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SIMULATED LENS, MACULAR AND ILLUMINATION CHANGES AND THEIR EFFECTS ON COLOUR VISION

by

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ABSTRACT

Two experiments investigated the effects of pre-receptoral absorption and levels of illumination on colour vision. Simulation filters approximating lens and macular pigment changes were constructed on the basis of previous investigations. Experiment I investigated the effects of these filters on young, normal subject performance. Shifts were found in the direction of ageing populations but not as great as is required. Experiment II investigated the additional effect of reductions in illumination. The two experimental manipulations together account for senile decreases in discrimination at slightly higher levels than previously reported.

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INTRODUCTION

The aim of the present investigation is to physically and extraneously simulate changes in the absorption characteristics of the human crystalline lens and macula lutea and to look at the effects of prereceptoral absorption on hue-discrimination, color matching and possibly, color confusion. In addition, the effect of reductions and increases in illumination on various tasks purported to measure the aforementioned color vision parameters will be examined in an attempt to estimate the reasons for decreased color discrimination in the ageing population.

In order for the radiation man calls light to be recognized as such it must first transverse the ocular media and retinal lattice to excite the end-organs or photo-receptors. From the air-corneal interface to its ultimate absorption and transduction into nerve impulses, light is refracted and attenuated. The latter, attenuation, can be achieved through the absorption of light by matter or the scattering of light in directions other than that of the original incident ray. This attenuation can be, in terms of wave-length, selective or non-selective depending upon the characteristics of the media which the ray passes through. In the human eye, the two most widely studied of these media are the crystalline lens and the macula lutea region of the

central retina.[1]

CRYSTALLINE LENS

The third optic media which light must pass through on its way to the retinal photoreceptors is the crystalline lens. In the normal eye the lens is a biconvex, transparent, nerveless and vessel-free structure which is composed of 60-70% water, 6% fat and relatively more protein than any other tissue (Brown, 1965). The lens contains a slightly yellow pigment which has tentatively been identified by McEwan (1959) to be a urochrome like that isolated from urine and not melanin as previously thought.[2] Spectral transmission characteristics for the human ocular media were first attempted by Aschkinass in 1895.[3] His methods were reportedly inaccurate and as well the visible spectrum was entered only to the extent of 670 nanometers (nm), in the far red. His conclusion was that the ocular media resembled water in terms of its absorption characteristics. Up until about 1938, this was the general consensus when Ludvigh and

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1. Boynton and Clarke (1964) point out that the corneal structure accounts for a reasonably large proportion of scatter.

2. McEwan (1959, pp 146) states that the urochrome substance found in the lens is probably a non-specific degradation product of protein. This finding is consistent with the finding that the lens structure is protein rich.

3. As cited by Ludvigh and McCarthy (1938)

McCarthy (1938) published estimates of the ocular media and reported that "it is the lens which accounts for the major part of the selective absorption of the eye in the visible spectrum".[4] Unfortunately, Ludvigh and McCarthy did not publish results on the individual components of the ocular media and it was not until 1945 that Wald published absorption characteristics for human lenses. Weale (1954) objects to Wald's (1945) findings on the basis that the lenses may have reached an "unphysiological degree of cloudiness"[5] by the time the measurements were made. Weale (1954) reports lenticular spectral absorption curves which were based on two melanotomous eyes and therefore his data may have been unreliable.[6] The first successful and comprehensive measurements made in situ on a cross section of age-groups was made by Said and Weale (1959). Using a technique by which comparisons of the small but measurable amounts of light reflected at the various media interfaces, otherwise known as Purkinje images, the authors derived lenticular spectral absorption curves at six ages. Their results are shown in Figure 1. McEwan (1959) suggests that the pigment may increase in concentration with age. Mellerio (1971)

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4. ibid. pp 48

5. Said and Weale (1959)

6. Up until about 1950, all measurements were made in situ on extirpated lenses. Said and Weale (1959) report that F. Salomon (1950) made some of the first in vivo measurements.

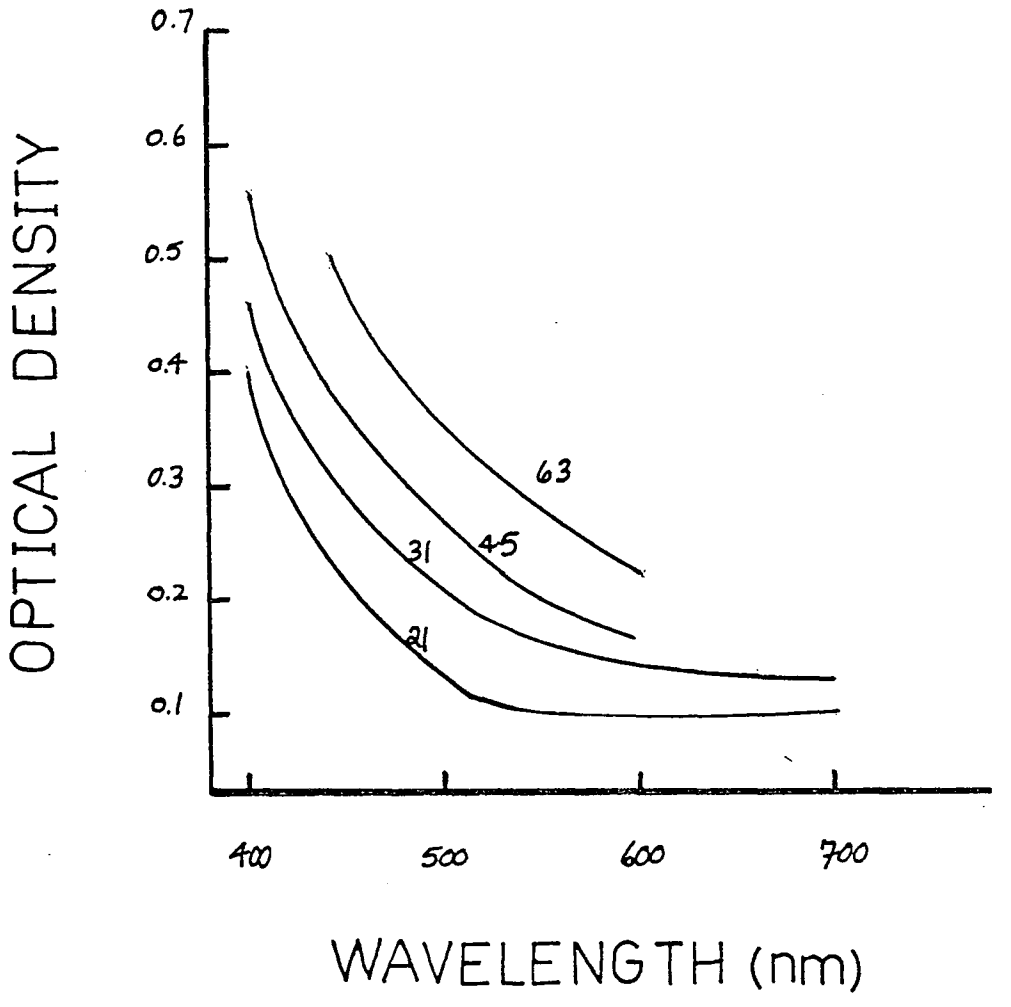

Figure 1 Spectral Absorption of Human Lenses as a function of age. from Said and Weale (1959).

suggests the attenuation of visible light through the lens by absorption and scatter[7] is due to a "hypothetical absorbing pigment", but because the light loss in the central 7-8 mm region remains constant between ages 20 and 60, the senile yellowing effect is seen as due to increases in lens thickness. Although in general agreement with this conclusion Weale (1961b) points out that this finding may be applicable to young and middle aged lenses only and not old lenses - which might have accumulated more dense pigment in the nucleus. Ruddock (1964) states that "it appears that the lens ageing, occurring without any accompanying changes in the receptoral response, can successfully predict the effect of age upon color vision".[8] He indicates that the scattering effect increases as a function of age and that this effect is analogous to the data obtained for color matching data. Ruddock (1964) further argues the scattering increase with age would help to account for the loss of visual acuity with age as well. Increases in scatter due to age effects are presented in Figure 2.[9] From the two preceding figures it can clearly be seen that the Lens pigment acts like a color filter, (i.e.

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7. When minute particles in a medium reflect light in a particular manner the light is said to be scattered. The Short wavelengths tend to produce more scatter than do longer ones. (see Riggs, 1965, pp 24) Mellerio does not state the relative contributions of absorption and scatter to the attenuation of light.

