin of the blind spot). Again, no recovery occurred. This implies the presence of a permanent tractional force in this eye, with its locus lying near the temporal margin of the blind spot. Results from the same locus in the second or control eye revealed a comparable nasal displacement of the S.–C. function (figure 10).

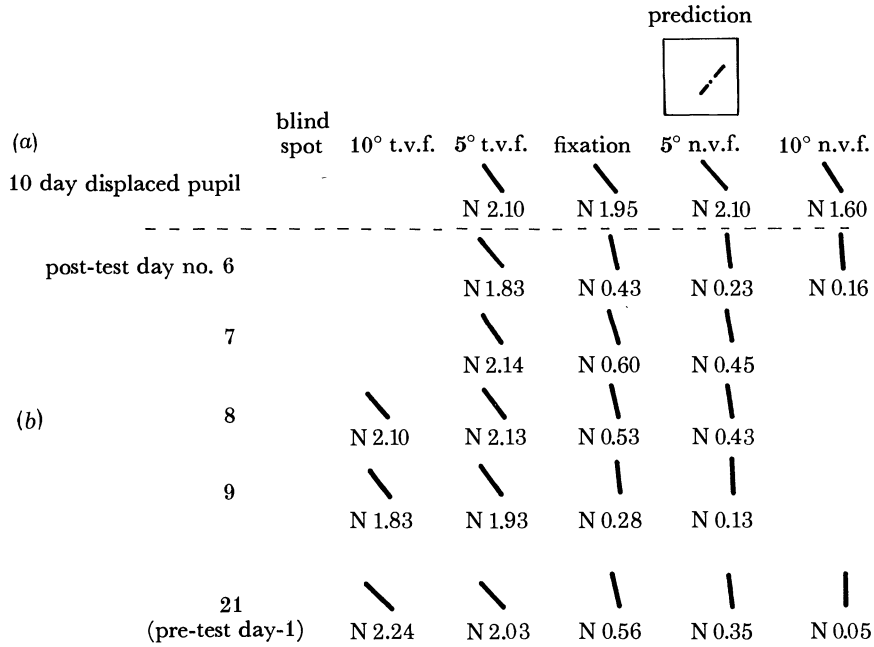

FIGURE 9. A presentation showing peak alignments of the measured S.–C. functions (rapid technique) determined at several test loci in the horizontal meridian. Mean data are indicated below the individual 'stick-like' figures. N2.10 indicates that the peak was displaced 2.1 mm nasally in the horizontal meridian of the entrance pupil of the right eye of J.M.E. A vertical orientation of the bar or stick corresponds to a ray striking the retina after having passed through the centre of the entrance (and exit) pupil of the eye. Angular deviations (2.5° = 1 mm) are magnified by a factor of 8. Nasal alignments are signified by a solid bar and temporal alignments with a dash-dot-dash bar. See text for further discussion of this display. The blind spot is just temporal in the visual field (nasal on the retina) to the 10° t.v.f. test locus. That which is shown here is the last day of testing during phase I (while the displaced pupil contact lens was worn). Subsequent data refer to days after removal of lens 1. The prediction, upper right hand corner, corresponds to a 2 mm displacement of the S.–C. peak in the temporal direction: this corresponds to the centre of the aperture of lens 1.

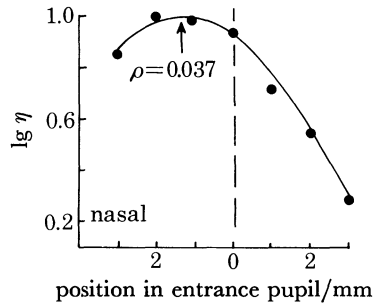

FIGURE 10. Data obtained at 10° t.v.f. in the left eye of observer J.M.E. (o.s.). Figures 8 and 9 and all that follow reference the right eye. There is a marked *nasal* displacement of the peak of the photopic S.–C. function of observer J.M.E. near the temporal retinal margin of the optic nerve head in the left eye as well. No contact lens had been worn in this eye. These data suggest that the biasing factor (influencing orientation near the temporal retinal boundary of the optic nerve head of the right eye of J.M.E.) is present in the left eye as well.

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Full S.–C. functions were determined across the horizontal meridian of the right retina (figure 11). Performing a least squares fit to determine directionality (ρ), shows directionality reduced in the zone where the peaks are apparently permanently displaced (5°, 10° t.v.f.). (The higher is ρ, the more peaked (narrower) is the function.) These S.–C. functions show increased directionality in the parafoveal area (5° n.v.f.) (Westheimer 1967; Enoch & Hope

