Ultraviolet Sensitivity in Aphakia and Pseudophakia

Terrence T. Williams

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Abstract

Ultraviolet Sensitivity in Aphakia and Pseudophakia

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Scotopic spectral sensitivity was measured in the range from 300 nm to 700 nm for five unilateral aphakic or pseudophakic observers. Aphakia and pseudophakia are conditions produced by cataract surgery; aphakia describes the absence of the crystalline lens while pseudophakia describes its replacement by an acrylic intraocular lens. The method employed was a single staircase procedure with decreasing stepsize using a fully automated quartz optical system. Sensitivity of the aphakic and pseudophakic eyes matched the phakic eyes at wavelengths longer than 500 nm, but not at shorter wavelengths. Sensitivity increased for the aphakic and pseudophakic eyes at shorter wavelengths, with a measure of sensitivity in the ultraviolet more than 300 times the minimum in the "visible" spectrum. No difference was found between aphakic and pseudophakic sensitivity functions.

Acknowledgements

I would like to thank Dr. Charles W. White for his support and encouragement throughout this project. I would also like to thank Olga Overbury and Dr. Bruce Jackson at the Low Vision Clinic of the Royal Victoria Hospital, McGill University, for their assistance in finding observers for this experiment. Thanks also to Stanley Rog for the excellent figures.

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To evoke a visual response, a minimum number of quanta must reach receptors located behind the refractive media of the eye. This fact has complicated the inherently difficult problem of relating the photochemical reactions of visual receptors to the visual sensitivity of organisms. Although Kuhne attempted to assess this functional relationship between scotopic luminosity functions and the spectral sensitivity of the rod photopigment rhodopsin more than one hundred years ago (Dartnall, 1972), rod-mediated vision in most descriptions then and now, is limited to the visible spectrum, between 380 nm and 700 nm. However, since rhodopsin is photosensitive to ultraviolet light, as well as to visible light, most of the previous research has ignored this part of the spectral range for comparing photopigment absorption and visual sensitivity.

The Commission Internationale de l'Eclairage (C.I.E.) scotopic standard observer describes an average human scotopic sensitivity function that is limited to the range from 380 nm to 750 nm; this range is commonly referred to as the visible spectrum and does not include measures in the ultraviolet. The standard scotopic function matches the photosensitivity of rhodopsin pigment as described by the Dartnall visual pigment nomogram (Dartnall, 1952, 1957) at longer wavelengths, but diverges at wavelengths shorter than 500 nm. This divergence is due to the progressively greater absorption by the ocular media of short wavelength radiation (Boettner and Wolter, 1962). The rod photopigment, in addition to a peak sensitivity in the visible range, has a secondary peak in the near ultraviolet between 300 nm and 380 nm called the cis peak. By including corrections for the absorption characteristics of the ocular media, the cis peak in

the ultraviolet has been matched at some wavelengths to the scotopic sensitivity of aphakic observers (Goodeve, Lythgoe and Schneider, 1942; Tan, 1971).

A standard of human scotopic sensitivity should describe the limits of normal visual experience that are produced by the interaction of photoreceptor sensitivity and the absorption characteristics of the intervening ocular media. A scotopic luminosity function of a normal human eye does not directly reflect the spectral sensitivity of the photoreceptors that mediate scotopic vision because the pre-retinal media are not spectrally neutral. Therefore, an accurate estimate of the photoreceptor's spectral response characteristics that includes the full range of sensitivity should minimize pre-receptor absorption effects. In order to evaluate the relationship between rhodopsin photosensitivity and scotopic sensitivity in the visible and near ultraviolet parts of the spectrum, a scotopic luminosity function must include measurements at wavelengths as short as possible. Since the crystalline lens is the primary filter of near ultraviolet radiation, aphakic observers without crystalline lenses or pseudophakic observers with prosthetic acrylic lenses are needed to assess rhodopsin sensitivity to ultraviolet and visible light. These observers are best suited to this task because the lack of filtration in the absence of the crystalline lens extends transmission to the retina, down to at least 300 nm.

It is the intent of this study to describe as accurately as possible a scotopic luminosity function that extends down to 300 nm for aphakic and pseudophakic observers. Further, this study will

compare the scotopic sensitivity of the aphakic or pseudophakic eye and the normal eye in the same observer, and the scotopic sensitivity of aphakic and pseudophakic eyes in different observers.

Rhodopsin and the Absorption of Ocular Media

The photochemical basis of scotopic vision in humans was first described by Kuhne in 1877 (Dartnall, 1972). He was able to see a pigment he called visual purple in the retina, but not in areas around the fovea and macula. In 1894, the pigment was extracted and isolated from human retinas by Koenig (Dartnall, 1972), who was the first to measure the rhodopsin photosensitivity of the human eye. The spectral sensitivity of the pigment was shown to be very similar to estimates of scotopic sensitivity at that time.

The next reported measure of human rod pigment was by Crescitelli and Dartnall (1953), who extracted the pigment from a human dark adapted eye. The spectral absorption of the extracted rhodopsin was described as having a peak at 497 nm, and as resembling the human scotopic luminosity function when corrected for absorption by the ocular media.

The transmission characteristics of the ocular media are such that only two components of the eye filter short wavelength visible and ultraviolet light to a significant degree outside of the fovea (Boettner and Wolter, 1962). The cornea does not transmit radiation below 300 nm and only reaches 80% transmission at 380 nm. The crystalline lens, as illustrated in Figure 1, absorbs much longer wavelength radiation, with a lower limit of approximately 350 nm and 80% transmission at 500 nm.

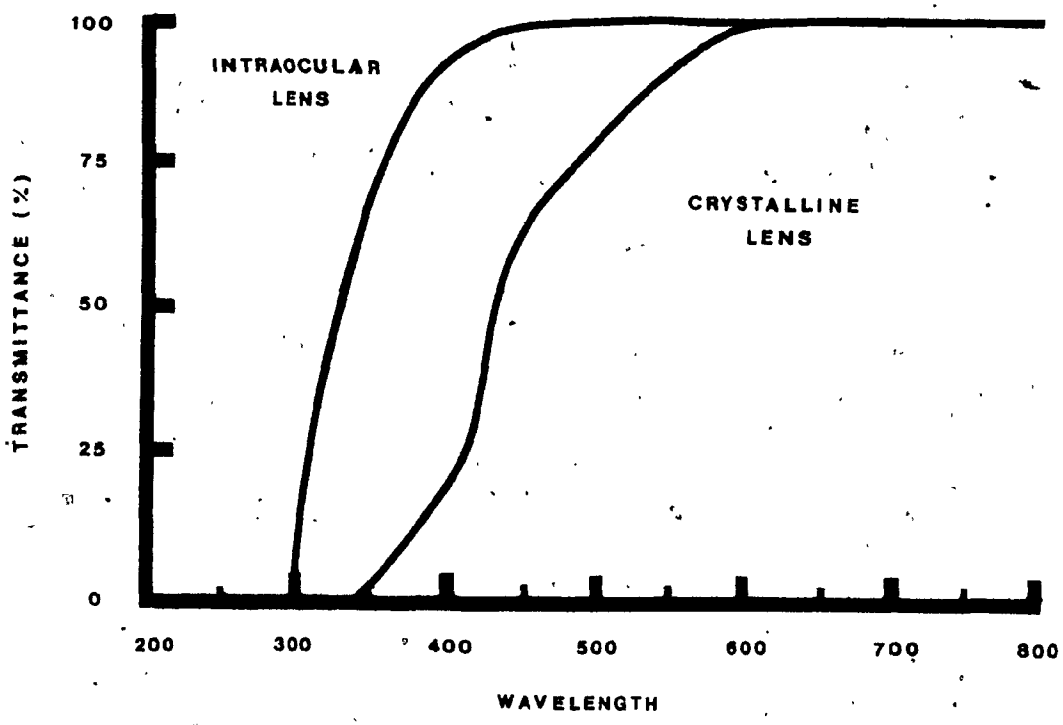


Figure 1. Transmission characteristics of the crystalline lens and intraocular lens. Wavelength is expressed in nanometers in all figures.

Further, lens absorption characteristics vary considerably among eyes with some lenses becoming opaque at 400 nm and only reaching 90% transmission at 540 nm. This increase in density is reported to be greatest in older eyes and there is evidence to suggest that short wavelength lens opacity can be predicted by age (Said and Weale, 1959; Alpern, Thompson and Lee, 1965; Werner, 1982), and may in some cases be caused by chronic exposure to ultraviolet radiation (Zigman, 1978; Zigman, Datiles and Torczynski, 1979). Another component of the eye that absorbs short wavelength radiation is the macular pigment. This pigment is located in the area of the fovea and because of its yellow colour is a strong filter of blue light. This filter however, is restricted to the fovea and has little effect on peripheral scotopic vision.

Scotopic Sensitivity

The CIE scotopic standard observer is based upon the results of Wald (1945) and Crawford (1949), and represents the average scotopic luminosity function for dark adapted observers less than 30 years of age. The maximum for this function occurs at 507 nm, and it extends from 380 nm to 750 nm. The reduction in luminous efficiency from the maximum is approximately 3 log units at the shortest wavelength and greater than 5 log units at the longest wavelength. When this function is corrected for absorption by the crystalline lens, a close match can be made with the rhodopsin action spectrum (Dartnall, 1953, 1957).

The scotopic luminosity function however, does not describe sensitivity in the ultraviolet at wavelengths shorter than 380 nm, and it does not apply to observers with a marked increase in sensitivity

in the blue and violet parts of the spectrum. Powers, Schneck and Teller (1981) and Werner (1982) have measured a greater-than-average sensitivity in infants and young children at wavelengths shorter than 450 nm in the visible spectrum. In additon, Werner (1982) reported a decrease in sensitivity to short wavelength visible light as a function of age, and attributed it to an increasing opacity of the lens to short wavelength light.