8. Ruddock (1964) pp. 191

9. ibid. pp. 137 (is an adapted figure)

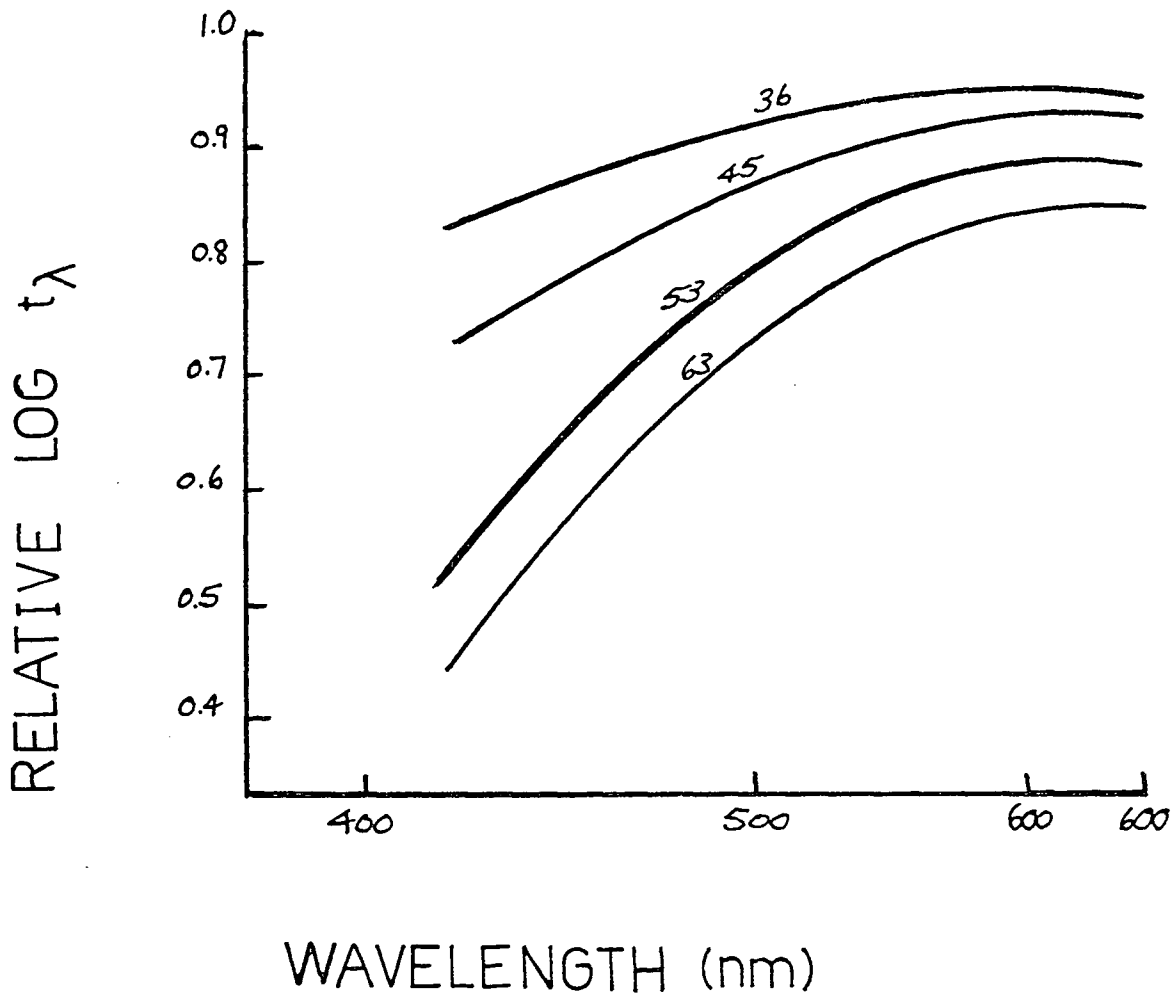

Figure 2 Estimates of Scatter in the Human Eye as a Function of Age. adapted from Ruddock (1964)

the color changes and the transparency changes at different wavelengths) and like a scattering filter of the Rayleigh-type, attenuating the short-wave end of the spectrum.[10] Ruddock (1972) reports that according to Vos and Boogaard (1963) light scattering 'centers' are not uniformly distributed throughout the lens volume and therefore scatter losses cannot be interpreted in terms of a uniformly distributed pigment. (Weale, 1961 (b))

THE MACULAR PIGMENT

The macula lutea is an area around and including the fovea centralis of about 3-5 mm in diameter. According to Ishak (1952) the macula lutea was first observed by Buzzi in 1682 and independently again by Soemmering in 1795. Soemmerring is reported to have observed the "macula pigment"[11] (according to Ruddock (1964)) and Gullstrand (1906) is reported (by the same author) to have identified the pigment as a carotenoid and, further, stated that it was a post-mortem effect. Hartridge, (1950) held the "post-mortem effect" viewpoint as well. Although some writers do not fully accept its existence in vivo (Trezona, 1970) there is a majority of

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10. Cooper and Robson (1969) point to the possibility of a second ultra-violet-absorbing pigment occurring in older lenses which would add to the general 'yellowness' of the lens color.

11. This may be a misinterpretation as a result of ambiguities in the thesis text. Soemmerring may have, in fact, only observed the macula lutea in vitro as the ophthalmoscope was invented by Helmholtz at a later date.

reports which do confirm its existence in the living human eye.

Xanthophyll's association with the oxidation process in plants plus the belief that the vascular retinal system at the foveal region appeared inadequate in and of itself, prompted Dartnall and Thompson (1949) to implicate the macular pigment in an oxygen-transport system to the foveal photoreceptors. Denton and Pirenne (1950) and Wald (1967) suggests that the macular pigment is an adaptive mechanism which serves to minimize chromatic aberration in the foveal region (region of the highest acuity) by absorbing much of the short wavelength light. Although the lens absorbs short wavelengths as well, the macular pigment 'peaks' in the 460 nm range whereas the lenticular pigment absorbs maximally closer to 400 nm.[12] Basically, two major types of evidence, albeit indirect, support the existence of the macular pigment in vivo.

(a) The comparison of foveal and para-foveal spectral sensitivities, and;

(b) entoptic color perception of Maxwell's Spot and the Haidinger Brushes.

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12. Wyszecki and Stiles (1967) use 403 nm as their reference point for the lens absorption and 455 nm for the macular pigment absorption.

A. COMPARISON OF FOVEAL AND PARAFOVEAL SPECTRAL SENSITIVITY

Wald (1945) extracted the pigment from a small number of human maculas and subsequently identified it as "a hydroxy-carotenoid or xanthophyll, in all probability lutein or leaf xanthophyll itself".[13] Wald further obtained psychophysical data based on comparisons of foveal and parafoveal 8^{o} spectral sensitivity and adjusted the optical density of the macular xanthophyll to fit this data.[14] The estimate of the macular pigment from both these findings is presented in Figure 3(a). Ishak (1952) investigated the macular pigment densities of 15 Egyptian subjects and noted that their average values were higher than those reported by British, American and German observers. His results and the investigations of others reported by him are present in Figure 3(b). Ruddock (1963) published estimated macular pigment densities of two observers. His estimate is based on his own visual system and is reproduced in Figure 3(c). It is to be noted that his second observer has almost no macular pigment according to the data presented, yet (Ruddock 1972 (b)) fundus reflectometry data estimates the densities to be equal in both

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13. Wald (1945) pp. 657

14. Wald (1949) tried to interpret the increased peripheral sensitivity to the blue-end of the spectrum as the absence of macular pigmentation. Weale (1953) suggests however, that the noted increase in blue-sensitivity may be due to improvements in the sensitivity of the peripheral photo-receptors.

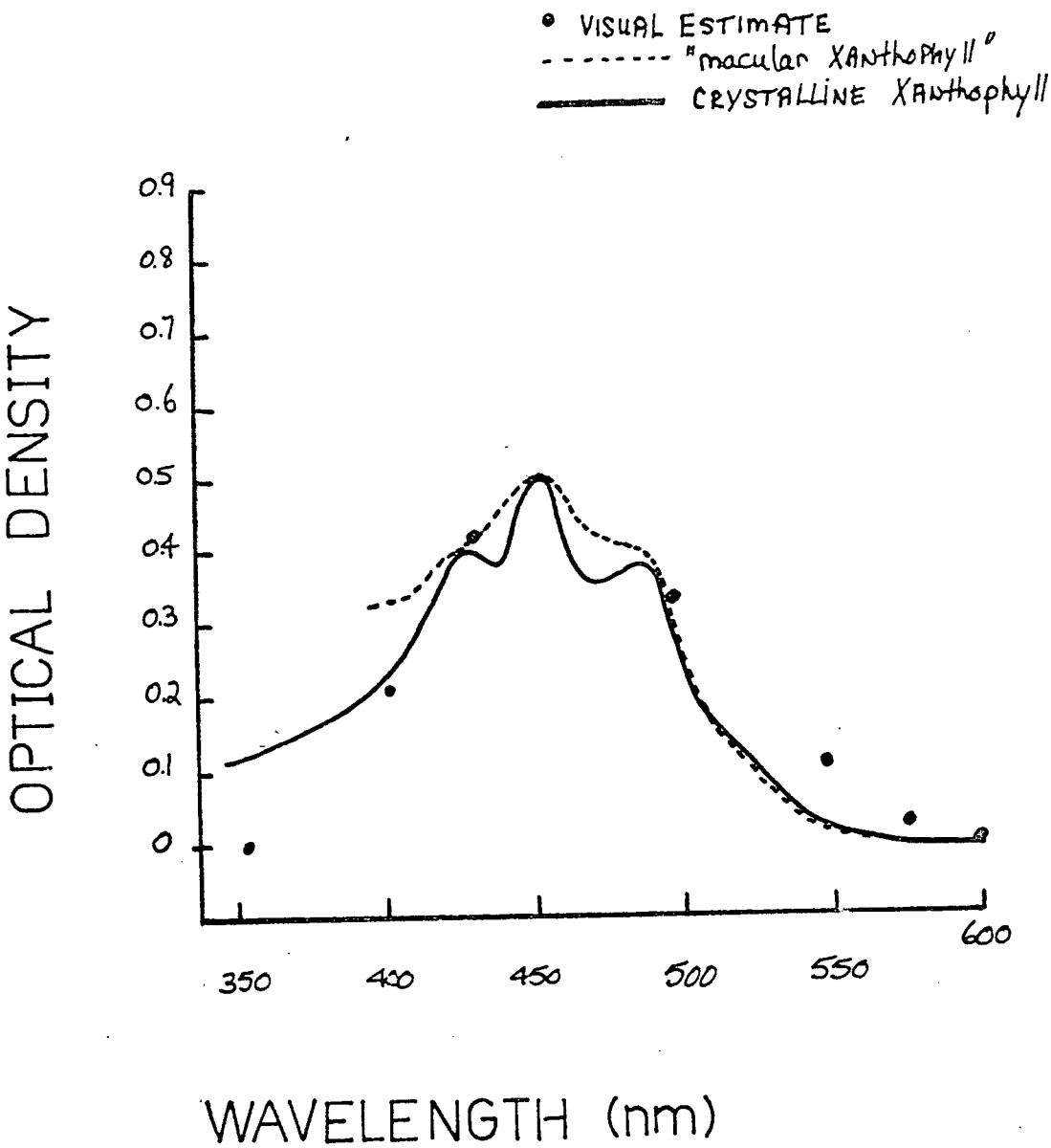

Figure 3a Wald's (1945) Estimate of the "macular pigment".