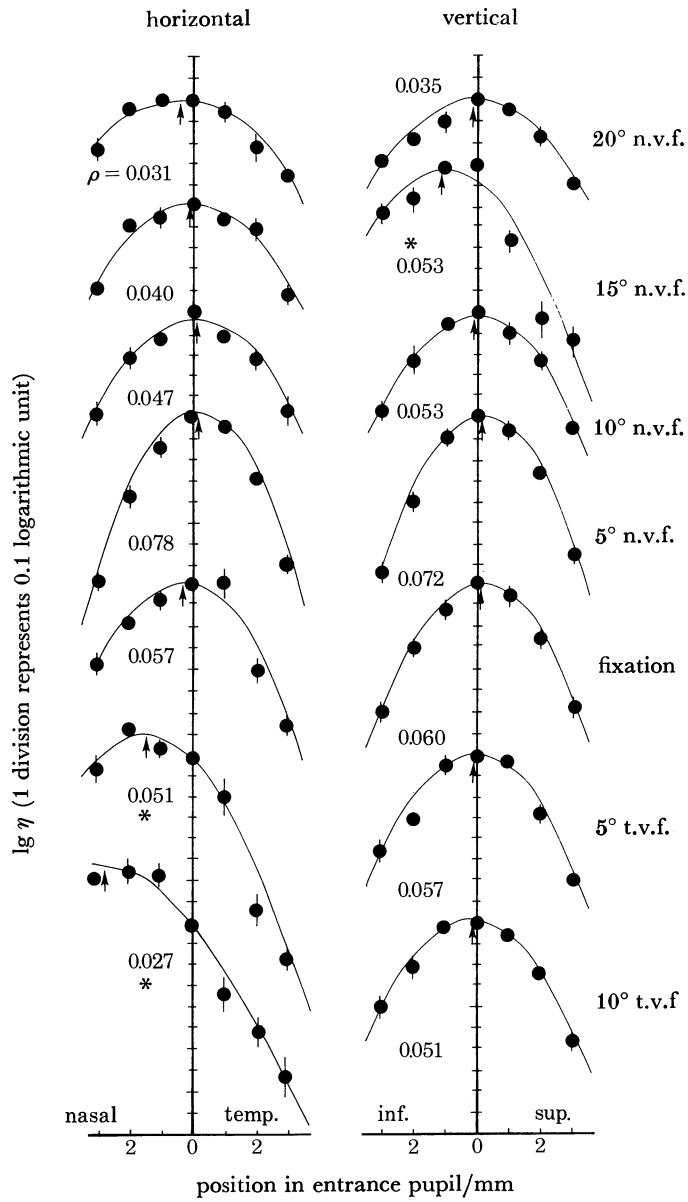

FIGURE 11. Photopic S.–C. functions measured at several loci in the visual field across the horizontal meridian of the right eye of observer J.M.E. Many comparable sets of data have been obtained and these may be regarded as a typical set. Computer-determined ρ and peak values are shown. The peaks are designated by the small arrow head and the ρ values are superimposed. The extent of ± 1 standard deviation is shown by a short vertical line on each point. If no vertical bar is seen, then one assumes that the variation was equal to or less than the size of the spot. S.–C. functions are presented for both the horizontal and vertical meridians in the entrance pupil of the eye. An asterisk is placed on functions where the peak was more than 1 mm from the centre of the entrance pupil of the eye. $I = 0.1$.

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1973), then flatten slowly (ρ decreases) after passing a peak in the parafovea (Enoch & Hope 1973; Bedell & Enoch 1979; Bedell 1980; see figure 4). Here, there was no rise in ρ recorded on the nasal retina (in the temporal visual field) (see, for example, Bedell 1980). There is another area showing a somewhat displaced S.–C. peak (vertical meridian, 15° n.v.f.). This retinal area will be considered in more detail at the end of the presentation of results obtained in phase II. Asterisks are placed on figure 11 where the S.–C. function peak was located more than 1.0 mm from the centre of the entrance pupil of the eye.

Physical examination of the eyes revealed the presence of a large cilio-retinal artery in the right eye (a much smaller one was present in the left eye) and evidence of some localized pigment epithelial degenerative changes near the temporal rim of the optic nerve head (this is an approximately 3 dioptres myopic eye); there was no evidence of any superficial tractional effect on the overlying fine retinal capillaries between the optic nerve head and the fovea and along the horizontal meridian in the right (or left) eye (Enoch & Birch 1980). Three small pigment epithelial window defects were noted in the foveal area of the right eye. These were probably the result of intense light studies conducted in the mid 1960s, since such changes were not seen in the left eye, which was not involved in those studies.† Intensive analysis of visual functions (Snellen acuity, interference acuity, contrast transfer functions, increment threshold, anomaloscope, S.–C. functions, dark adaptation, etc.) after the current experiments were completed revealed no measureable decrements in visual response in the foveal area of the right eye.

Phase II

On the basis of results obtained in phase I, it was hypothesized that there was a trans-retinal traction force expressed in the horizontal meridian of this retina, acting on the photoreceptor–pigment epithelial interface. This force was believed to have origin near the optic nerve head, to extend a good distance across the retina, and the have decreasing effect as a function of distance across the retina. It was further argued that a light-induced alignment mechanism countered this effect across most of the retina under normal viewing conditions. To test these hypotheses, the experiment was replicated by means of lens 1 (table 1), but testing was extended to cover a larger sample of retinal points, and the subject was exposed to more light (Florida summer patio, a minimum of 3 h per day). At the same time, lens 3 (table 1) was ordered. This had a larger aperture and would favour a positive phototropic response. In phase II extensive tests of changes in other visual functions were undertaken and added questions relative to recovery processes were explored.

Figure 12 is a display similar to figure 9. Phase II included four parts: (1) a pre-test during

† The after-image studies of Brindley were replicated (Brindley 1962). Brindley had observed a blue-green negative chromatic after-image, which had enlarged in time in the long wavelength end of the spectrum, and a negative red after-image, which changed similarly in the central portion of the spectrum. He predicted the presence of a similar enlarging negative yellow after-image in the short wavelength portion of the spectrum, but he was not able to observe this by means of the light source available to him. Brindley argued for the presence of some diffusing factor, unique to individual cone classes, that caused the increasing size of after-images.

Since J.M.E. had a 1000 W xenon arc (which has a meaningful short wavelength output), light from that source was passed through a 1 in (2.54 cm) water bath (infrared absorber) and focused on the entrance slit of an available Hilger–Watts spectrometer. A spectrum was formed and fixated in the plane of the exit slit (the exit slit was removed). Brindley's observations were confirmed and the yellow negative after-image at the short wavelength end of the spectrum was readily observed. Experiments were discontinued without report because persistent after-images (lasting for days) were experienced at the time. A recently published report by Tso & Fine (1979) should discourage comparable experimentation.

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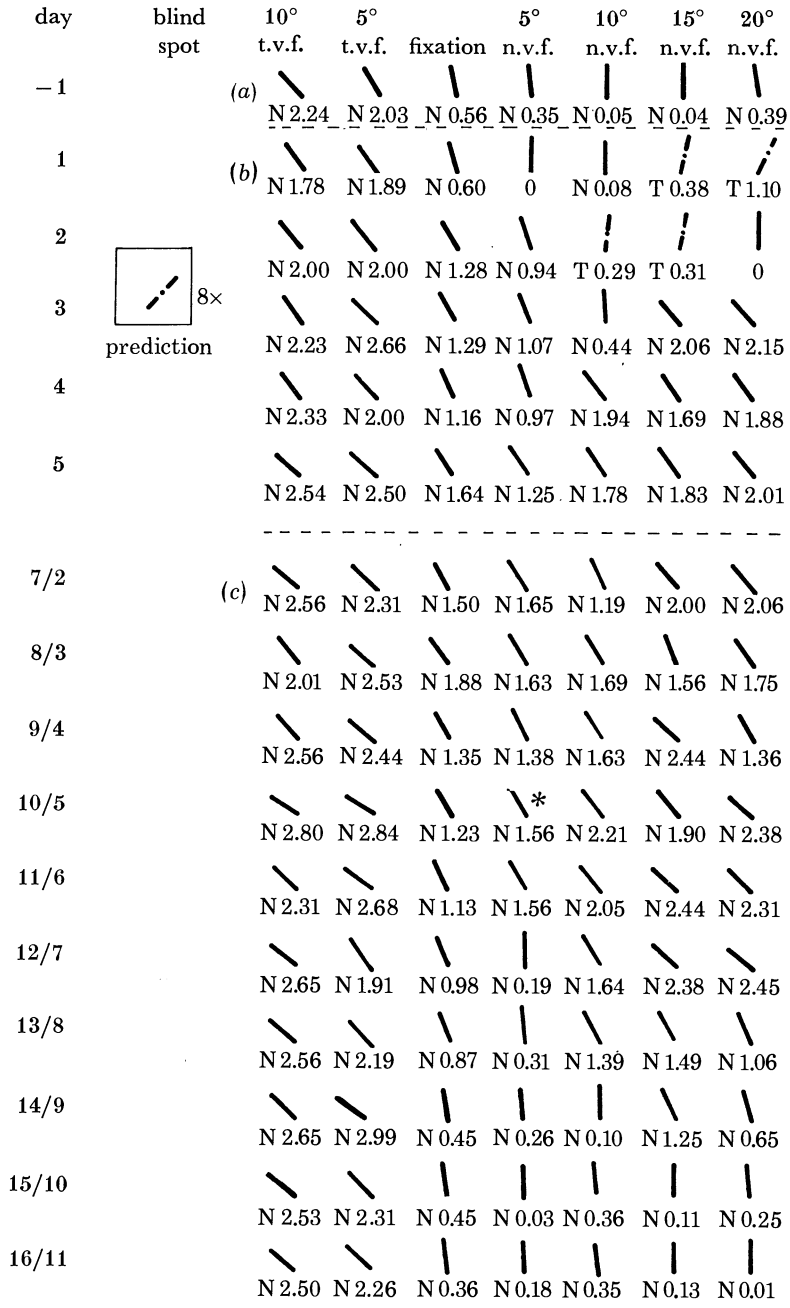