In addition to these estimates of sensitivity to violet and blue light, measures of sensitivity to ultraviolet light have been made. Goodéve (1934) reported rod-mediated vision as far into the ultraviolet as 312 nm, using a simple detection task following dark adaptation. In a further study he measured scotopic sensitivity in the ultraviolet in the phakic eye (Goodeve, Lythgoe and Schneider, 1942) and found that sensitivity at 365 nm was approximately 8 log units less than the maximum in the visible range. More recent estimates, using longer dark adaptation periods, increase the average sensitivity by an additional two to four log units (Dodt and Walther, 1958; Tan, 1971). A great amount of variability in measures of scotopic sensitivity in the ultraviolet should be expected when the crystalline lens is part of the optical path, because the absorption spectra of the crystalline lens at short wavelengths varies as a function of age and within groups of the same age (Boeltner and Wolters, 1962; Werner, 1982). As a result measures of scotopic sensitivity cannot be corrected with the precision necessary to reveal an <u>in vivo</u> rhodopsin luminosity function. An aphakic observer, who has had the crystalline lens removed, could provide more complete and accurate <u>in vivo</u> measures.

Scotopic Sensitivity of the Aphakic Eye

The first description of scotopic sensitivity of an aphakic observer in the ultraviolet was by Gaydon (1938), who became aphakic due to a laboratory accident. He reported that he was able to see very low intensity light transmited through an ultraviolet filter, especially when it was presented in his peripheral visual field after an extended dark adaptation period. His report was a subjective description of his visual experience, and no attempt was made to measure his sensitivity to the ultraviolet part of the spectrum. However, Goodéve, Lythgoe and Schneider (1942), in addition to assessing the scotopic sensitivity of normals in the ultraviolet, measured the sensitivity of Gaydon's aphakic eye at 365 nm. They found the scotopic luminosity factor at that wavelength to be approximately four log units more sensitive than phakic eyes.

Two other studies of scotopic sensitivity have found similar results. Dodt and Walther (1958) used an electroretinographic sensitivity method to determine thresholds at wavelengths as short as 341 nm. The luminosity factors calculated were in agreement with the estimates by Wald (1945). Although, the relative scotopic measures were similar, the small differences between these studies can be accounted for by the variability introduced by the procedures used and sample size. The electroretinographic technique requires stimulus intensities much above absolute threshold, while a method of adjustment, similar to Wald's, uses the lowest levels possible. A difference in stimulus characteristics of this sort could account for small differences. Further, the number of observers tested in the

Dodt and Walther study was limited to two aphakics, while the results of Wald are based upon 39 aphakic eyes in 24 observers. In both cases, aphakic observers demonstrated a departure from the standard scotopic function, with increased sensitivity beginning at approximately 500 nm. Wald's data described scotopic sensitivity at 365 nm in the aphakic eye to be 1.3 log units less than peak sensitivity at 492 nm, and 1.7 log units more sensitive than phakic eyes at the same wavelength. In fact, sensitivity and acuity were reported to be great enough to allow aphakic observers to read a complete Snellen chart - an impossible task for phakic observers. It is interesting to note that the data from the study by Wald were used by the CIE to establish a standard that was limited to the "visible" range (380 nm as the lower limit), but his data describing phakic and aphakic sensitivity in the near ultraviolet was not used. If this data had been incorporated into the standard, the lower limit would have been extended to 365 nm and a description of the underlying ultraviolet sensitivity might have been included.

A more extensive study of aphakic sensitivity was made by Tan (1971). Using the psychophysical method of adjustment, observers increased the stimulus intensity to a point that was judged to be just visible. A scotopic luminosity function was determined for normal and aphakic observers and it was found that aphakic sensitivity in the ultraviolet was at least 2.5 log units greater than phakic sensitivity and only 0.9 log units less than the maximum at 500 nm. From this function, and correcting for the remaining ocular media, Tan calculated a curve that matched the rhodopsin photosensitivity function at wavelengths as short as 330 nm and longer than 700 nm.

Current estimates of aphakic sensitivity in the short wavelength visible spectrum are in accord with earlier estimates that included ultraviolet thresholds (Powers, Schnek and Davida, 1981; Werner, 1982). Pseudophakic thresholds however, have only been shown to match aphakic luminosity factors in the visible spectrum (Werner and Hardenberg, 1982).

To date, estimates of *in vivo* rhodopsin photosensitivity, based upon aphakic scotopic sensitivity and corrections for the absorption spectra of remaining ocular media, have matched *in vitro* estimates at many points, although, the lower limit of spectral sensitivity has not been determined. The remaining ocular media in the aphakic and pseudophakic eye should allow transmission of incident radiation down to a wavelength of approximately 300 nm (Boettner and Wolter, 1962). It is the intent of this study to extend the *in vivo* measure of rhodopsin sensitivity to that limit.

The results of this study should provide a more comprehensive estimate of aphakic sensitivity in the ultraviolet and may point to the necessity of adequate optical compensation for the increased sensitivity. That is, the results may suggest the need to include ultraviolet filtration in optical corrections prescribed for the aphakic and pseudophakic eye in order to reduce problems such as excessive glare, photophobia, and aphakic erythropsia (Kamel and Parker, 1973).

METHOD

The method was designed to determine absolute scotopic thresholds for dark adapted monocular aphakic and pseudophakic observers. The psychophysical procedure employed was a single staircase procedure with decreasing step size. The optical system consisted of a Xenon arc lamp, a monochromator and fixed and variable neutral density filters. Wavelength selection and image intensity were adjusted by servo mechanisms controlled by a microcomputer, which also recorded observer responses. Thresholds were determined at 10 nm intervals between 300 nm and 400 nm, and at 20 nm intervals between 400 nm and 700 nm.

Subjects

The five observers were monocular aphakics or pseudophakics ranging in age from 52 to 77 years. In three cases, following removal of the crystalline lens, an acryllic intraocular lens was implanted after cataract extraction. The absorption characteristics of acrylic lenses are described in Figure 1: The color vision of all observers was assesed using the AO H-R-R Pseudoisochromatic Plates (copyright 1957, American Optical Corporation). None of the observers were currently suffering from eye diseases. Table 1 presents a summary of observer information.

Observers were recruited with the assistance of an ophthamology clinic. Each observer was paid an hourly rate of four dollars and transportation costs. Observers were free to terminate their participation at any time.

TABLE 1

Observer Information

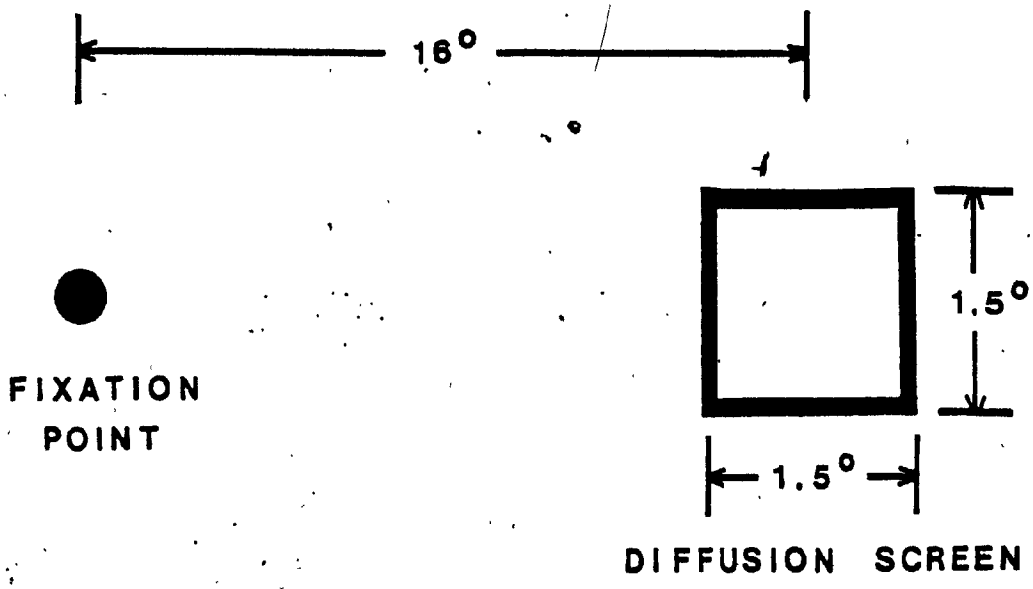
Observer	Sex	Age	Time since cataract extraction	corrected acuity	Condition
P1	m	77	6 months	OD 20/30 OS 20/30	pseudophakic normal
P2	m	66	22 months	OD 20/20 OS 20/20	pseudophakic normal
P3	f	64	1.5 months	OD 20/30 OS 20/30	pseudophakic normal
A1	f	52	4 months	OD n/a OS 20/25	aphakic normal
A2	m	63	7 months	OD n/a OS n/a	aphakic normal

Apparatus

Optical system. All testing was carried out in a dark room. The subject's head was maintained in a fixed position with the aid of a chin rest. An artificial pupil with a 2 mm diameter was placed 5 mm in front of the observer's eye perpendicular to the apparatus' optical axis.

The square test stimulus was a 100 msec flash subtending 1.5 degrees of visual angle on each side. The test stimulus was always presented 16 degrees temporally from a miniature red light emitting diode, as illustrated in Figure 2.