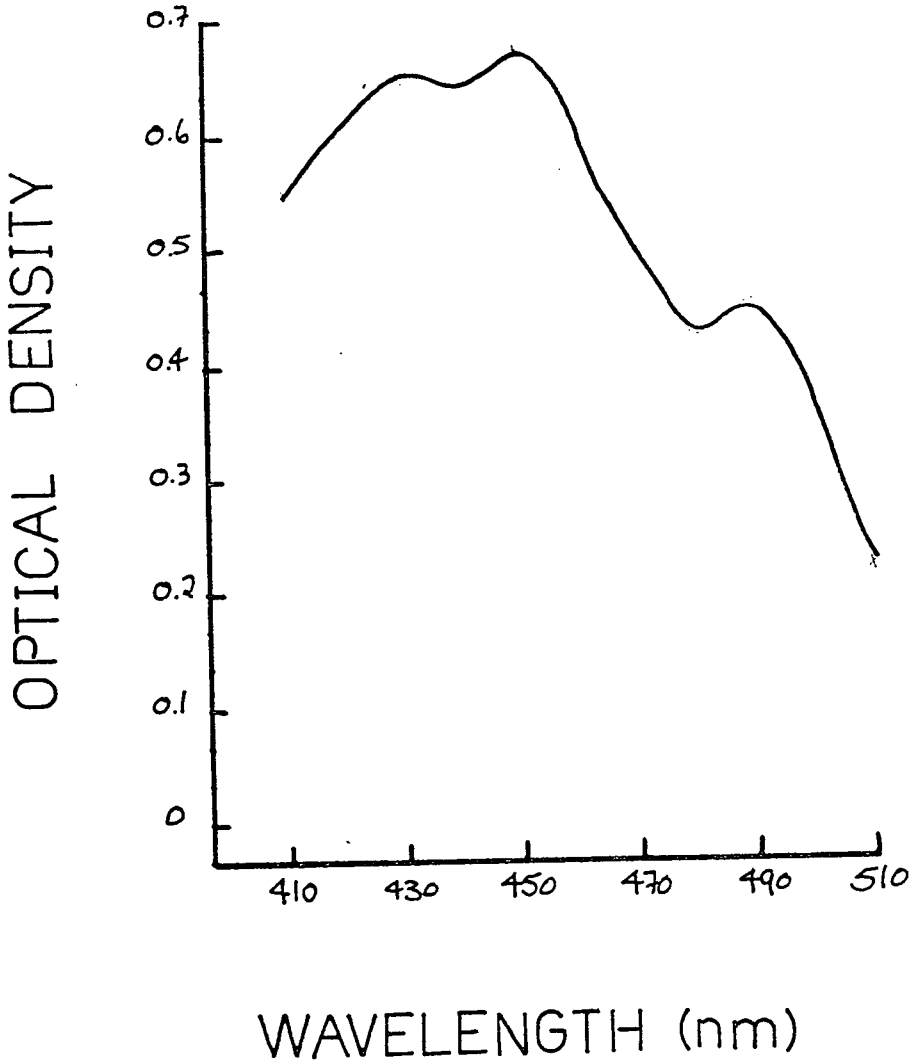

Figure 3 b Ishak's (1953) Estimate of the 'macular pigment'.

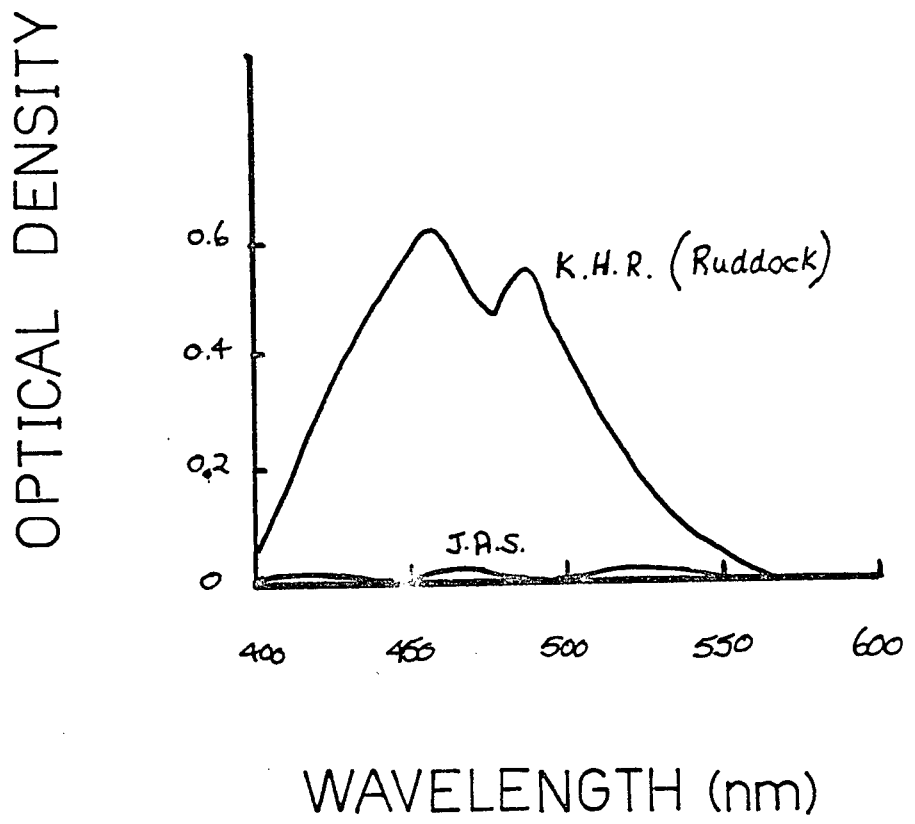

Figure 3c Ruddock's (1964) Estimate of the 'macular pigment'.

observers. Bone and Sparrock (1971) report a rather comprehensive study which include macular pigment estimates of 49 observers. Their comparisons are included in Figure 3(d + e). Groups contrasted in the latter study included those of Table I. From their investigation it appears as if darkly pigmented peoples tend to have slightly more macular pigment than do lightly pigmented people.[15]

B. ENTOPTIC COLOR PERCEPTION OF MAXWELL'S SPOT AND THE HAIDINGER BRUSHES.

The second major method of estimating the macular pigment is with the use of entoptic phenomena. If for example a subject views a uniform field (which is illuminated by a continuous source) alternately through a non-selective grey filter and a purple gelatin filter (transmitting only near the short-wave (blue-violet) and the long-wave (red) ends of the spectrum) he will most likely notice a spot subtending about $3\text{-}4^{\circ}$ about the fixation point of respect. This spot was first described by Maxwell who interpreted it as due to decreased effectiveness of blue light in stimulating the cones of the foveal region because if its absorption by the macular pigment.

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15. One notable exception as seen in Table I is of the red-haired versus non-red-haired comparison. The named authors are reportedly investigating this finding further because of the small number of subjects.