FIGURE 12. This figure is similar in format to figure 9. These are phase II measurements of the peaks of the photopic S.–C. function (rapid technique) determined at several test loci along the horizontal meridian of the right eye of J.M.E. Data are presented for one pre-test day (day −1, (*a*)). This set is representative of several comparable pre-test data sets. Lens (eccentric pupil) 1 was worn from days 1–6 (*b*). It was removed early on day 6 which was used for testing, and then on that same day lens 2 (centred 1 mm pupil) was substituted (*c*). Thus, day 7/2 corresponds to the seventh day after the initiation of the test of lens 1, but refers to the second day of wear of lens 2. All peaks aligned nasally are shown as solid bars: those that are aligned temporally are shown as dash-dot-dash bars. The asterisk noted at 5° n.v.f. on day 10/5 refers to a determination that must be compared with data obtained in figure 13.

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which no contact lens was employed; (2) a test period during which lens 1 (2 mm aperture displaced 2 mm temporal) was worn; (3) a recovery period during which lens 2 (1 mm aperture centred) was worn; and (4) a post-test period when no contact lens was used. Figure 12 covers only the first three test periods. Pre-test data (day −1 was typical) were comparable to post-test findings shown in figure 9; the clear nasal bias present at 5 and 10° t.v.f. was present at the outset and did not alter meaningfully through the entire experimental sequence. All other test points, fixation to 20° n.v.f., showed a much more modest initial nasal bias.

When the 2 mm displaced aperture was worn, there was an initial tendency for test points located away from the blind spot in the nasal visual field to align more temporally, that is towards the displaced aperture (test days 1, 2). Some points even showed a temporal peak displacement. However, on day 2, at fixation and at 5° n.v.f., and on day 3, across the horizontal meridian all the way to 20° n.v.f., the 'force' having origin near the blind spot (and spreading out horizontally from that locus) apparently *mobilized* and dominated response at all points tested. In short, the light-induced alignment response (to the wear of the displaced 2 mm aperture) was overwhelmed by this second force. S.–C. peak alignments remained essentially stable thereafter through day 5. Thus, the results in this portion of the test were comparable to those recorded at the end of phase I.

Extensive testing of related visual functions was undertaken before termination of this portion of the experiment during both phases I and II. These data were compared to pre- and post-test data. At this time the peak of the S.–C. function was displaced more than 1 mm nasally, and ρ was essentially unchanged (see below). It was found that interferometrically determined resolution was altered at low luminance levels (Enoch & Birch 1980), that is, there was little change at 1000 trolands† (He–Ne red wavelength 623 nm), but a marked effect was present below about 100 td. Objects appeared slightly 'greener' and anomaloscope matches required slightly more red (Birch *et al.* 1980). These changes exhibited recovery with recovery of the S.–C. function.

While the S.–C. functions were all exhibiting a nasal peak alignment, lens 2 (centred 1 mm aperture, table 1) was substituted for lens 1. We wanted to know whether it was the location of the aperture, or the amount of light, or both, that influenced recovery. As is obvious from figure 12, not much happened for several days (days 7/2–11/6) when the rapid technique was used. (Read 7/2 as follows: day 7 of the experiment from the time lens 1 was first worn, day 2 of wear of lens 2.) In fact, we were about to discontinue on day 10/5 and we were obtaining a final set of full S.–C. functions. Although the rapid technique revealed a 1.56 mm nasal S.–C. peak displacement at 5° n.v.f., the full S.–C. function measured at this test locus exhibited surprising recovery (figure 13). In both figures 12 and 13 this test point and data set are marked with an asterisk. To see if this was due to a difference in sampled retinal area (figure 2), the test target used in the standard technique was moved into the areas tested by the rapid method. The S.–C. peaks in those areas had not yet shifted back, although the small test area lying exactly between those areas on the horizontal meridian *had shifted* back. This point acted as a *trigger* for recovery of the S.–C. function peaks at all points, exluding 5° and 10° t.v.f. On day 12/7 at 5° n.v.f., realignment was evident with the rapid technique. From this area realignment spread out or was *mobilized* across an increasing retinal area until on day 14/9 or 15/10 a distribution comparable to the pre-test S.–C. peaks was noted.

† 1 troland (td) is the retinal illumination produced by a surface having a luminance of 1 cd/m² when the area of the pupil of the eye is 1 mm². The luminance is measured in the plane of the entrance pupil of the eye.

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Thus, slowly, the light-induced effect of this small centred aperture became dominant. However, that is not the complete story. Although the peaks showed realignment towards their original orientations, the directionality of the function ρ was undergoing change while the 1 mm aperture was worn (figure 14). When the displaced or eccentric 2 mm lens was worn in both phases I and II, ρ did not alter meaningfully, but, when the small aperture centred contact lens was worn, ρ slowly decreased. Thus, although the peak shifted with the 2 mm aperture lens 1, the distributive quality was not greatly altered. A similar finding was reported in the unique centre-of-the-retinal-sphere pointing case reported by Bedell & Enoch (1980).