The optical system is described in Figure 3. A 75-watt Xenon arc (Osram XBO-1) was focused with two quartz lenses on the entrance slit of a Schoeffel GM-100 grating monochromator with an aperture ratio of 4.7 and a focal length of 100 mm. A square aperture (1x1 cm) was positioned in front of the condensing lens to ensure an aperture ratio less than the manufacturer's specifications in order to minimize scattered light within the monochromator. The diffraction grating used was blazed at 1180 lines/mm to provide peak efficiency in the ultraviolet. The entrance and exit slits were 0.5 mm wide by 6.5 mm high; the bandwidth was 4.25 nm with a dispersion ratio of 8.5 nm/mm slit width. The proportion of contamination by scattered light was estimated by the manufacturer to be .0018.



TEST FIELD

Figure 2. Test stimulus and display

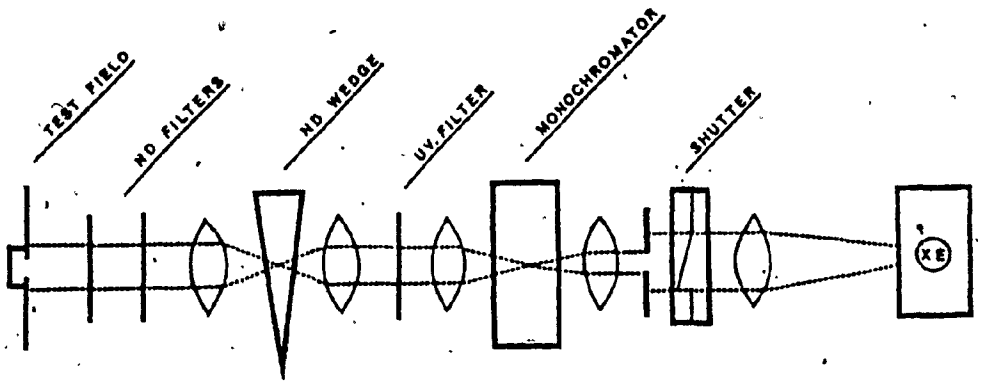


Figure 3. Optical system components

The light emerging from the exit slit was collimated and then focused at the position of a quartz neutral density wedge (Metavac Inc. catalogue no.1531) with a range from 0 to 2.4 optical density units, measured at 580 nm. At wavelengths shorter than 380 nm, a visible blocking-ultraviolet transmitting optical filter (Schott model UG-11) was introduced between the neutral density wedge and the monochromator in order to minimize possible contamination by longer wavelength scattered light. A final quartz lens was used to collimate the beam through two fixed neutral density filters and to slightly overfill a square aperture at the diffusion screen. The fixed density quartz filters (Ealing Catalogue no.35-6287 and no.35-6261) had values of 2 and 3 density units, measured at 580 nm, and the 12 mm by 12 mm mask produced the 1.5 deg square test stimulus.

A shutter (Uniblitz model 225) between the light source and the monochromator was used to control the duration of the test flash. Light baffles were used extensively to eliminate reflections of scattered light.

Automatic control. A microcomputer (Apple II Plus) was used to control the optical system and simultaneously record subject responses. Two type 6522 Versatile Interface Adapters were interfaced with the computer using a parallel interface peripheral card (John Bell,Inc). This interface provided the input and output of logic signals necessary to control electro-mechanical devices and receive input from switch closures. The monochromator and neutral density wedge settings were adjusted using a stepper motor (Phillips # 82700) and control circuitry (Amsi Inc.# 2003-db). The filters were positioned in the optical path using 12 volt solenoids.

The computer programs for control of the optical system and data collection were developed and executed within the Apple Pascal 1.1 language system.

Calibration and measurement. The spectral output of the Xenon arc lamp and monochromator was measured at the position of the observer's pupil by an EG&G radiometer, model 550-1 with the 550-2B multiprobe. Both the electronic circuitry and silicon photodiode were calibrated by the manufacturer and traceable to the United States National Bureau of Standards. The transparent optical media between the light source and photodiode and the diffusion screen in the test field were in place for all measures. The ultraviolet transmitting-visible blocking filter was included for measures of wavelengths shorter than 380 nm.

The spectral transmission of the fixed neutral density filters and gradient density wedge was measured each 10 nm in the range between 300 nm and 700 nm. This measure was repeated at nine points along the circumference of the neutral density wedge. Optical density was estimated with a regression equation expressing density as a function of position.

The wavelength adjustment of the monochromator was calibrated by comparing the wavelength setting to the maximum spectral transmission of four narrow band interference filters.

Procedure

Observers were dark adapted for 25 minutes prior to each test session. The psychophysical procedure used to determine absolute scotopic thresholds was a single staircase procedure with decreasing step size as illustrated in Figure 4.

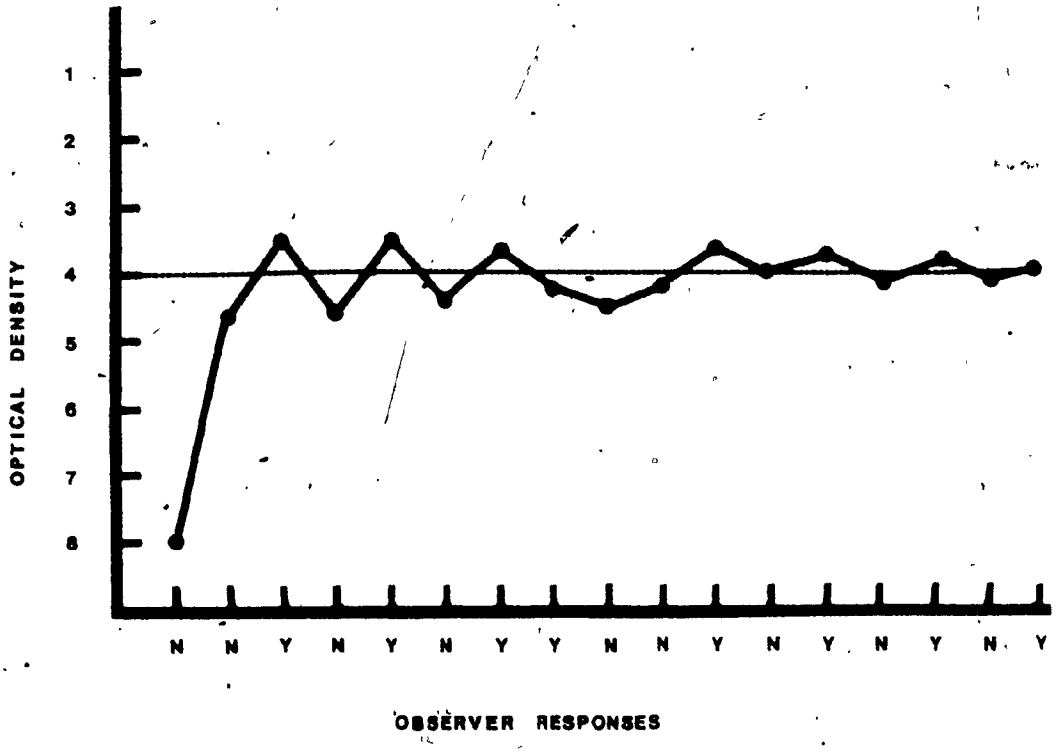


Figure 4. Example of single staircase procedure

For each trial at a particular wavelength, the observer depressed a key to indicate the presence or absence of the stimulus. Each presentation of the stimulus was immediately preceded by a one second tone generated by the microcomputer. Each time the observer switched from a positive to a negative response or vice-versa, the stepsize was decreased by the smallest change in stepsize possible in the optical system. When the stepsize reached the physical minimum of .053 optical density units (at 580 nm), the trial was terminated and the optical density in the optical path was recorded. The absolute thresholds were calculated using the energy measured at the test wavelength and the optical density (corrected for spectral transmission) recorded at threshold.

During each test session observers were tested at 10 nm intervals begining at 300 nm, and at 20 nm intervals between 400 nm and 700 nm, in order to minimize observer fatigue at short wavelengths. In total, thresholds were determined at 26 wavelengths in the range from 300 nm to 700 nm. The order of presentation of wavelengths proceeded from 300 nm to 700 nm during each test session.

Test sessions were repeated once each test day with each observer, to allow separate measures of phakic and aphakic or pseudophakic eyes. The order of testing of observers' eyes was reversed each test day. A single test session including dark adaptation was approximately one hour in duration. Each observer was tested on three separate days during a period that did not exceed ten days.

RESULTS

The mean results for five observers are illustrated in Figure 5, with sensitivity expressed on a common log scale as a function of wavelength. The standard error for these data were calculated using observer mean scores, each given equal weight. All data presented are based upon absolute energy thresholds and have not been transformed to relative measures. Figures 6 to 10 describe the individual results of three test sessions with each observer, and each figure allows a direct comparison between phakic and aphakic or pseudophakic eyes within the same observer. All measures determined are shown, with two exceptions: The data for the first normal test session with observer P1 were excluded as a result of the observer's misunderstanding the instructions. Also, there were only two test sessions for observer P3; a third test session was not possible.

The normal eye data generally match the data of Wald and Crawford as embodied in the C.I.E. standard scotopic observer, as illustrated in Figure 11. The only consistent difference is at short wavelengths, where sensitivity falls below the standard. The data taken with the observer's aphakic or pseudophakic eye is different from the standard function at wavelengths shorter than 520 nm. This difference is expressed by increased sensitivity at shorter wavelengths in the visible spectrum.