Table I

Variations in Pigment Density for Different Groups

(from Bone and Sparrock, 1971)

Wavelength	East Indian	Non-East Indian	Red haired	Non-red haired
400	0.49	0.35	0.54	0.34
410	0.52	0.38	0.57	0.36
420	0.53	0.40	0.62	0.39
430	0.59	0.44	0.66	0.43
440	0.63	0.48	0.71	0.46
450	0.68	0.52	0.74	0.50
460	0.69	0.52	0.73	0.51
470	0.64	0.49	0.68	0.48
480	0.56	0.44	0.63	0.43
490	0.46	0.36	0.52	0.35
500	0.36	0.28	0.41	0.27
510	0.29	0.22	0.32	0.21
520	0.21	0.16	0.24	0.16
530	0.16	0.13	0.19	0.12
540	0.12	0.10	0.14	0.09
550	0.08	0.07	0.09	0.07

Table I

Variations in Pigment Density for Different Groups (from Bone and Sparrock, 1971)

Wavelength (nm)	Age Over 30	Age Under 22
400	0.34	0.36
410	0.37	0.38
420	0.41	0.41
430	0.43	0.44
440	0.48	0.48
450	0.52	0.51
460	0.53	0.52
470	0.49	0.48
480	0.45	0.43
490	0.35	0.36
500	0.27	0.28
510	0.22	0.22
520	0.16	0.17
530	0.12	0.14
540	0.08	0.11
550	0.06	0.08

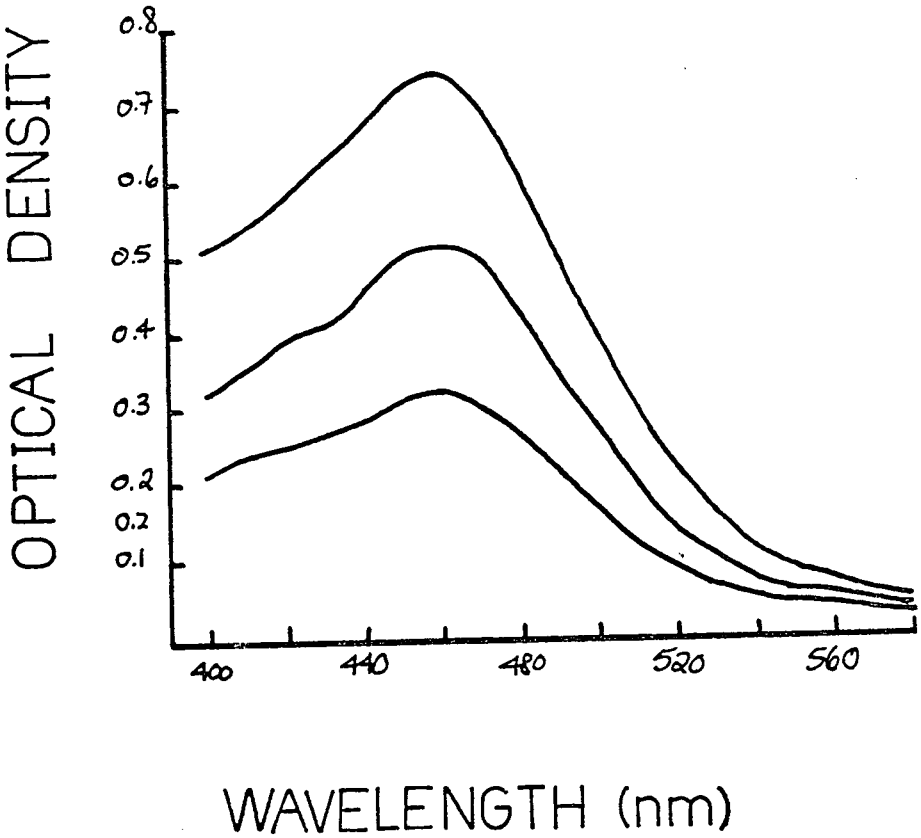

Figure 3d Bone and Sparrock's(1971) 3 densities of estimated 'macular pigment'.

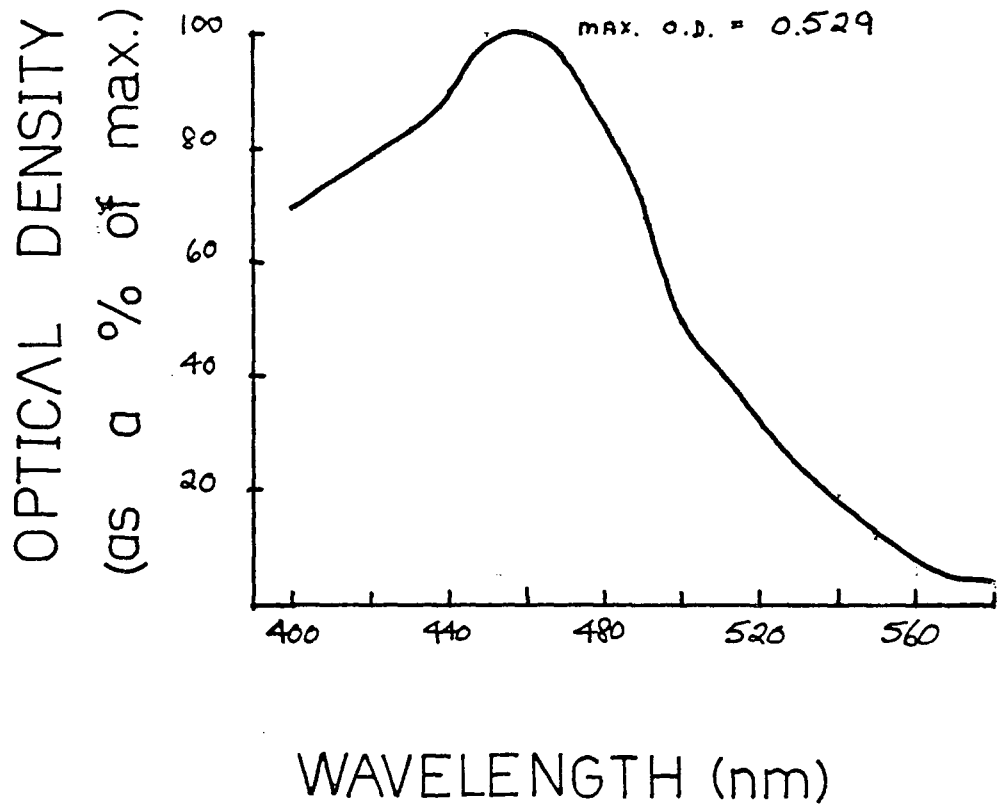

Figure 3 e Bone and Sparrock's (1971) Average estimate of the 'macular pigment'.

Judd (1953) reported:

According to the assumed three-components theory the macular pigment should be visible entoptically by means of the walls purple filter and a non-selective grey filter of about one percent transmittance used alternately even though there is no difference between macular and extra-macular receptors either as to population density, as suggested by Walls, or as to spectral sensitivity apart from difference introduced by the macular pigment itself...

and:

To explain Maxwell's Spot, there is no need to assume the existence of macular receptors having spectral sensitivities or population densities which are different from those of the extra-macular receptors. On the other hand, this analysis leaves open the possibility that such macular receptors do exist and contribute to Maxwell's Spot.[16]

Although Judd did his analysis on the standard observer (which is based on real observers but not real itself) his results indicate that the Maxwellian spot is an entoptic perception of the macular pigment.[17] Judd used Wald's (1945) estimates of the macular pigment for his analysis and did not estimate a density with real or theoretical observers.

Ruddock (1965) points out that:

the Maxwell-spot effect is associated with wavelengths at which the macular pigment is expected to absorb. It is not seen by observers who, from consideration of color matches in the fovea and parafovea, would be classified as non-pigmented. When a plane polarizer is rotated before the observer's eye, the maxwell spot breaks up into a form typical of Haidinger's brushes. The brushes ... are similar in color to the usual Maxwell spot, whereas the intervening space appears the same as the surrounding field. This breakdown of central uniformity in polarized light supports

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16. Judd (1953) pp. 20

17. This is a confirmation of Maxwell's own report according to Judd (1953).

the theory that the nonuniformity itself, and hence the associated changes in color matching, is due to light losses which occur prior to visual excitation. The observation also links the Maxwell-spot and Haidinger brush phenomena.[18]

Trezona (1970) feels that the macular pigment is not needed to explain Maxwell's spot:

Light is absorbed by the rods most effectively in the blue-green, this gives a blue sensation in the periphery and the fovea appears yellow simultaneous contrast.[19]

In fact Trezona's argument extends to practically all of the evidence in support of the macular pigment. The Haidinger "brushes" or Haidinger effect was used to estimate the macular pigment extant in human subjects by DeVries, Spoor and Jiellöf(1953). However, they used a larger test field than contains the macular pigment[20] and thus their results are open to criticism along these lines. Naylor and Stanworth (1954) used 1^{o} field for stimulation to produce the effect.[21] They calculated their results ON THE PREMISE that the macular pigment was responsible for the effect. They found that, as opposed to calculating information on the premise that the orientation of blue receptors was responsible, the data best fit the former interpretation.[22] They concluded

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18. Ruddock (1965) pp. 1180

19. Trezona (1970) pp. 330

20. or as an alternative hypothesis would have it, the orientation of blue-receptors

21. DeVries et.al. (1953) discuss the reasoning for the Haidinger effect.

22. In an earlier paper, Stanworth and Naylor (1950) stated that the latter was the cause of Haidinger's effect.

that the Haidinger effect was caused absorption of light by the oriented macular pigment. Their estimate of the oriented pigment is in Figure 3(f). Naylor and Stanworth state tenuously that their macular pigment curve corresponds with that of Xanthophyll but that its positive identification cannot be considered certain because of an additional maximum absorption at 515 mm and anomalies in Xanthophyll's peak absorption point with different solvents.[23] The macular pigment has also been implicated in the Haidinger brush effect by Sloan and Naquin (1955). Because of the difficulty in interpreting the results, Wyszecki and Stiles (1967) and Ruddock (1972) have suggested less weight be placed on estimates of macular pigment density made by use of the entoptic phenomena.

INCREASES IN THE MACULAR PIGMENT DUE TO AGEING

Stiles and Burch (1959) indicate that the macular pigment density increases as a function of the age of the observer. By noting observer variations in the results of their 10° color matching investigation a correlation with age was found. Because not all of the variance could be accounted for in lens pigmentation increases as a function of age, they suggested that the macular pigment might increase with age

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23. According to my data on solvents for xanthophyll, chloroform produces a peak at approximately 455 nm while other solvents (such as ethanol 98% and acetone) shift this peak as much as 10 nm.