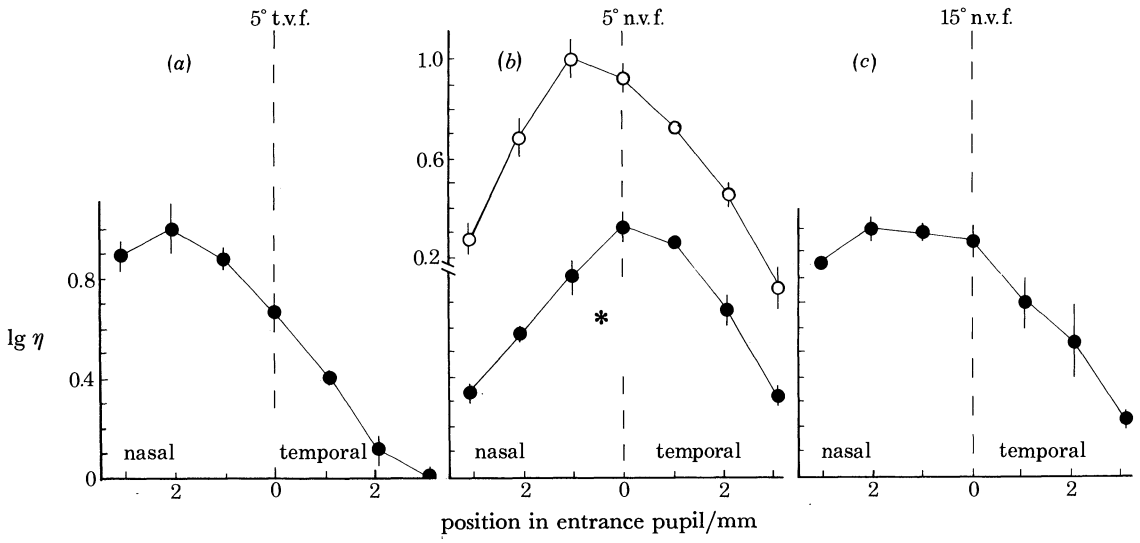

FIGURE 13. These S.–C. functions, determined by the standard technique, were measured at various times during phase II experiments on observer J.M.E., right eye: (*a*) day 12/7 or day 7 of wear of lens 2, the centred aperture contact lens; (*b*) top data set (○), day 5, lens 1, eccentric pupillary aperture; (*b*) bottom data set (●, ✱), day 10/5 or day 5 of wear of lens 2 (centred aperture); (*c*) day 9/4 or day 4 of wear of the centred aperture lens. For reference to days and lenses see figure 12. Note that in (*b*), bottom data set, this function was centred at the time of that measurement, but that the determination made by means of the rapid technique (figure 12) was not (see text). These data represent the fortuitous location of a 'trigger-point' that served to mobilize further alignment changes across the horizontal meridian (see figure 12, days 10/5–16/11).

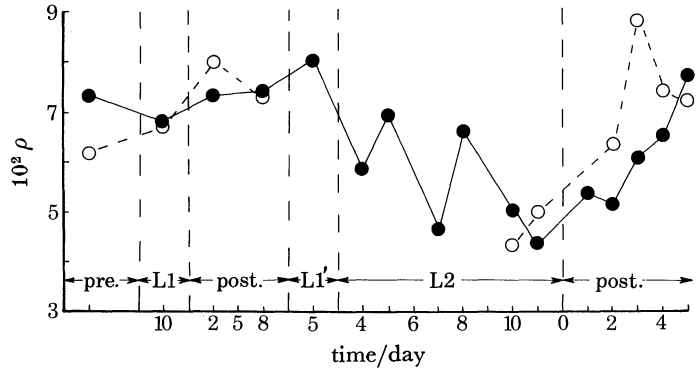

FIGURE 14. Measures of ρ for observer J.M.E., right eye, determined at 5° n.v.f. in both the horizontal (●) and vertical (○) meridians. These ρ values were computed from determinations of the photopic S.–C. function. During phase I (first period of wear of eccentric aperture contact lens (c.l., L1) there was no meaningful alteration in ρ. During phase II, when the same eccentric aperture contact lens (L1′) was worn, there also was no change in ρ. However, when the centred small aperture contact lens was worn (c.l., L2), there was a general flattening or reduction of directionality (ρ) recorded in the S.–C. function. The S.–C. function showed return to normal form within a few days after removal of lens 2 (c.l., L2).

When the 1 mm aperture lens 2 was worn, ρ flattened to a lesser degree than that recorded when a black patch was worn (figures 4, 5), but it changed a recordable amount (figures 14, 15).

Although the peaks had recovered to their pre-test loci, a fourth section was added to phase II. In that section we sought to follow recovery of ρ. As in the experiment in which the black patches were worn, recovery occurred within 3–4 days. However, there was an added

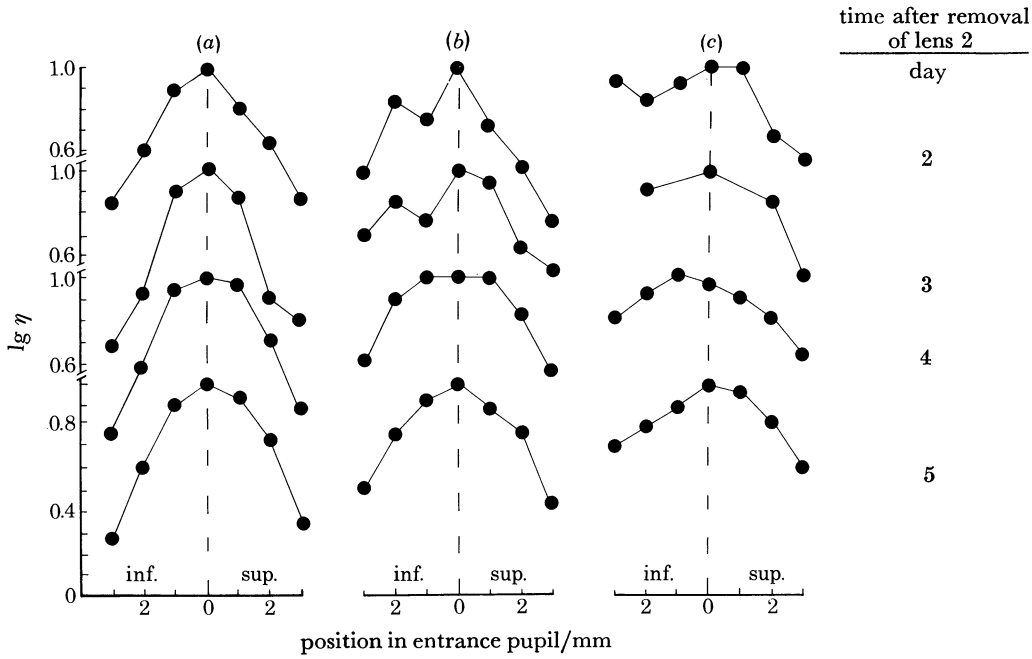

FIGURE 15. Photopic S.–C. function data obtained at three loci (*a*) 5°, (*b*) 10°, (*c*) 20°, in the nasal visual field (n.v.f.), observer J.M.E., right eye, at the end of phase II testing. A 5° n.v.f. on the second day after removal of lens 2, the S.–C. function was still slightly flat. By the fifth day after removal of lens 2, the S.–C. function had returned to its original form. The S.–C. functions determined at 10°, 15° and 20° in the *vertical pupillary meridian* are of interest. Here data obtained at 10°, and 20° are shown. In the immediate post-wear period, sub-peaks 'welled up' in these S.–C. functions at 10°, 15° and 20° in the inferior portion of the field. These changes were unquestionably real. They were tested and retested. The mechanism giving rise to this effect is not known; however, data obtained in the *vertical* meridian at 15° n.v.f. in figure 11 suggest that something is different at this test locus in this eye. Functions recovered by the fifth post-lens wear day.