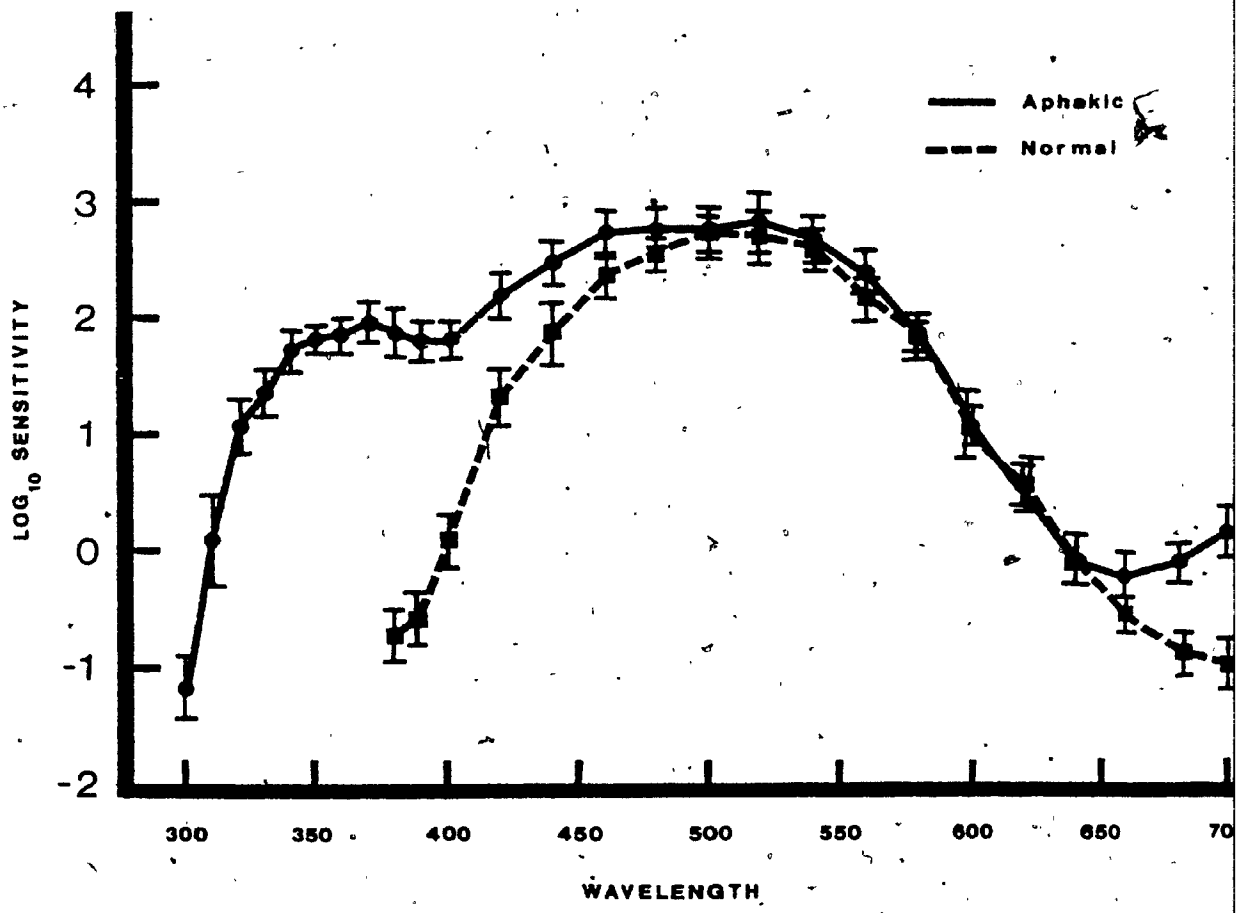


Figure 5. Average results for all subjects

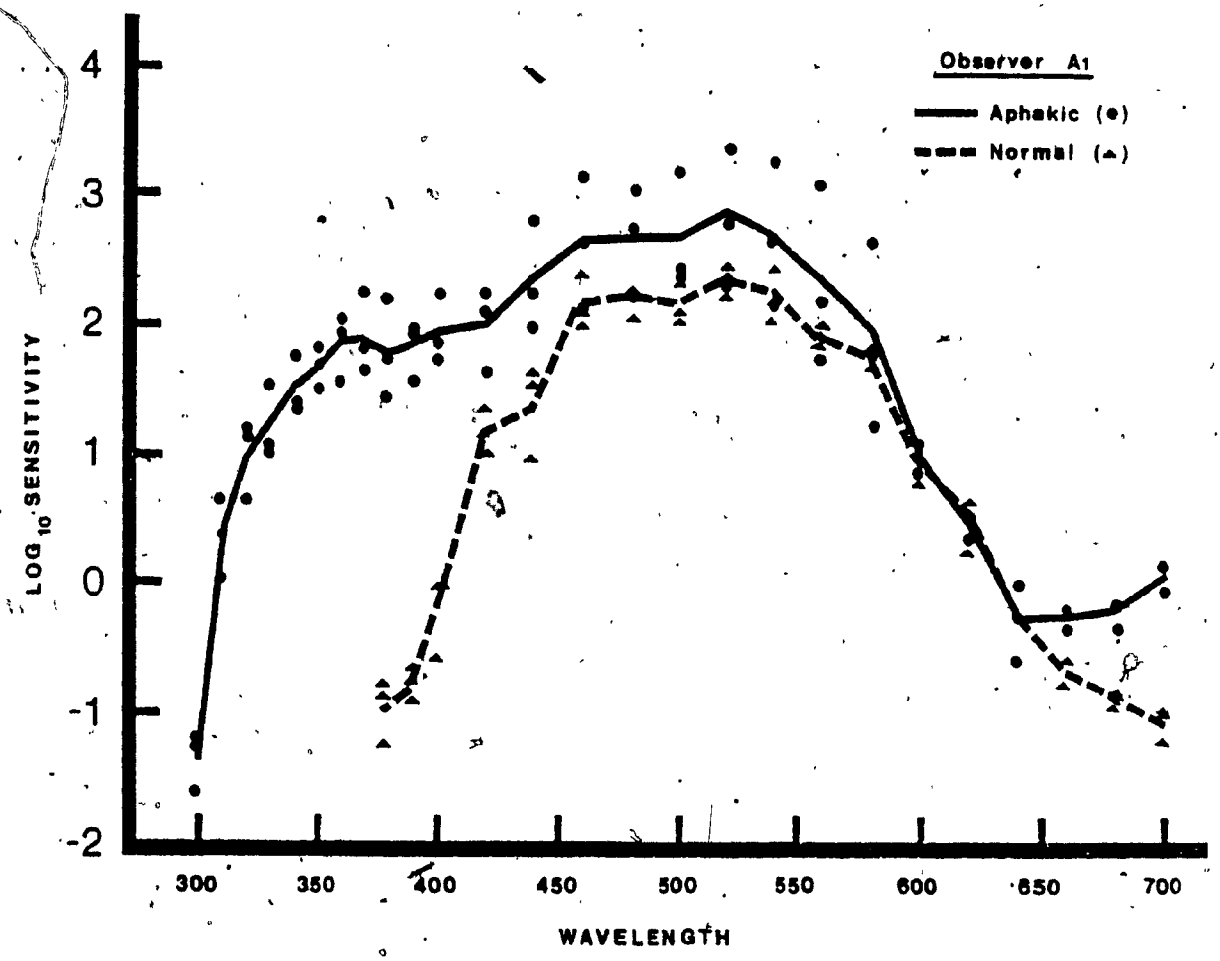


Figure 6. Individual data for Observer A1. Solid lines connect the means at wavelengths tested.