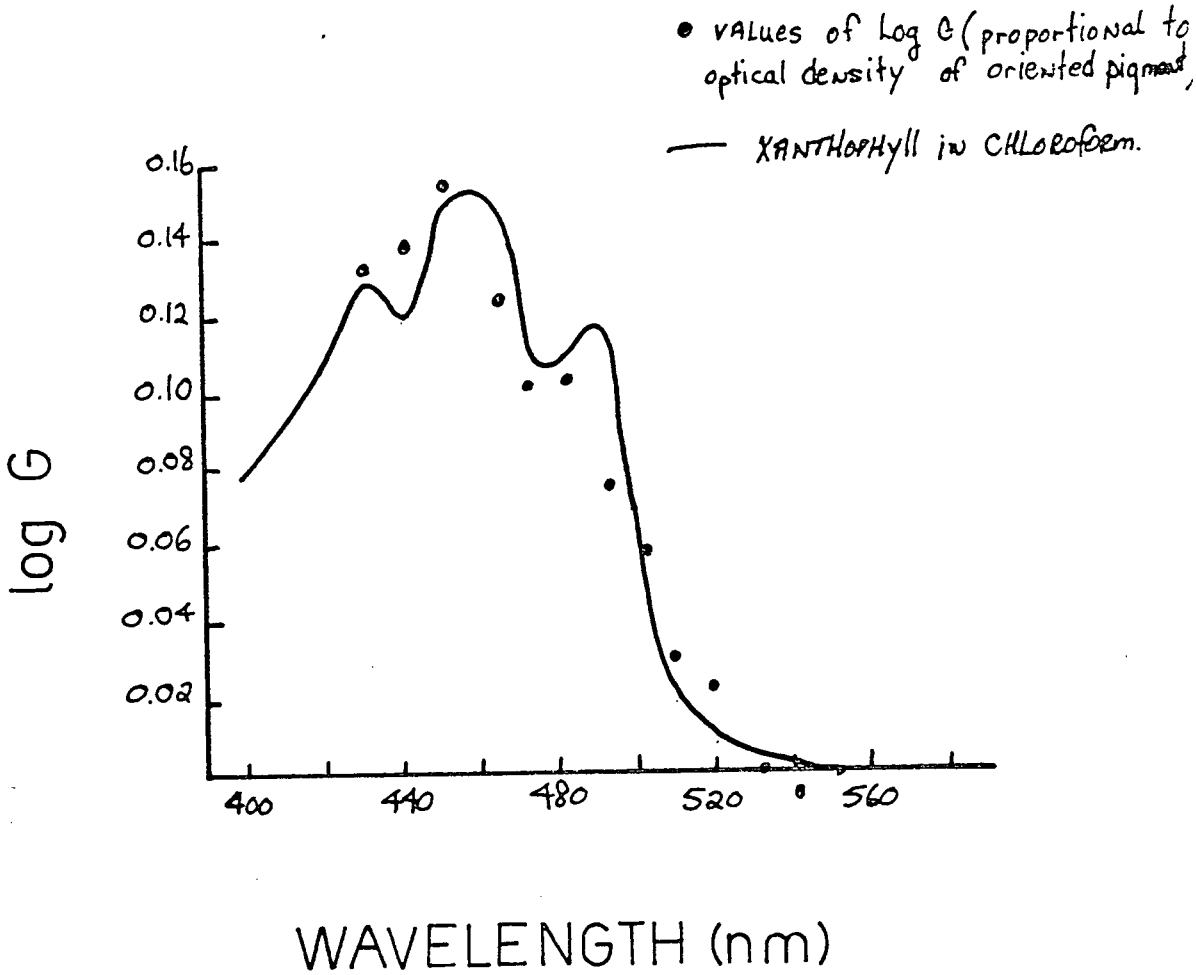

Figure 3f Estimate of the macular pigment by Naylor and Stanworth (1954)

also.

Warburton (1953) came to a similar conclusion based upon the variations in the matches of illuminant 'B' (expressed as a color temperature) made by two groups of observers. The first group aged 16-25 years matched the stimulus closer to illuminant 'C' whereas the second group aged 56-65 years matched the stimulus near illuminant 'A'. Warburton interpreted this difference in terms of increases in macular pigment density. Bone and Sparrock's (1971) data indicate a very slight upward trend in the over 30-under 22 age contrast but do not include information with respect to these two groups as to the total age differentials examined. Wright (1946), Weale (1963) and Ruddock (1965) have found no significant increase in macular pigment density with observer age. The latter investigator found that age changes in color matching data correspond closely to the calculated changes in LENS absorption. Ruddock (1972) points out that the macular pigment cannot account for all of the difference between the C.I.E.[24] 2^{o} and 10^{o} color matching functions and therefore, some receptoral response differences must be included.

COLOR VISION TESTING

The measurement of the so called normal/abnormal dimen-

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24. Commission Internationale d'Eclairage otherwise known as the International Commission on Illumination.

sions of color vision have taken three characteristic forms: (a) color matching (b) hue discrimination and (c) color confusion.[25]

(a) COLOR MATCHING

There are two general methods of color matching. Firstly, a moveable set of samples can be matched to another fixed set which exhibit a one-to-one correspondence. (An example of this type of method can be seen in the ISCC Color Aptitude test (1953)). Secondly, two colors can be matched for hue saturation and brightness even though they a re composed of different spectral characteristic. METAMERIC MATCHING makes use of this fact.. Additive or subtractive mixtures of light can be made to match just about any spectral color, including non spectral purples. Additive metameric matching for color vision testing can be achieved by the use of a simple additive colorimeter known as an anomaloscope,[26] while subtractive metameric matching can be achieved by the use of a subtractive colorimeter such as the tintometer.[27] The most common meta-

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25. The last form can be seen as an attempt to separate the human population into two firstly, two groups; normal and defective color vision, and further, this last group into subgroups according to the color confusions which they exhibit.

26. As a particular make and model of this instrument is used in the present investigations, it will be discussed later.

27. The Lovibond Schofield Tintometer is a subtractive visual colorimeter which is in wide us in industry for specification of color. It requires a fairly specialized observer and proper methodology to maintain consistency.

meric in use for diagnosis of color vision defectives and research into color vision parameters in general, is the Rayleigh match.[28] By the additive mixture of red and green light one can produce a yellow light which can be matched to another "pure" yellow light. If the two "yellows" match to a particular observer, the two are defined as a metameric pair. Now in the normal population there is a range of ratios (i.e. amount of red to amount of green) that will produce a yellow which is accepted as matching the pure yellow. Extreme increases or extreme decreases in this ratio are stimulus parameters which helpful in defining and diagnosing red-green color defective observers. As well as the Rayleigh equation, other metameric matches are presently employed in research, notably the yellow-blue equation and the blue-green or violet/blue-green equation. Lakowski (1971) points out that any number of other equations could be used. Presumably, the Rayleigh, yellow-blue and blue-green equations are useful in determining the normality/abnormality of observers who fall into the historically defined color defect classifications.

(b) COLOR DISCRIMINATION

As opposed to matching of colors, color discrimination requires the observer to note the emphasis of differences and

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28. Named after Lord Rayleigh noted English physicist in the 19th Century..

not just similarities. Two basic methods are employed at present. Wavelength discrimination involving spectral color is generally carried out with the use of several monochromators or double monochromators which present a comparison for the observer. In much the same way as the anomaloscope is used, the observer is required to note similarities and differences in the two stimuli presented. The data however, is usually interpreted in terms of just noticeable differences in color or as a difference threshold for color plotted as a function of wavelength. Another method of determining color discrimination parameters is the use of the Farnsworth-Munsell 100-hue test. The test is composed of 85 moveable caps, each containing a separate Munsell color. The test is divided into four boxes or series each containing about 21 caps. There are two fixed caps in each box which represent the ends of the so-called continium of colors contained in the box. In each box the caps can be arranged in a CORRECT (perfect) order in which case the box score = 0. The degree to which the caps are displaced out of this correct order increases the score received. A useful part of the scoring procedure of this test is that score of each cap can be graphed in a polar configuration. The resultant figure can be glanced at by an experienced tester and the degree of normality/abnormality on its characteristics can be quickly determined. Several authors have published population and age norms for the 100-

hue test and these are summarized by Lakowski 1969 (b)

(c) COLOR CONFUSION

Color confusion tests can be used to determine the extent to which an observer deviates from normal color vision. Lakowski 1969 (a) differentiates between color discrimination and color confusion thus:

> Normal observers are capable of distinguishing a large number of colors whereas according to some authorities the dichromat's color world is limited to less than 30 discriminible hues. These subjects confuse colors that are easily recognizeable by the man in the street. If someone mistakes one primary color for another we use the term color confusion to indicate the gross nature of the mistake, but for those whose losses are less extreme we talk about poor color discrimination, recognizing that there are wide variations in this ability.[29]

Generally, there are a set of tests which only dichotomize those who confuse colors from those who do not. These are called Pseudoisochromatic plates (PIC plates) and generally consist of a figure-ground pattern in a set of colors which are confused by a certain classification of color defective observers. The Ishiliara PIC plates, for example, use numbers, on a circular background. The entire pattern is composed of circles of various sizes - the figure being composed of one particular colored or group of coloured circles that could be confused with the background. Normal subjects see the figure-ground relationship whereas defectives do not. One difficulty in interpreting these tests as pointed out by

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29. Lakowski 1969 (a) pg 186.