revealing set of findings. At 15° n.v.f. (figure 11, pre-test data) the S.–C. peak shows a modest inferior displacement. In the same retinal area, and restricted to data recorded in the vertical meridian, in addition to a reduced ρ, there were strange 'release' responses recorded with removal of lens 2. These were replicated after removal of lens 3 in phase III as well. Between 10° and 20° n.v.f., multiple peaks (not previously seen) 'welled up' (figure 15, post-day 2) in the final post-wear period, and took three days or so to resolve. Compare the slightly flatter S.–C. function at 5° n.v.f. with the multiple-peaked and variable functions measured at 10° and 20° n.v.f. during this post-test period. By post-day 5 all had settled down. At 15° n.v.f. the modest vertical peak displacement remained. Thus, a third (possible mechanical) force acting to influence alignment was revealed.

At this point it seemed apparent that at least three forces influenced alignment in the areas tested. One mechanical factor had origin near the blind spot and acted horizontally across the retina, a second possible mechanical force acted vertically near the 15° n.v.f., and a third light-induced response acted across the retina.

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Phase III

In this phase of the experiment, a more positive response to light was sought. Here lens 3, a 3 mm aperture with its peak displaced 2.5 mm from the centre, was used. Again, attempts were made to maximize light exposure. Figure 16 shows the day-by-day data of the S.–C. peaks at the same points tested in phase II. Because 5° n.v.f. had served as 'trigger point' in

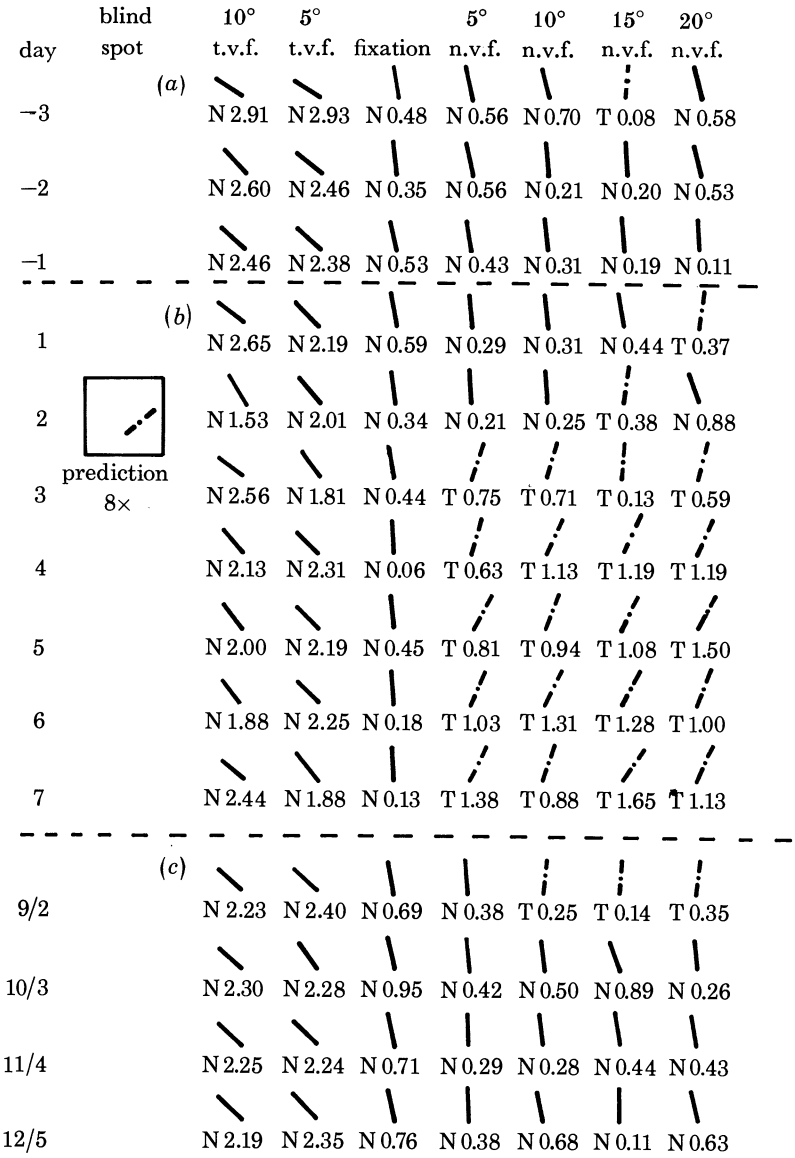

FIGURE 16. In phase III of this experiment, successful shifts of the peak of the photopic S.–C. function were achieved, observer J.M.E. right eye. These data are presented in a form similar to figures 9 and 12. These are plots of the horizontal peaks of the S.–C. function determined by the rapid method. Peaks displaced nasally are shown by solid bars; those displaced temporally are shown as dash-dot-dash bars. T 0.75 corresponds to a S.–C. peak displaced 0.75 mm temporally in the entrance pupil of the eye. (*a*) Negative days refer to days before lens 3 (eccentric pupil) was worn. (*b*) The lens was worn through the seventh day, with the eighth day dedicated to testing. (*c*) Day 9/2 means the ninth day after the initiation of the wear of lens 3, and the second day after lens removal. Clearly, there were shifts in the peaks of the photopic S.–C. photopic curves at test loci between 5° and 20° n.v.f. As in all cases, nothing meaningfully altered results at 5° and 10° t.v.f. Here the S.–C. peak determinations at fixation (presumed fovea) were also not meaningfully affected.

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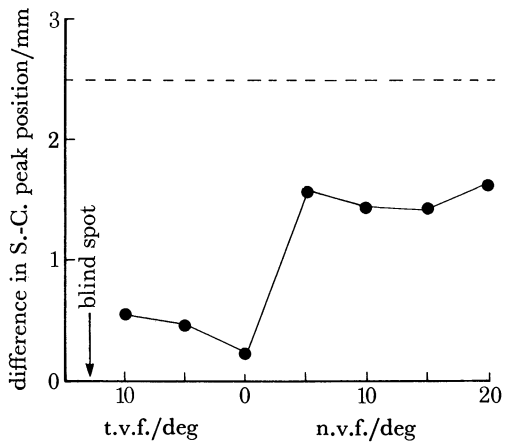

FIGURE 17. Mean shifts of the peak of the photopic S.–C. function in the horizontal pupillary meridian during phase III. A mean was determined for peak location at each test locus for the three days before initiation of testing (figure 16), and a mean was computed for the last three days of wear of lens 3 by observer J.M.E. The difference is plotted; the prediction (– – – –) corresponds to a 2.5 mm displacement of the centre of the pupillary aperture. All points showed a tendency to shift towards the predicted direction. There was a sharp transition between fixation and 5° n.v.f. All measured distances in the figures represent temporal displacements.