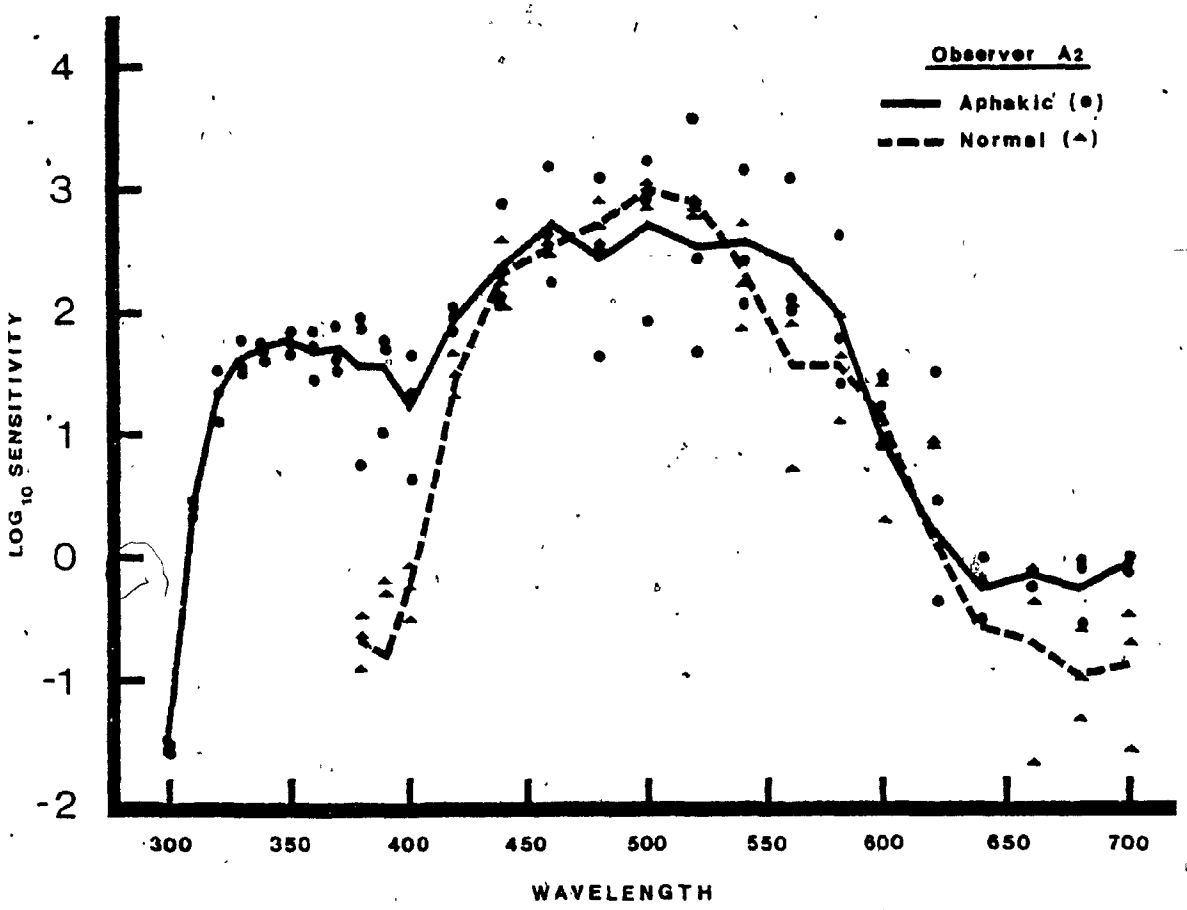


Figure 7. Individual data for Observer A2. Solid lines connect the means at wavelengths tested.

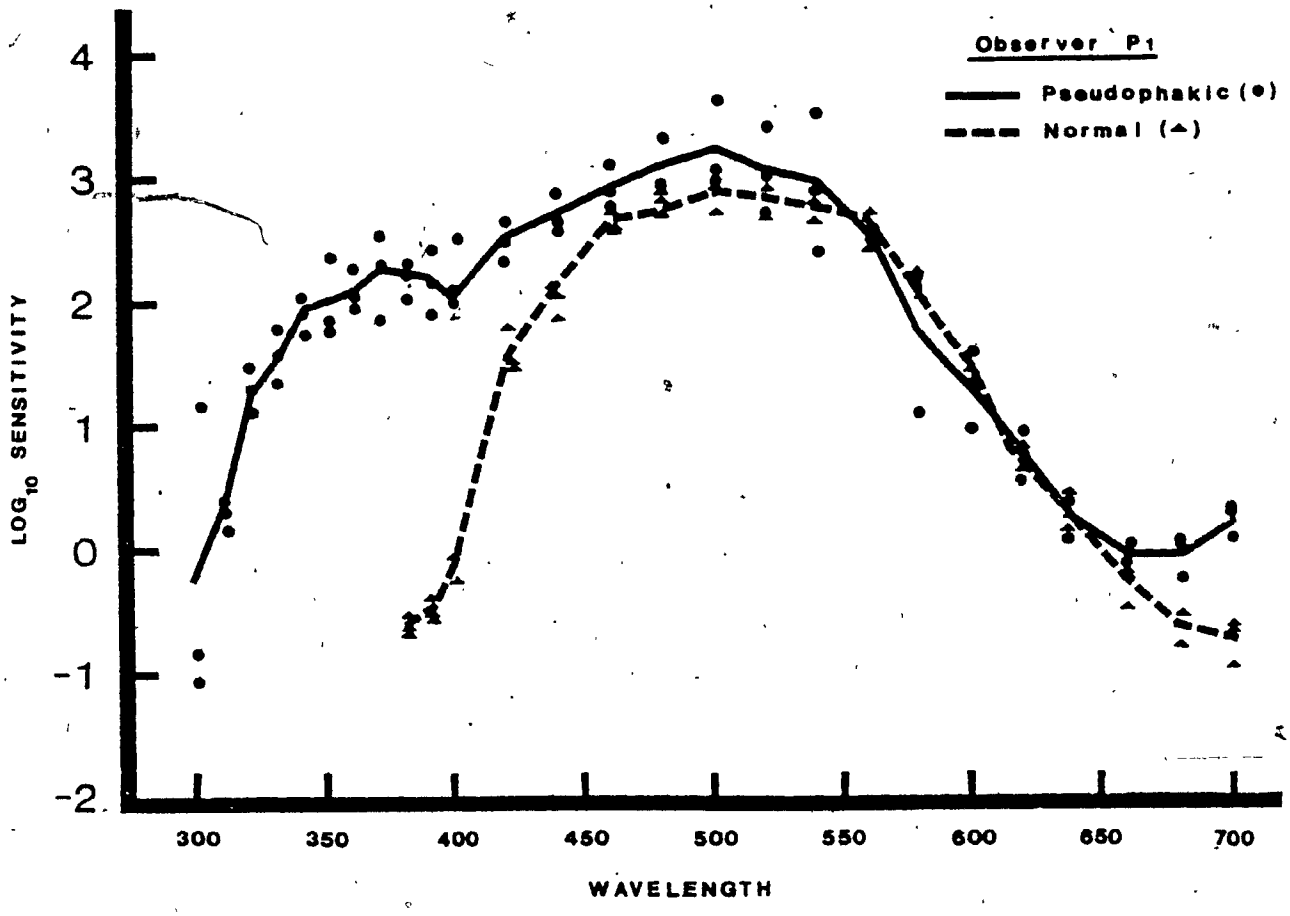


Figure 8. Individual data for Observer P1. Solid lines connect the means at wavelengths tested.

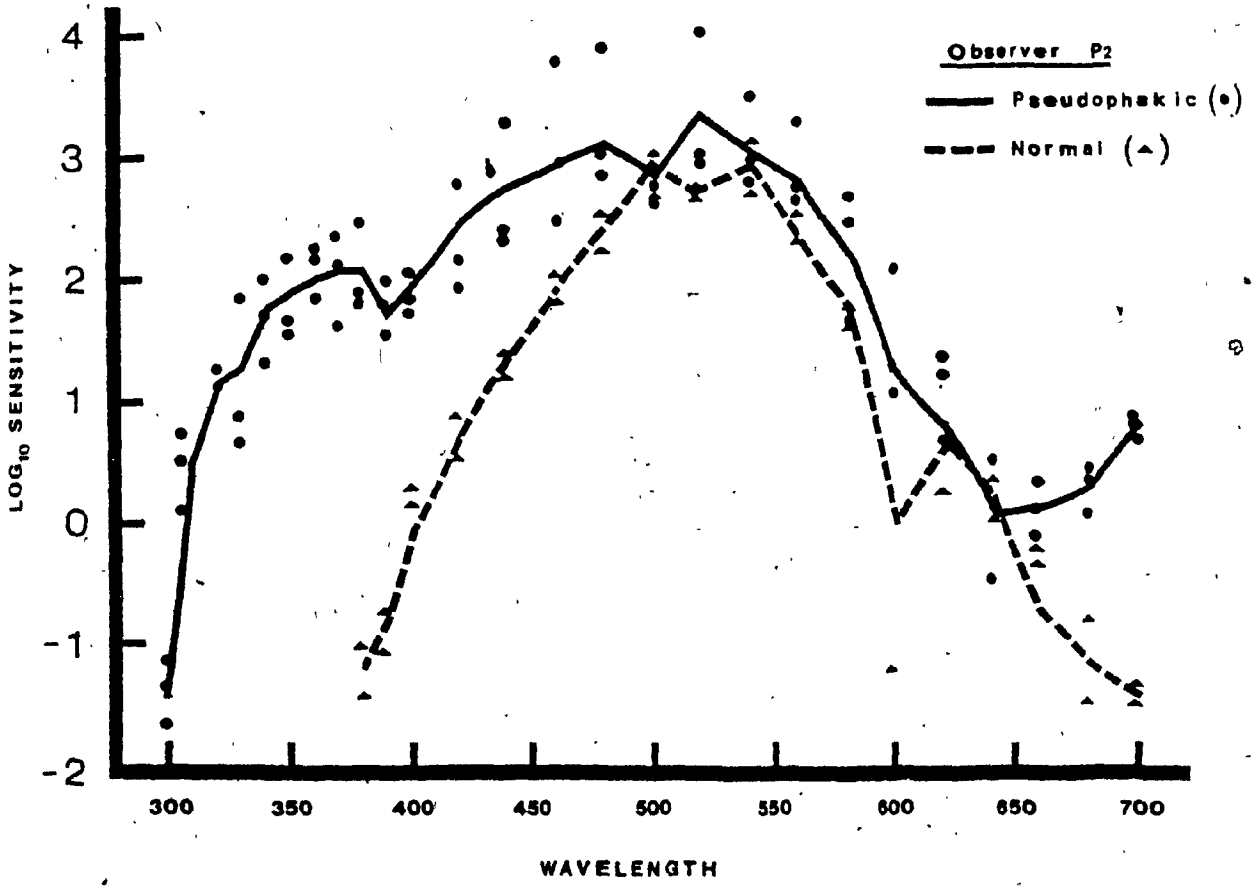


Figure 9. Individual data for Observer P2. Solid lines connect the means at wavelengths tested.