Lakowski (1964) that the figure can sometimes be discerned on the basis of brightness cues and not just color cues. These tests are generally considered useful only for screening and testing of gross defects.

> A confusion test based on the 100 hue test idea was developed by Farnsworth (1943) called the Farnsworth Dichotomous Test or Panel D-15 is useful for gross measures like the PIC plates. Again as in the 100-hue test the scoring pattern can be diagrammed and visual estimate of defects readily made.

It can be seen that the aforementioned tests in (a) and (b) can also be used for investigating color confusion. In general, because of the relatively short period of time required to test each subject, the 100 hue test, the anomoloscope, and the PIC tests are most often used.

COLOR VISION AND AGEING

According to Gilbert (1957) and Lakowski (1964), the first major studies of the effects of ageing on color discrimination were done in the early 1940's. Tiffin and Kuhn (1942) investigated the color discrimination of factory workers and noted progressive deterioration ability to discriminate colors between the ages of 25 and 55 years. Smith (1943) however noted no strong trend to deterioration of color discrimination with age until over 65. As a response to Tiffin and Kuhn's findings (Lakowski, 1964 pg. 57.) Boice, Tinker and Paterson (1948) found no significant deterioration due to ageing between 20 and 59 years - neither did Chapanis (1950). However, Chapanis reported several earlier studies pointing to the

tendency of older subjects to have greater difficulty with blue-green, blue, and violet discrimination. These earlier authors stated that the yellowing of the lens with age may play a role in the discrimination of the blue-end of the spectrum by acting like a minus-blue absorption filter (Gilbert, (1957)). Lakowski (1964) reports that Ouellette (1955) found age differences in color discrimination between two groups aged 20-30 and 75-85. However, Ouellette's differences in color discrimination extended to red, yellow and green as well as blue (Gilbert, 1957). Stiles and Burch (1959) noted changes in color matching with age and along with Warburton (1953) attributed part of these changes with changes in the macular pigment density as well as the lens transmission characteristics. Wright (1952) also points out that elderly observers may exhibit some of the characteristics of tritanopia on account of yellowing of the eye media and the macular pigment.[30]

EXPERIMENTAL PRODUCTION OF DECREASES IN COLOR DISCRIMINATION CAUSED BY HYPOTHETICAL AGEING PROCESSES.

Several investigators have attempted to reproduce the characteristic decreases in color discrimination observed in various ageing studies. In general, the experimental variables include attempts at estimating the ocular transmission characteristics and macular pigment density required

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30. Wright (1952) pg 510

to produce color discrimination of the order noted in ageing observers. Lakowski (1962b) investigated the effects of increases in the selective absorption of both lens and macular pigments on younger subjects, and made comparisons to the data of older subjects. His design entailed the placement of minus-blue color filters over the observer's eyes and testing their matching ranges on the three anomaloscope equations (mentioned in an earlier section). Figure 4 is the absorption characteristics of the Ilford filters as reported by Lakowski (1962). Although the filters are supposed to compensate for the difference between the 21 year old subjects and the values reported for older observers, the curves indicate that the approximations are all over-estimated by the Ilford series filters. Even so, Lakowski reports that only the two most dense Ilford filters (106 and 109) produced anomaloscope matching responses in the 21 year old subjects which were comparable to the best scores on the same measure of the last two age groups (56-65 and 66+). He further points out that it required a filter with density characteristics of the order of twice the estimated values of Said and Weales's (1959) olders subject's lens. This result was interpreted as indicating that further absorptions may be required in the experimental lenses of young normal observers in order to account for the changes found in aged subjects. Because the addition of the macular pigment density (estimated by Wald

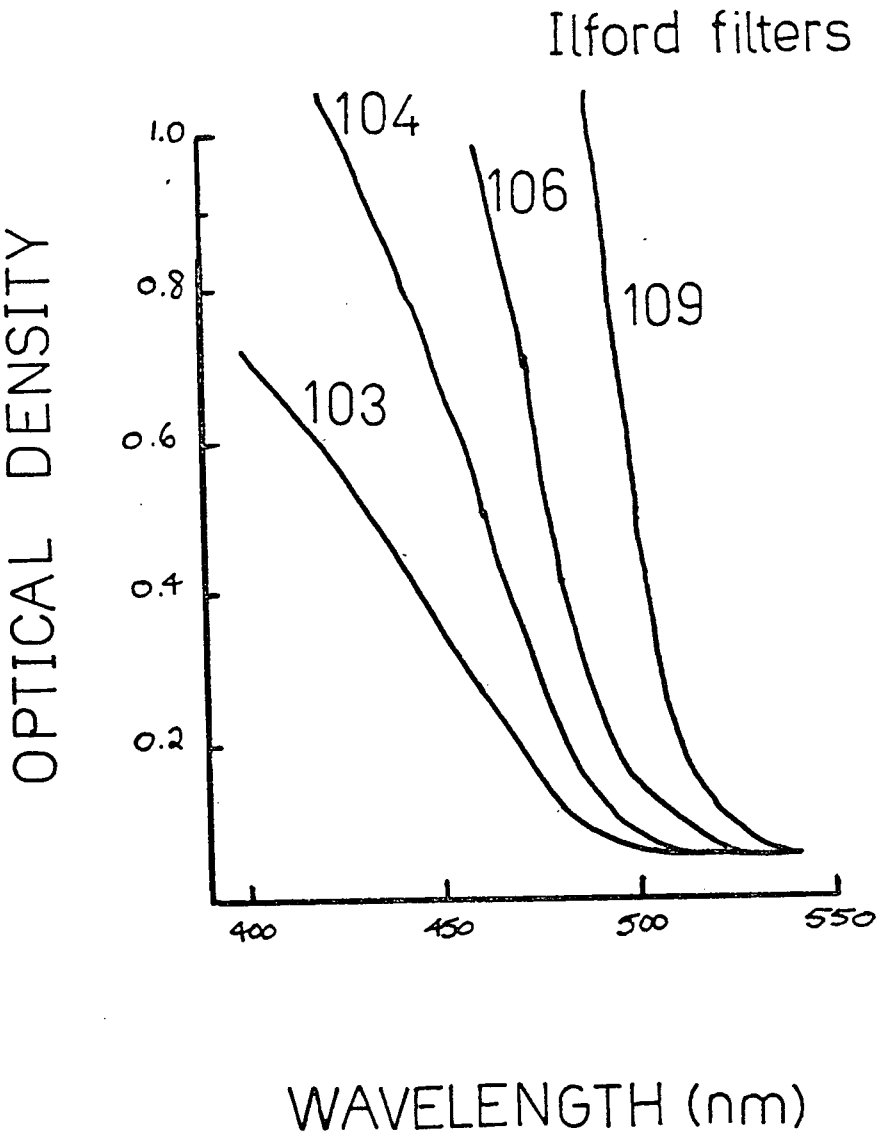

Figure 4 Experimental simulation filters used by Lakowski (1962)

for a 60 year observer to be 1 optical density at 460 nm) would increase the curve characteristics to be closer to the densest Ilford filters, Lakowski concluded that not just the lens medium or the macular pigment but at least both were needed to explain color vision losses as a function of losses in transmission through the optical media and macula:

> In the normal group we noticed that age has effects on the way people discriminate colors. There is a gradual loss of fine discrimination and there also seems to be an increase in the incidence of people whose performance is like that of major defectives. The general picture that this group presents in terms of the typical changes as subjects get older, could be explained PARTLY by the reported increases in optical lens densities plus the increase in macular pigmentation that is so often postulated. Some matching patterns however, are too 'bizarre' to be explained in terms of such ocular changes alone.[31]

It was also pointed out in this same paper that lens changes could 'quite safely' account for deterioration in color discrimination but that greater values at the violet end of the spectrum would need to be postulated in order to account for the lens as being the ONLY factor involved in the observed deterioration due to age.[32]

Verriest (1963 (a)) made use of a group of filters resembling values which increase in transmission from

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31. Lakowski (1962) pg 84.

32. ibid. pg 85.

approximately 5 times the value of the ocular media as calculated by Ludvigh and McCarthy (1938).[33] He also used an extreme minus-blue filter which absorbed virtually all wavelengths below 500 nm. The filter characteristics are shown in Figure 5. Subjects were examined on a battery of color vision tests including AO H-R-R pseudo-isochromatic plates, 100 hue, panel D-15 and (Rayleigh match) plus Trendelenburg's Tritan match and violet-blue/green equations with the Nagel Anomaloscope.[34]

Unfortunately, Verriest did not attempt to account for learning effects by counterbalancing the order of presentation[35] and the sequence of filters worn and therefore the results reported may not truly represent the effects of the experimental filters reported. Verriest reports matching ratios for equations requiring short-wave-lengths are generally weighted towards the blue filter of the pair. This finding is understandable in terms of the physical properties of the experimental filters, i.e., they absorb blue light. Further, the matching ranges are enlarged, according to Verriest, especially in the Trendelberg match (Tritan match) using the denser filters, and for the K filter no match was possible.