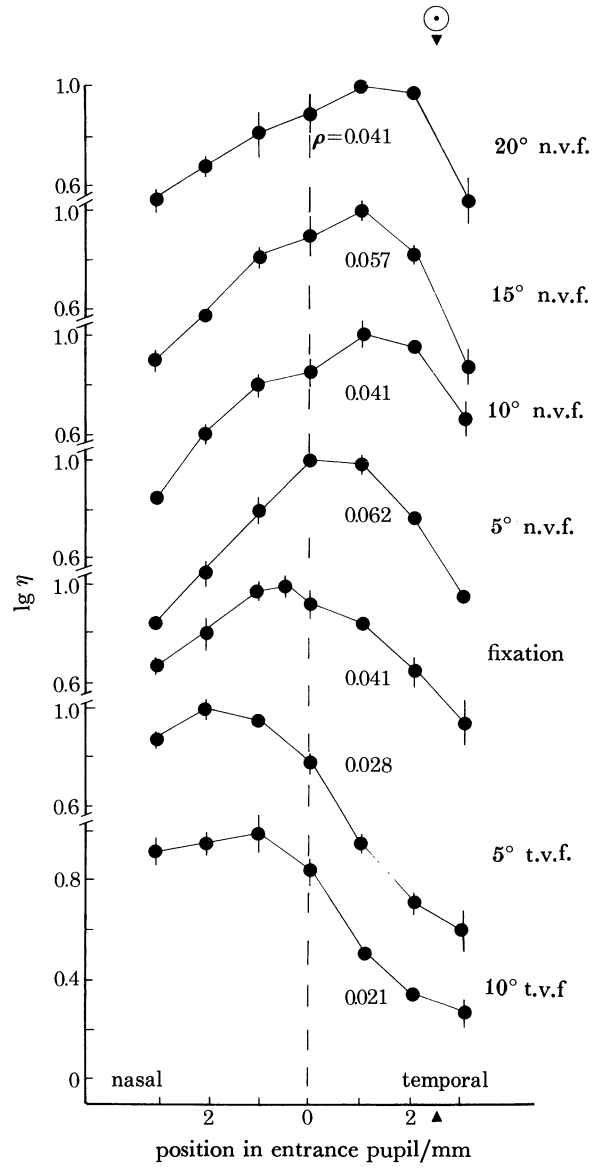

FIGURE 18. Full function S.–C. curves determined in the horizontal pupillary meridian in the right eye of observer J.M.E. Points tested lay along the horizontal meridian of the visual field. Vertical pupillary meridian data were obtained, but showed little change during wear of lens 3 (3 mm aperture contact lens). These data were obtained on day 7 after lens 3 was worn. They should be compared with figure 11 (horizontal pupillary meridian). The S.–C. functions were clearly altered between 5° and 20° n.v.f. Determinations of ρ, shown in the figure, were based on measures taken within 3 mm of the computed peak. The location of the centre of the aperture of lens 3 is indicated by the small circular symbol with centred dot and arrowhead at the top of the figure and the small arrowhead on the abscissa.

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phase II, full S.–C. functions were obtained at that locus daily. To some extent, this may have influenced response at that locus.

Clearly, this time, the displaced aperture dominated response. Change was triggered more peripherally along the horizontal meridian and the response was mobilized by day 3 of the test. Here the fixation point served as sort of fulcrum between the mechanical force having origin near the optic nerve head and the light induced response. The S.–C. peaks moved into the aperture but did not centre in the aperture. In figure 17 mean difference in peak location 3 days pre-test and test days 5–7 are plotted. All peaks shift somewhat temporally, with major change occurring between 0° and 5° n.v.f. Recovery was essentially complete by day 11/4 in the post-test period. At no time was alignment at 5° and 10° t.v.f. meaningfully altered. Figures 11 and 18, each obtained on a single day of testing, allow comparison of full S.–C. functions. Clearly, in figure 18, the functions plotted in the horizontal meridian at test points lying between 5° and 20° n.v.f. show substantial temporal shifts. Comparative values of ρ are listed in table 2.

TABLE 2. VALUES OF ρ (HORIZONTAL), PHASE III

test position deg	pre-test†	day 7‡	Δ(pre-test − day 7)
20, n.v.f.	0.031	0.041	−0.010
15, n.v.f.	0.040	0.057	−0.017
10, n.v.f.	0.047	0.041	+0.006
5, n.v.f.	0.078	0.062	+0.016
0, fixation	0.057	0.041	+0.016
5, t.v.f.	0.051	0.028	+0.023
10, t.v.f.	0.027	0.021	+0.006

† Values obtained from figure 11.
‡ Values obtained from figure 18.

From table 2, it is not clear that a meaningful change in ρ occurred. Where light-induced response was greatest, directionality tended to increase ($-\Delta$); where the two responses (mechanical optical nerve head-based response and light-induced response) were in greatest opposition, the S.–C. function tended to exhibit modest flattening ($+\Delta$). This would be consistent with a push–pull type argument.

DISCUSSION

Although one might wish for an eye to test that is less complex than the right eye of J.M.E., those complexities provided much information about the underlying mechanisms. Clearly, there is a response driven by radiant energy influencing the directional sensitivity of the eye. Let us assume that the action spectrum is in the visible spectrum; although a difficult task, this must be tested. Just as clearly, there are added mechanical forces acting, and the measured results reflect a sum of influences. That sum need not be a simple linear relation. The notion of a non-changing, stable S.–C. function seems no longer viable. Rather, this is an active response exhibiting great stability in time. The weight of evidence presented here firmly supports the notion that the light-induced component is positiviely phototropic. The dynamics of peak alignment and distributive factors clearly need not be identical (phase II, recentration of the peak while ρ flattens) (Bedell & Enoch 1980). While the peak finally translated in the anticipated direction (phase III), alignment with the displaced aperture was not complete. However, total translation approached the expected result (figure 17). The discrepancy needs to be better understood. Small centration errors could be contributory.

We asked whether some part of the discrepancy could be due to the displacement of the entrance pupil of the eye forward to the corneal surface from a point just in front of the true pupil, and to the effective projection of these two entrance pupils to their respective exit pupils. The plane of the exit pupil is shifted of necessity when wearing the painted-iris, limiting-aperture, contact lens. The retina 'sees' the exit pupil. By performing a chief ray trace through an emmetropized Gullstrand schematic eye (Southall 1933), length-adjusted, one can solve the necessary relationships. One may then compare the angular projection at the retina from the exit pupil of the eye with the aperture displaced to the corneal plane, with a projection from the exit pupil of the natural eye for a point displaced 1.0 mm in the two entrance pupils. Thin-lens assumptions are used for simplicity. No difference was found in angle of incidence at the retina (table 3).