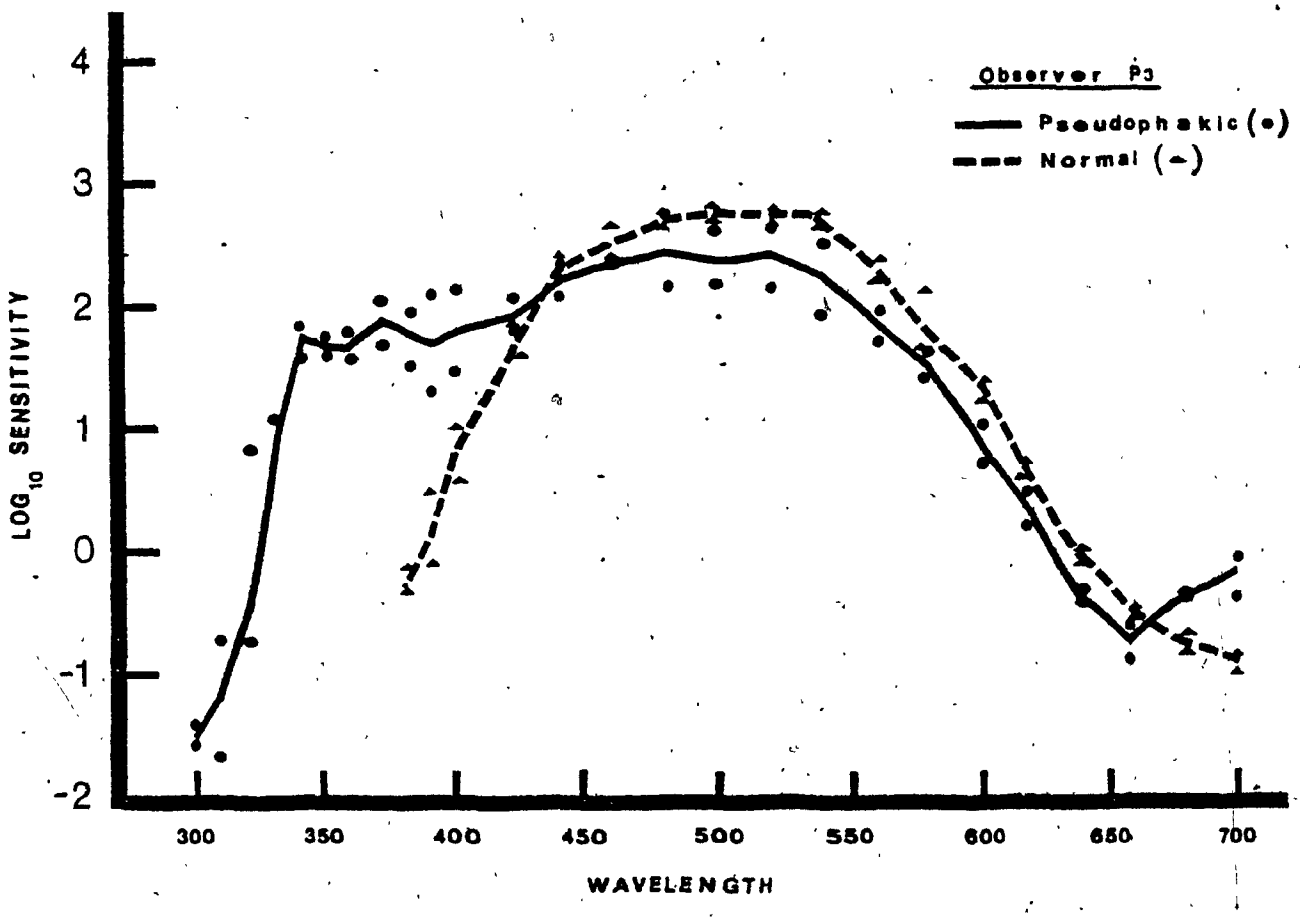


Figure 10. Individual data for Observer P3. Solid lines connect the means at wavelengths tested.

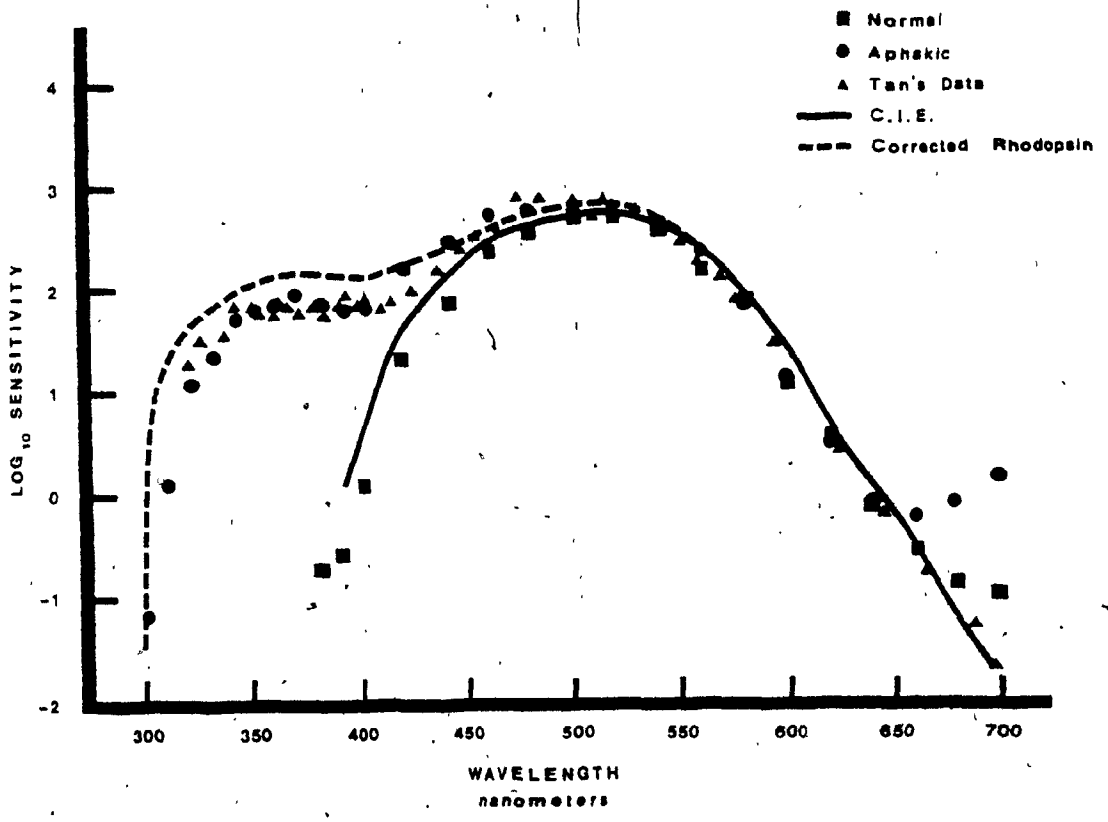


Figure 11. A comparison of the average results for all observers, the data from Tan (1971) and the C.I.E. standard scotopic observer. The corrected rhodopsin function is the combination of the Dartnall nomogram (1953) and a measure of rhodopsin sensitivity (Collins, Love and Morton, 1952) at wavelengths shorter than 400 nm corrected for the absorption of the ocular media exclusive of the crystalline lens (Boettner and Wolter, 1962). The relative measures are normalized to the measure of sensitivity of the average aphakic results at 520 nm.

The divergence between the aphakic or pseudophakic data and the C.I.E. standard is greatest at shorter wavelengths, with the most pronounced difference in the ultraviolet. This increased sensitivity can be described graphically as a shoulder extending into the ultraviolet with mean thresholds 0.9 log units less than the peak sensitivity in the visible spectrum. The mean standard error for the phakic data is 0.16 log units and 0.14 log units for the aphakic and pseudophakic measures. Sensitivity in the ultraviolet disappears below about 310 nm.

The sensitivity of aphakic and pseudophakic observers at wavelengths greater than 650 nm, appears to increase and diverge from the normal data. This increase in the long wavelength portion of the spectrum is an artifact of the contamination of the stimulus by scattered ultaviolet light produced by higher order diffraction at the monochromator and does not reflect the actual sensitivity at those wavelengths. That is, sensitivity measured at these wavelengths is in fact another measure of ultraviolet sensitivity rather than an estimate of sensitivity to the wavelengths described.

Comparisons of aphakic and pseudophakic thresholds in the visible and ultraviolet have not revealed any differences, which suggests that the ultraviolet absorption of the implanted intraocular lenses is negligible. The similarity between aphakic and pseudophakic observers is illustrated in Figure 12, with average sensitivity functions for each observer displaced by approximately two to six log units to facilitate comparisons.

All observers were informally questioned about the quality of the

visual experience upon completion of testing, including any differences that were noticed between the two eyes during testing, and any differences or changes in the stimulus that was noticed at any time during the experimental sessions. The observers generally described the stimulus as square or rectangular in shape and grey in appearance, always located in the same relative position, and changing only in brightness.