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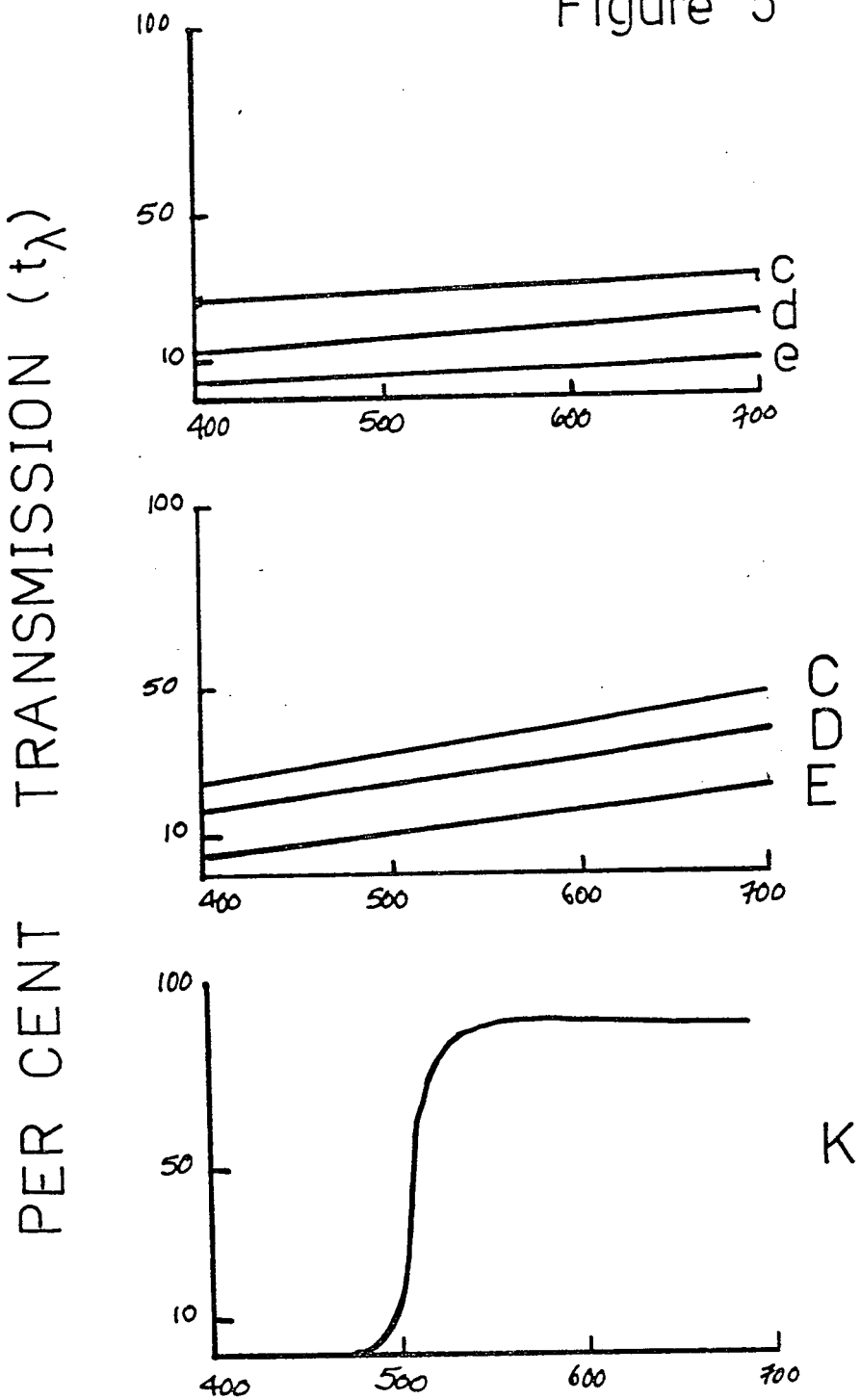
33. As reported by Judd, Plaza and Farnsworth (1950).

34. See section on the anomaloscope.

35. Aspinall (1968)

Figure 5



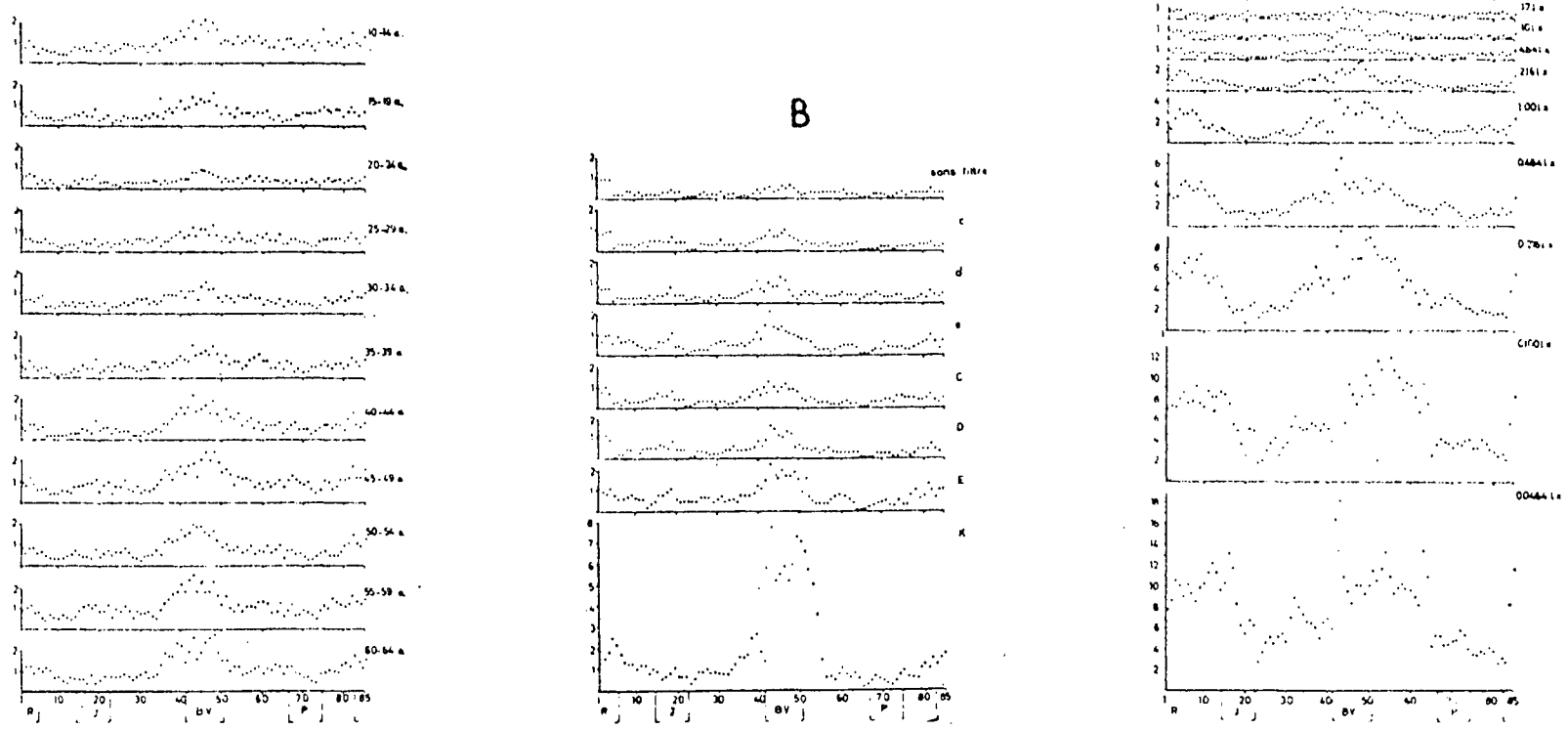
Verriest (1963) Experimental filters.

FIGURE 6

A

B

C



Age groups.

Yellow filters.

Illumination levels.

100-Hue

Mean Partial Error Score Plots.

(Verriest et al.)

In addition, the experimental filters produced detrimental effects in color discrimination, as measured by the 100 hue test, mainly in the regions of the blue-green and red hues.[36] A tritanopic characteristic was only observed when the extreme minus-blue filter "K" was used with the Panel D-15 test or AO H-R-R Plates, or under severely reduced illumination. In a related study, Verriest et al. (1963 b) report that normal subjects become wholly tritanopic at 0.216 Lx. The results of reduced illumination upon 100 hue scores for 25 normal subjects aged 20-24 under illuminant 'C' are presented in Figure 6. Effects of pupil size should be taken into consideration according to Weale (1961)[37] who postulates that absorption characteristics of lens increases at the centre of the lens due to increases in the optical path length (Bouger's Law). Verriest stresses this factor as one of possible importance in accounting for the ageing population parameters of color vision.

Aspinall (1968) investigated the effects of simulated macular changes on the 100 hue test. As with Verriest, one of the experimental filters used by the author was extreme. Figure 7 shows the spectral densities of the macular simul-

36. Verriest points out that of the two regions, the blue/green region is effected more than the red (1963) pg.188

37. ibid. (1963)

ation filters used by Aspinall in the above mentioned study. He did not note the xanthophyll solvent.[38] His illumination levels were calculated to be in accordance with the reported levels of Verriest's C and E filters and in using three densities of xanthophyll had six experimented conditions plus a baseline measure on all subjects. With the experimental filters on young normal eyes Aspinall found a shift in the expected error axis, due to ageing of observers, about five or so caps clockwise. Verriest's data on this point suggest a shift in the same direction although not as large at the red end as reported by Aspinall. A small error 'bulge' increased with increasing filter density at cap 25 as well. Test experience is purported to play a role in the results and Aspinall analyzed the differences between experienced and inexperienced subjects. He found that experienced subjects performed generally better in all conditions than did inexperienced subjects and, that as all apparent luminosities are the same, the differential effect of the experimental filters must be due to differences in the spectral characteristics of the filters. Further analysis of the data led the author to report significant differences for both luminosity and filter absorption changes but that "increased filter density is more detrimental to 100 hue performance than reductions in luminosity". The

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38. As has been noted earlier, the peak absorption may vary as a function of the solvent but, it appears from the data presented by the author that chloroform was used.