TABLE 3. APERTURE RELATIONSHIPS IN GULLSTRAND SCHEMATIC EYE MADE EMMETROPIC

	aperture plane	
	anterior corneal surface†	anterior lens surface
distance, corneal apex to x/mm		
entrance pupil	0	+3.047
aperture plane	0	+3.60
exit pupil	−0.346	+3.67
secondary focal point (F′)‡	+24.387	+24.387
distance, exit pupil to F′/mm	+24.733	+20.717
magnification ratio, exit pupil: entrance pupil	+1.086	+0.9094
angle of incidence at retina for a point displaced 1 mm in entrance pupil	$\tan\theta = \frac{1.086}{24.733}$, $\theta = 2°32'$	$\tan\theta = \frac{0.9094}{20.717}$, $\theta = 2°31'$

† Assumed plane of contact lens aperture.
‡ Here taken as the retinal plane.

In addition, in phases I and II, it is clear that the mechanical force acting near the optic nerve head expressed itself across much of the horizontal plane of the retina. This continuing force could contribute to the measured discrepancy as well.

Clearly, each eye (figures 5, 6) and locality on the retina (see, for example, figures 9, 12, 16) act somewhat independently. However, one area seems able to mobilize response over a broad retinal region (see, for example, figures 12, 16). The triggering and mobilization mechanisms also must be clarified. The location of the trigger need not be identical under different stimulus conditions, that is, light passing through the aperture of lens 2 (table 1) apparently triggered peak realignment at 5° n.v.f. during phase II (figure 12). However, light-induced alteration in alignment determined in phase III was triggered at a more peripheral retinal locus (figure 16).

The most likely anatomical unit affecting these phototropic changes is the photoreceptor inner–outer segment or the outer segment, coupled with the microvilli of the underlying pigment epithelium (p.e.). The role of other components, such as the alignment of the membranous photoreceptor disks in the outer segment and the distribution of p.e. pigment, needs to be considered in the analysis.

One might ask how an error in alignment as sampled by a positive phototropic system might

be signalled and what sort of detector can be anticipated. The mechanism apparently has to meet at least the following conditions based on these results.

1. Under normal viewing conditions, alignment is maintained with remarkable stability and accuracy relative to the centre of the two-dimensional exit pupil of the eye. There may be a modest constant error.

2. The alignment mechanism has a relatively long half-time for response (one or more days).

3. The alignment mechanism exhibits apparent dispersal in the dark, and exhibits recovery in the light. This dispersal is comparable with changes that occur in certain retinal pathologies (such as retinal detachment) known to alter alignment.

4. Displacement of the exit pupil centre results in a translation of the alignment centrum towards the displaced exit pupil centre. The mechanism reverts to its original alignment when the original exit pupil is restored.

5. Partial dispersal is possible, and dispersal can occur while central tendency for alignment is altered.

6. Local changes can and do occur. One area may trigger response in a larger zone, effectively mobilizing a broader response.

7. Based on our studies, it is apparent that the pigment epithelium plays a participant role (Fitzgerald *et al.* 1980*b*).

In addition, there are constraints due to packing of the photoreceptors (Laties & Enoch 1971), and interdigitations between the photoreceptors and the microvilli of the pigment epithelium. Two fundamentally different classes of working hypotheses can be offered to account for these results.

(*a*) A comparator mechanism may be postulated which samples the time-averaged response of receptors (or groups of receptors) to light entering superiorly and inferiorly in the pupil as well as nasally and temporally (or the two-dimensional equivalent). Such a comparator might seek to maintain a balance between these responses. At this time there is no evidence that such a planned mechanism exists in the vertebrate retina. It would require detection of, and extensive processing of directional information. Without signal, i.e., in the dark or in the presence of reduced light levels, the midpoint balance in any given local area might execute random (or at least less controlled) alterations. These alterations could result in dispersal. Stated alternatively, because of finding 3 above, the balance may be functional only in the light, and removal of the light may allow other more random mechanisms to dominate.

(*b*) A second mechanism may be postulated which is not so purposeful, but which can achieve the same ends. Assume that the photoreceptor unit can execute random angular movements in the dark within some confine or bound defined by inter-receptor spacing and p.e. interdigitations. The presence of actin molecules and fibrillar structures provides an effector mechanism. Differential growth or ionic shifts could also be contributory. At first glance, it does not seem significant whether these random motions have origin at the outer limiting membrane or at the cilium connecting the inner and outer segments. These motions would allow roughly equivalent modest dispersal of alignments in all directions in the dark.

Further, assume that with an increase in the time-averaged response to light these random motions are progressively inhibited, i.e. the more the response to light, the greater the inhibition of motion. Thus, in a given population of receptors, there will be a tendency to align with and more effectively 'lock onto' a more intense source of light within the defined restraints. The cells

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that are most reactive to light presumably execute less motion and bias orientation and directionality. This argument predicts rather narrow acceptance angles (apertures) in individual cells or small groups (Tobey *et al.* 1975). If enough of the photoreceptor cells act in a comparable manner, the bound or confine will slowly shift towards a displaced or altered aperture, i.e. a source of more light. Thus, the centrum about which the random motions take place, through packing etc. will shift and alter mean alignment. This mechanism is also compatible with the changes recorded by means of the small aperture in phase II above. It could also provide great stability in response in time.

If one carries this argument to its limit, if enough light reaches the aligned elements, all random motion would be inhibited or become negligible; however, given normal light level variations day and night, pupil size adjustments etc., this probably never occurs. Study of responses in the presence of high light levels will determine whether an added mechanism needs to be postulated that reacts to differences in stimulus levels rather than summed levels. However, that would be a more complex mechanism, i.e., it implies added storage capability and some form of comparison.

Neither hypothesis (*a*) nor (*b*) explains the unique case reported by Bedell & Enoch (1980).

Our colleague, Mary Bernstein, points out that one need not hypothesize only a single stage mechanism at the cellular level, particularly in a response that seems to have an extended time domain.

A positive phototropic mechanism, coupled with the limiting aperture of the receptor waveguide, would tend to optimize response to the pertinent visual signal transmitted through the pupillary aperture and limit stray light noise bouncing about in the integrating sphere-like scleral globe (Enoch 1972). Such development is consistent with evolutionary mechanisms for survival (optimal detection of meaningful visual stimuli).

One is often amazed by the extent of evolutionary development that takes place for modest gains. For example, tapetal back reflexion of light through the retina provides a second pass of energy through photoreceptors in many species (not normal humans). This back-reflecting tapetal layer is often shielded by dark pigment at higher light levels in many animals. The maximum possible gain by back reflexion is $10^{0.3}$ (i.e. a factor of 2) in a system whose total dynamic range may be of the order of $10^{10.0}$ (see, for example, Weale 1961). This argument presupposes that the tapetum evolved for the described purpose. Following this line of reasoning, the gains offered by precise alignment of photoreceptors have obvious survival value.