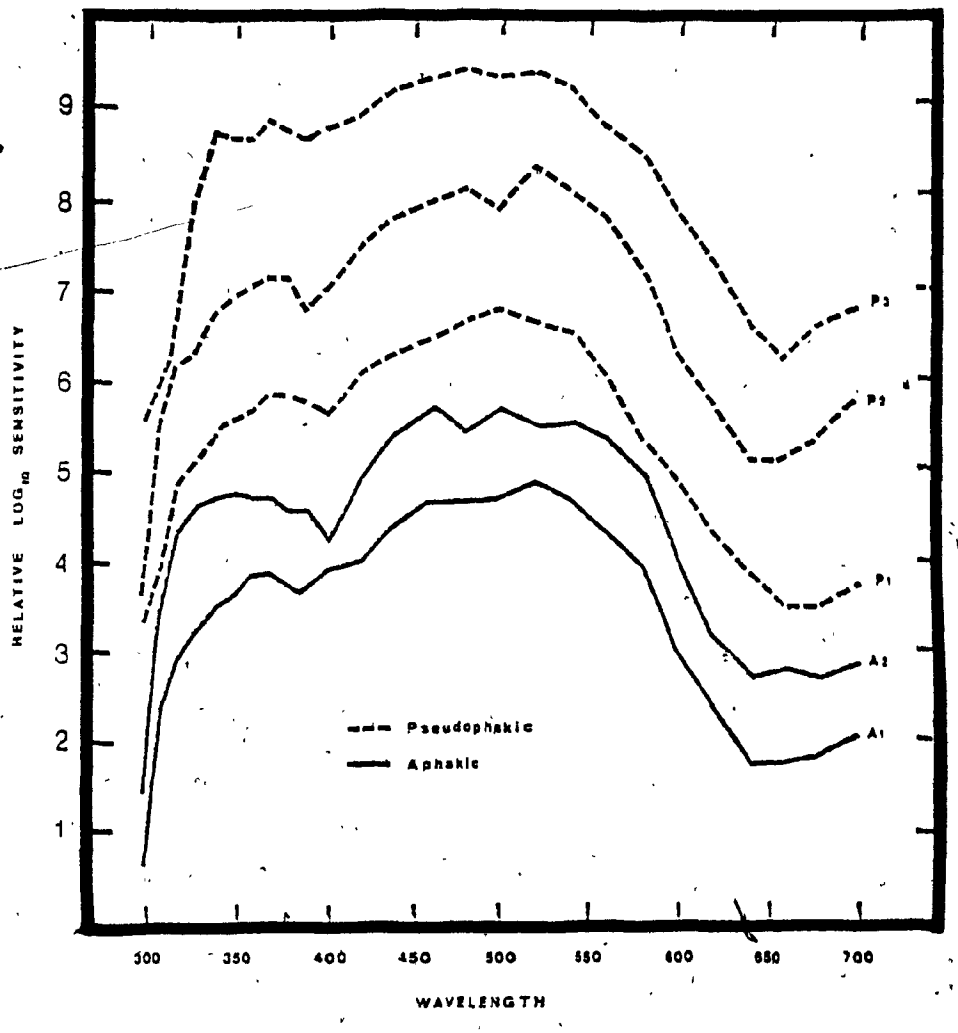


Figure 12. Comparison of aphakic and pseudophakic data.

DISCUSSION

The purpose of this study was to extend the scotopic sensitivity functions of aphakic and pseudophakic observers as far into the ultraviolet as possible, and to compare these functions to phakic scotopic sensitivity in the same observer. In addition, comparisons were made between aphakic and pseudophakic spectral sensitivity.

Both aphakic and pseudophakic sensitivity in the ultraviolet part of the spectrum at 350 nm, were found to be at least 2.5 log units more sensitive than the maximum sensitivity of phakic eyes at short wavelengths. This increased sensitivity is at least 300 times greater than normal. The aphakic data departs from the standard observer as a result of the reduction in ocular absorption caused by the absence of the crystalline lens. This increase in relative scotopic sensitivity down to 300 nm describes the maximum photosensitivity to be expected of the photoreceptors in vivo, that is, the maximum sensitivity to be measured in a healthy functioning eye that has the minimum pre-receptor absorption possible.

The normal or phakic data is in agreement with the C.I.E. standard observer and supports the accuracy of the method adopted to measure scotopic sensitivity. There is a small difference (less than 0.2 log units) between the phakic data and the scotopic standard at shorter wavelengths, with measures of sensitivity consistently below the standard function. It may be that the lower sensitivity is due to the short wavelength lens opacity expected with this age group. These short wavelength measures may reflect the filtration produced by the naturally yellow lens in individuals of this age (Said and Weale, 1959; Alpern, Thompson and Lee, 1965; Werner, 1982).

Photosensitivity

If the photoreceptor's sensitivity is based upon the photopigment's absorption characteristics, then a comparison between scotopic sensitivity and rhodopsin's absorption spectrum should reveal a close match. Using Dartnall's nomogram (1953) describing rhodopsin absorption in the visible spectrum and an addition to the function describing sensitivity in the ultraviolet (Collins, Love and Morton, 1952), an obvious relationship with the psychophysically derived scotopic sensitivity function can be found. The similarity between these functions is illustrated in Figure 11. Small differences between these measures may be attributed to spectral absorption by the remaining ocular media in the aphakic or pseudophakic eye or to measurement error. The comparison using the combined results of aphakic and pseudophakic eyes is made possible by the similarity in the derived functions, as illustrated in Figure 12.

The findings of this study are in agreement with estimates of aphakic sensitivity determined in earlier studies by Tan (1971), Wald (1945) and Dodt and Walther (1958). It should be noted that these studies all reveal scotopic functions that approximate the rhodopsin absorption spectrum, but only the present study includes the ultraviolet minimum.

Fluorescence of the Ocular Media

An alternate explanation of sensitivity in the ultraviolet is based upon fluorescence, that is, the emission of longer wavelength light by ocular media that absorb ultraviolet radiation. According to this explanation, the visual threshold would be determined by the receptor's response to the fluorescent visible light, not to the

incident ultraviolet radiation. This explanation is not very plausible, for the following reasons: (1) If fluorescence of ocular media anterior to the retina were responsible, the observer would not be able to localize the target; the visible emission would appear as a veiling glare. However, the observers in the present experiment were always able to localize the target. (2) Another possibility is fluorescence within the retina itself. Although this could conceivably produce a visual sensation, it could not account for the magnitude of sensitivity that was obtained. The thinness of the retina and the unusual and inefficient angle of entry by quanta at the receptor would preclude this possibility (Stark and Tan, 1982). (3) Another argument against mediation by fluorescence is the very high photosensitivity of the rhodopsin pigment itself. Given these arguments against fluorescence, it is improbable that it mediates the visual sensation measured in this study.

Clinical Implications

The degree of sensitivity of aphakic and pseudophakic observers in the ultraviolet as measured in this study is approximately 300 times greater than the minimum of normal sensitivity. Since there is no demonstrable difference in sensitivity between the aphakic and pseudophakic eyes, the retinas of such eyes are exposed to higher than normal levels of ultraviolet radiation. This increase in absorption of radiation may have negative consequences. For example, chromatic aberration may impair visual acuity, and enhanced glare sensitivity and photophobia are often symptomatic of aphakia and pseudophakia. Also, aphakic erythropsia is an aftereffect of reddish vision following exposure to high levels of ultraviolet radiation (Kamel and

Parker, 1973). Finally, there is some evidence to suggest that chronic exposure to short wavelength radiation may result in damage to the retina and in particular the blue cone system (Ham, Mueller and Sliney, 1976; Ham, Mueller and Ruffulo, 1981). The damage reported was not described as thermal injury, but as damage produced by a photochemical mechanism maximally sensitive to short wavelength radiation. If this is the case, then short wavelength radiation of long duration may produce damage of a photochemical nature similar to that typically found in thermal damage by high intensity long wavelength radiation. Given these possible consequences of increased ultraviolet exposure, it is important to consider the spectral transmission characteristics of corrective lens material and the ultraviolet screening protection included in post-cataract refraction.

Implications for Color Vision

Future research will examine the spectral sensitivities of the cone systems both in the visible and ultraviolet parts of the spectrum in an attempt to describe the basic elements of color vision. A model of color vision presently describes three classes of cones, each having a spectral sensitivity function based upon the Dartnall nomogram with the primary peak in the visible spectrum, and an added secondary cis peak in the ultraviolet (White and Wolbarsht, 1975). Using aphakic and pseudophakic observers in color matching and wavelength discrimination paradigms, it may be possible with the additional information found in the ultraviolet, to establish the spectral characteristics of the three cones involved. The intent of future research will be to describe the cone systems using some of the techniques developed in this study.

Summary

The scotopic sensitivity of the human eye was measured in the presence and absence of the crystalline lens within the same observers. Results for normal eyes agreed with the C.I.E. standard observer for scotopic vision, but the ultraviolet sensitivity of aphakic and pseudophakic observers was less then one log unit below the peak sensitivity in the visible spectrum, and more than 2.5 log units greater than the ultraviolet sensitivity of the normal phakic eye. There were no differences between the phakic and pseudophakic sensitivity functions.

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Appendix

Individual Measures of Scotopic Sensitivity

Log sensitivity of observer Al

	normal eye				aphakic eye			
nm.	Test 1	Test 2	Test 3	Mean	Test 1	Test 2	Test 3	Mean
300	—	—	—	—	-1.60	-1.22	-1.22	-1.35
310	—	—	—	—	0.05	0.67	0.24	0.32
320	—	—	—	—	0.69	1.13	1.19	1.00
330	—	—	—	—	1.01	1.57	1.08	1.22
340	—	—	—	—	1.39	1.76	1.39	1.51
350	—	—	—	—	1.51	1.82	1.64	1.66
360	—	—	—	—	1.58	1.93	2.04	1.85
370	—	—	—	—	1.68	1.65	2.27	1.87
380	-1.23	-0.75	-0.87	-0.95	1.43	1.74	2.21	1.79
390	-0.71	-0.65	-0.89	-0.75	1.59	1.97	1.95	1.84
400	0.01	0.01	-0.53	-0.17	1.77	1.89	2.26	1.97
420	1.08	1.37	1.02	1.16	1.66	2.10	2.23	2.00
440	0.97	1.57	1.63	1.39	2.00	2.26	2.81	2.36
460	2.12	2.42	2.02	2.18	2.13	2.64	3.16	2.65
480	2.30	2.08	2.30	2.23	2.25	2.75	3.07	2.69
500	2.11	2.06	2.39	2.19	2.44	2.39	3.20	2.68
520	2.48	2.26	2.42	2.39	2.37	2.81	3.40	2.86
540	2.48	2.05	2.32	2.28	2.10	2.64	3.30	2.68
560	1.97	1.87	2.03	1.96	1.77	2.24	3.11	2.38
580	1.85	1.69	1.64	1.73	1.27	1.80	2.67	1.91
600	1.05	0.79	1.15	1.00	0.89	0.99	1.05	0.98
620	0.63	0.27	0.63	0.51	—	0.53	0.32	0.42
640	-0.14	-0.19	-0.24	-0.19	—	0.01	-0.55	-0.27
660	—	-0.60	-0.75	-0.68	—	-0.26	-0.31	-0.28
680	—	-0.90	-0.85	-0.88	—	-0.12	-0.31	-0.21
700	—	-0.95	-1.19	-1.07	—	0.17	-0.03	0.07