One may ask also why active mechanisms for alignment are necessary. Unlike the plasticity found in many other neural mechanisms (e.g. during the development of 'binocular' neurons) which is active primarily during a critical period of development, plasticity in photoreceptor alignment continues into adulthood. Presumably, the ever-changing forces acting on the photoreceptors (due to accommodation, changes in intra-ocular pressure, eye movements, gravity etc.) preclude a passive, fixed structure. Furthermore, the structure itself is continuously undergoing renewal (Young 1976) and thus may require an active mechanism to retain accurate alignment.

It is well known that the retinal receptor is a modified cilium, as are several other primary sense cells. In many vertebrate species, but not in mammals, these same cells are known to be highly motile, responding to light adaptation and other influences (see, for example, Ali 1971). These photomotile reactions represent selective alterations in the receptor inner segment along

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the long axis of the receptor. Here we consider an 'angling' response, of some one or more components. Initial animal experiments designed to localize the site and nature of these alterations have been initiated (Enoch 1980).

In addition to localizing the site of change, effector mechanisms (Spira & Millman 1979; Laties & Burnside 1979) and the nature of the underlying control mechanisms need to be defined. Enoch & Birch (1980) consider certain aspects of the rate of and the nature of the recovery process. See also Enoch *et al.* (1979*b*; 1980) for further discussion of rate factors with monocular occlusion, and Enoch (1975) for consideration of recovery processes following marked accommodation.

These results plus earlier work suggest the presence of at least two systems that determine alignment of receptors with a point approximating the exit pupil centre. A positive phototropic one has been considered here; a prenatal one was defined previously by Laties (Laties & Enoch 1971; Enoch & Laties 1971; Enoch 1972). Near-term pregnant rhesus macaque monkeys were delivered by Cesarean section. Anterior receptor pointing was present already in these foetuses. Presumably little light penetrates the womb of the rhesus macaque. Similar experiments have been conducted on chick eggs, with comparable results. However, in the natural environment, light clearly penetrates the egg shell. Certainly, many research opportunities are available to help clarify these aspects of the problem.

The findings presented here, plus growing evidence of receptor disk renewal, phagocytosis of outer segment components (see, for example, Young 1976) etc., suggest that the environment of the retinal receptor is highly dynamic and active. It will be some time before the full implications of these collective findings are understood both in normal eyes and in those exhibiting anomalies.

Associated with the changes in directionality described herein, there are a number of related modifications in visual function. Initial findings are summarized in table 4.

Enhancement in sensitivity with flattening of the S.–C. function is not a simple phenomenon. To date, this has been quantified only for scotopic vision. In essence, sensitivity at the centre of the pupil changed little while there was an increase in sensitivity towards the periphery of the pupil. No single or simple mechanism explains the surprisingly large decrease in absolute threshold (Birch *et al.* 1980).

Changes in perceived hue and saturation, and alterations in anomaloscope matches are reported in conjunction with both experimental paradigms (patching and displaced pupil) considered here (Enoch *et al.* 1979*a*; Birch *et al.* 1980; Enoch & Birch 1980). In the anomaloscope tests, both small beams entered the pupil at the same point, generally about centre. Slightly more red was required for a yellow match with both the flattened and the peak-displaced S.–C. functions. Although the argument is limited, comparable change suggests a somewhat comparable physical alteration. If the flattening of the S.–C. function simply represented the splaying apart of individual cells or groups of receptors, and the peak shift represented a bulk shift in alignment away from the pupil centre, in both cases energy directed through the centre of the pupil would strike many cells in the 2° field more obliquely. Thus a certain commonality in change of response might be expected.

This argument does not quite hold for the resolution case because smaller fields were used, and because the result depended on the particular alignment of some modest number of retinal units at the centre of the fovea. Some observers, whose S.–C. functions flattened, showed changes in resolution while others did not. A flat S.–C. function implies that some units remain in

alignment while other elements splay. On the other hand, with the peak of the S.–C. function displaced at the end of phase I and II, there was a clear loss in visual resolution capability at lower levels of retinal illuminance (1–10 td) and little effect at higher stimulus levels (1000 td). Clearly, these changes in visual function paralleling alterations in directional sensitivity will need further elaboration in the future.

TABLE 4. ASSOCIATED VISUAL CHANGES

visual function tested	black patching 7–10 day light exclusion S.–C. flattening	receptor alignment displaced relative to pupil centre
threshold response	absolute scotopic threshold decreased (sensitivity increased)†	linearity of photopic threshold against intensity curve still holds§
perceived colour	objects appear slightly 'green'†‡	objects appear slightly 'green'†§
anomaloscope	slight added red needed in anomaloscope yellow match†	slight added red needed in anomaloscope yellow match†§
contrast sensitivity	general contrast sensitivity reduction†; in some individuals there is a modest reduction in high frequency performance (visual resolution)†	reduction in resolution as f (luminance)§; effect is greatest at lower luminances§

† Birch *et al* (1980).

‡ A comparable change is seen in patients with flat S.–C. functions due to retinal detachment (Fitzgerald *et al.* 1980) and flat S.–C. functions following uniocular patching. Smith *et al.* (1978) also report comparable colour changes and altered S.–C. functions in senile macular choroidopathy. S.–C. functions in senile macular choroidopathy were also considered by Fankhauser & Enoch (1962), Enoch (1978), and Fitzgerald *et al.* (1979).

§ Enoch & Birch (1980).

Some comment needs to be made relative to the utilization of black patching in various therapies and the possibility of therapeutic intervention either with contact lenses or alterations in the eye pupil. Black patching in amblyopia therapy is a common procedure. We have no reason to suspect that there is any difference in response between the adult and child's eye, and the effects here seem to be quite reversible over a period of days. However, even a transient decrease in directional sensitivity during the critical period in childhood could be detrimental to the developing visual system. These findings add one more suggestion for caution during the critical period.

All our data here are based on normal observers. The use of black patching following surgery or in the presence of ocular pathology may influence the physiological mechanisms mediating the responses considered here. In patients without photophobia, why not use a diffusing patch or bandage in place of a black patch? That is, it seems preferable to approach the normal physiological state.

If one can alter the S.–C. function from its more usual location with a displaced pupil, the possibility of corrective action in the presence of an anomalous directional sensitivity pattern also needs to be considered. However, there was little change in receptor alignment at 5° and 10° in the temporal visual field (t.v.f.) of the right eye of J.M.E. in any phase of this experiment.

Above all, that which is achieved here is the demonstration of an active alteration in retinal directional sensitivity. It is suggested that the retinal receptors are positively phototropic. Clearly, this is the opening phase of a large set of analyses that must be conducted in the future.

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