Log sensitivity of observer A2

	normal eye				aphakic eye			
nm.	Test 1	Test 2	Test 3	Mean	Test 1	Test 2	Test 3	Mean
300	—	—	—	—	-1.29	-1.60	-1.60	-1.49
310	—	—	—	—	0.61	0.36	0.24	0.40
320	—	—	—	—	1.38	1.56	1.13	1.35
330	—	—	—	—	1.81	1.57	1.51	1.63
340	—	—	—	—	1.71	1.82	1.63	1.72
350	—	—	—	—	1.79	1.88	1.70	1.79
360	—	—	—	—	1.87	1.75	1.45	1.69
370	—	—	—	—	1.92	1.62	1.56	1.70
380	-0.63	-0.45	-0.87	-0.65	1.97	1.92	0.77	1.55
390	-0.24	-0.18	-1.96	-0.79	1.74	1.80	1.05	1.53
400	-0.23	-0.05	-0.47	-0.25	1.37	1.66	0.65	1.22
420	1.26	1.70	1.40	1.45	2.05	1.93	1.84	1.94
440	2.26	2.61	2.09	2.32	2.15	2.09	2.92	2.39
460	2.59	2.53	2.53	2.55	2.70	2.30	3.22	2.74
480	2.92	2.70	2.58	2.73	2.53	1.68	3.13	2.45
500	3.06	3.06	2.89	3.00	2.94	1.94	3.25	2.71
520	2.97	2.92	2.81	2.90	2.42	1.71	3.51	2.55
540	2.26	2.75	1.89	2.30	2.10	2.48	3.19	2.59
560	1.92	2.08	0.75	1.59	2.13	2.03	3.11	2.43
580	2.01	1.64	1.11	1.59	1.80	1.43	2.62	1.95
600	1.56	1.51	0.35	1.14	0.45	1.41	1.05	0.97
620	0.94	-1.63	0.94	0.08	0.53	-0.34	0.48	0.22
640	0.29	-1.71	-0.19	-0.54	0.01	-0.19	-0.50	-0.23
660	-0.11	-0.31	-1.65	-0.69	-0.16	-0.21	-0.01	-0.12
680	-1.30	-0.56	-0.95	-0.94	-0.07	-0.02	-0.56	-0.21
700	-0.66	-0.46	-1.53	-0.88	-0.03	0.02	-0.03	-0.01

Log sensitivity of observer P1

	normal eye				pseudophakic eye			
nm.	Test 1	Test 2	Test 3	Mean	Test 1	Test 2	Test 3	Mean
300	—	—	—	—	-0.85	1.16	-0.91	-0.20
310	—	—	—	—	0.24	0.30	0.49	0.34
320	—	—	—	—	1.50	1.19	1.13	1.27
330	—	—	—	—	1.38	1.81	1.51	1.57
340	—	—	—	—	1.76	1.96	2.08	1.93
350	—	—	—	—	1.79	1.85	2.40	2.01
360	—	—	—	—	1.99	2.06	2.28	2.11
370	—	—	—	—	1.86	2.37	2.57	2.27
380	-0.51	-0.69	-0.63	-0.61	2.09	2.27	2.33	2.23
390	-0.53	-0.35	-0.53	-0.47	1.92	2.21	2.43	2.18
400	-0.11	-0.05	-0.23	-0.13	2.13	2.07	2.01	2.07
420	1.49	1.37	1.81	1.56	2.34	2.51	2.69	2.51
440	1.92	2.20	2.09	2.07	2.67	2.61	2.92	2.73
460	2.70	2.70	2.59	2.66	2.93	2.81	3.16	2.97
480	2.53	2.87	2.81	2.73	2.98	2.98	3.35	3.10
500	2.78	2.89	3.00	2.89	3.11	3.00	3.64	3.25
520	2.75	2.97	2.86	2.86	2.75	3.03	3.45	3.08
540	2.70	2.81	2.81	2.77	2.43	2.97	3.57	2.99
560	2.46	2.78	2.62	2.62	2.62	2.51	2.58	2.57
580	1.75	2.27	2.22	2.08	2.17	2.06	1.11	1.78
600	1.30	1.57	1.47	1.45	1.30	1.62	1.00	1.31
620	0.63	1.06	0.89	0.86	0.78	0.99	0.53	0.77
640	0.06	0.41	0.26	0.25	0.36	0.26	0.06	0.23
660	-0.46	-0.16	-0.21	-0.27	0.04	-0.06	-0.11	-0.04
680	-0.75	-0.61	-0.51	-0.62	0.08	0.03	-0.21	-0.03
700	-0.95	-0.61	-0.61	-0.72	0.31	0.31	0.07	0.23

Log sensitivity of observer P2

	normal eye				pseudophakic eye			
nm.	Test 1	Test 2	Test 3	Mean	Test 1	Test 2	Test 3	Mean
300	—	—	—	—	-1.16	-1.38	-1.67	-1.40
310	—	—	—	—	0.07	0.50	0.72	0.43
320	—	—	—	—	1.28	0.85	1.11	1.08
330	—	—	—	—	1.82	1.31	0.65	1.26
340	—	—	—	—	1.62	1.55	1.99	1.72
350	—	—	—	—	1.63	1.85	2.14	1.87
360	—	—	—	—	2.15	1.60	2.22	1.99
370	—	—	—	—	2.06	1.84	2.35	2.08
380	—	-1.45	-1.01	-1.23	1.77	1.99	2.46	2.07
390	—	-0.73	-1.02	-0.88	1.78	1.71	1.56	1.68
400	—	0.16	-0.28	-0.06	2.06	1.91	1.87	1.95
420	—	0.58	0.87	0.72	2.18	2.33	2.77	2.43
440	—	1.39	1.31	1.35	2.41	2.49	3.29	2.73
460	—	2.01	1.84	1.92	2.13	3.01	3.77	2.97
480	—	2.52	2.23	2.38	2.82	2.60	3.88	3.10
500	—	3.01	2.71	2.86	2.86	3.01	2.72	2.86
520	—	2.71	2.71	2.71	3.00	2.93	4.01	3.31
540	—	3.16	2.72	2.94	2.80	2.72	3.50	3.01
560	—	2.53	2.31	2.42	2.68	2.46	3.29	2.81
580	—	1.87	1.72	1.79	1.65	2.09	2.67	2.14
600	—	1.22	-1.22	0.00	1.29	1.36	1.07	1.24
620	—	0.23	1.16	0.69	0.67	0.52	1.23	0.81
640	—	0.34	0.04	0.19	0.12	0.56	-0.47	0.07
660	—	-0.34	-1.15	-0.75	0.10	0.32	-0.12	0.10
680	—	-1.46	-0.87	-1.16	0.45	0.30	0.08	0.28
700	—	-1.33	-1.47	-1.40	0.80	0.80	0.80	0.80

Log sensitivity of observer P3

	normal eye				pseudophakic eye			
nm.	Test 1	Test 2	Test 3	Mean	Test 1	Test 2	Test 3	Mean
300	—	—	—	—	-1.47	-1.60	—	-1.54
310	—	—	—	—	-1.69	-0.76	—	-1.23
320	—	—	—	—	-0.75	1.81	—	0.53
330	—	—	—	—	1.01	—	—	1.01
340	—	—	—	—	1.57	1.88	—	1.73
350	—	—	—	—	1.64	1.73	—	1.68
360	—	—	—	—	1.58	1.69	—	1.63
370	—	—	—	—	1.68	2.01	—	1.85
380	-0.15	-0.39	—	-0.27	1.49	1.97	—	1.73
390	0.48	-0.18	—	0.15	1.29	2.09	—	1.69
400	1.00	0.59	—	0.79	1.42	2.12	—	1.77
420	1.84	1.55	—	1.69	1.75	2.05	—	1.90
440	2.32	2.20	—	2.26	2.09	2.32	—	2.20
460	2.64	2.36	—	2.50	2.36	2.30	—	2.33
480	2.64	2.75	—	2.70	2.13	2.70	—	2.42
500	2.78	2.72	—	2.75	2.17	2.61	—	2.39
520	2.70	2.75	—	2.73	2.15	2.64	—	2.40
540	2.75	2.64	—	2.70	1.94	2.32	—	2.13
560	2.40	2.19	—	2.29	1.71	1.97	—	1.84
580	2.12	1.85	—	1.98	1.43	1.64	—	1.53
600	1.31	1.41	—	1.36	0.69	1.05	—	0.87
620	0.68	0.58	—	0.63	0.22	0.48	—	0.35
640	0.01	-0.09	—	-0.04	-0.40	-0.35	—	-0.37
660	-0.56	-0.41	—	-0.48	-0.95	-0.70	—	-0.83
680	-0.75	-0.71	—	-0.73	-0.36	-0.31	—	-0.34
700	-0.80	-1.00	—	-0.90	-0.41	0.07	—	-0.17