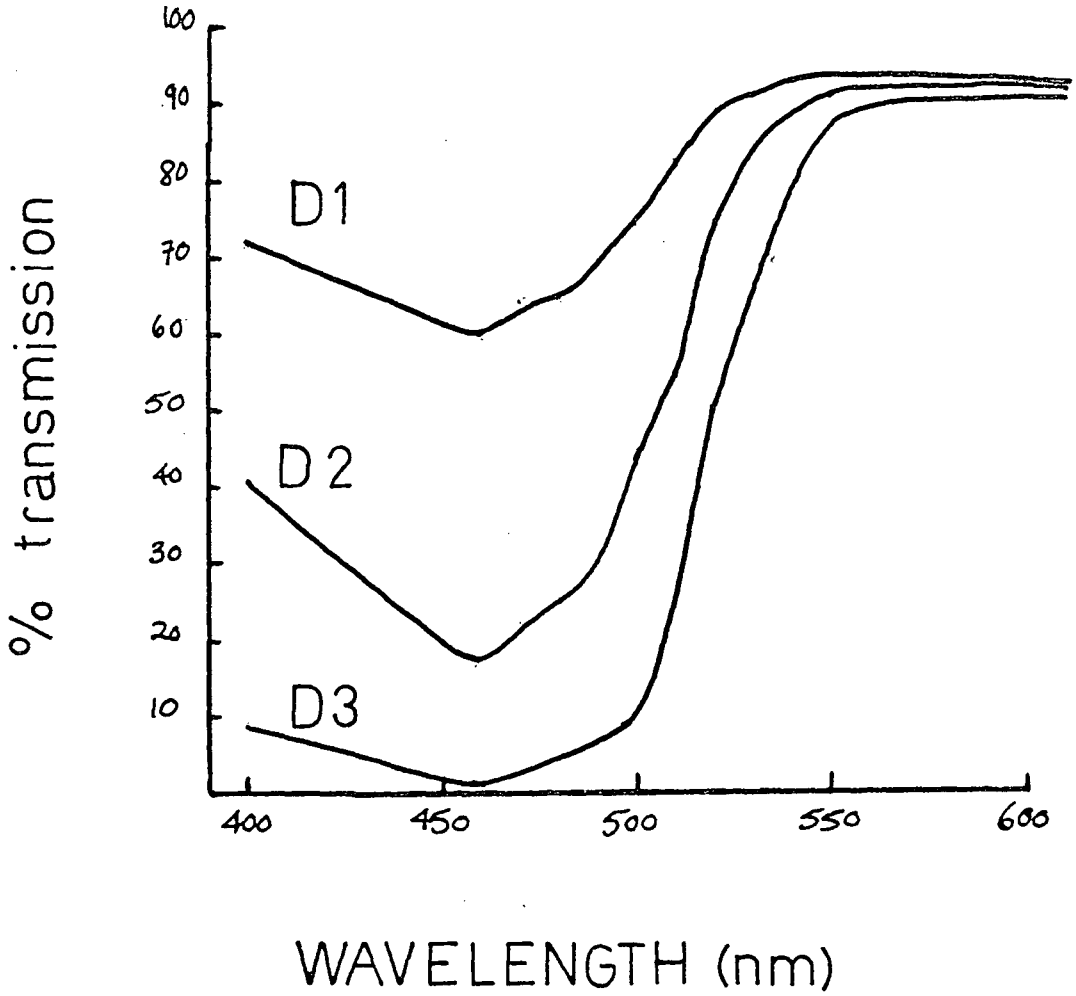

Figure 7 Aspinall's (1968) Experimental simulated Macular Pigment filters (Xanthophyll in Chloroform).

conclusion stated here is understandable in view of the extreme concentrations used in the experimental filters.

SUMMARY AND PROPOSAL

It can be seen from the preceding review that (a) there is evidence for the existence of both macular and lenticular pigmentation in the human eye and (b) that these pigments affect performance on color vision tests. Further, it can be postulated from a reasonably large amount of comparative and experimental evidence that one or both of the pigments increase in vivo with age and, along with reductions in retinal illumination (either as a result of these increases or due to pupillary changes etc.) contribute to the observed deterioration of color vision with ageing. Experimental approximations of these two pigments have not been as accurate as possible in view of the psychophysical and physiological evidence accumulated for their existence and, as these approximations affect the interpretation of results in terms of there generalizability to human ageing processes, a higher degree of accuracy might be desirable.

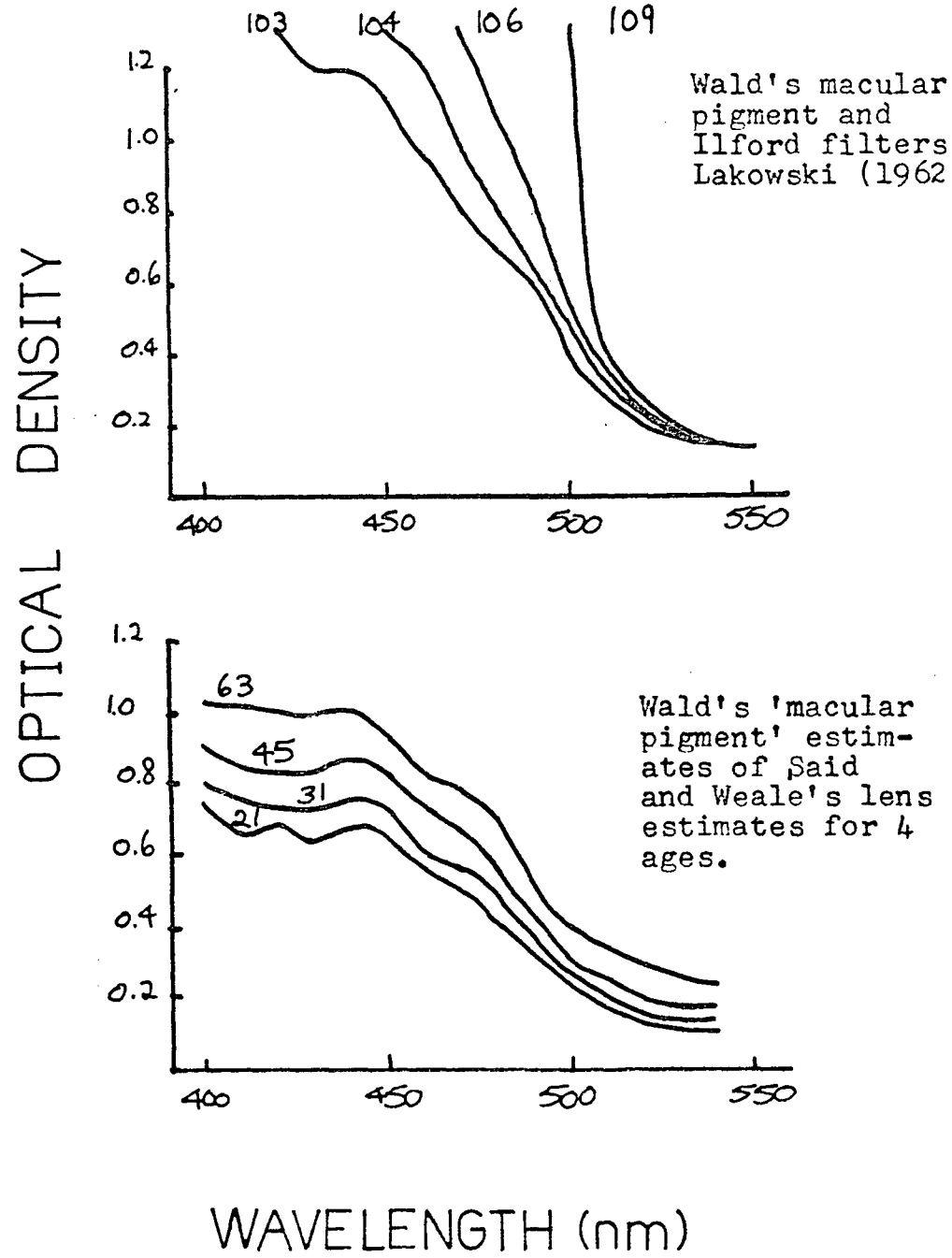
103
104
106
109
1.2
1.0
0.8
0.6
0.4
0.2
400
450
500
550
Wald's macular pigment and Ilford filters Lakowski (1962)
OPTICAL DENSITY
63
45
31
21
Wald's 'macular pigment' estimates of Said and Weale's lens estimates for 4 ages.
WAVELENGTH (nm)

Figure 8

EXPERIMENT I.

The present experiment was based upon the Lakowski (1962), Verriest (1963) and Aspinall (1968) studies although numerous modifications were instituted in line with the experimental aims presented above. The author attempted to simulate the lens and macular absorption characteristics separately, based upon the reports of various authors covered earlier, and study their effects upon performance of several color vision tests.

APPARATUS

The Lens Simulation Filters

The lens approximation filters were based upon the characteristic age-dependant curves as reported by Said and Weale (1959). Compensation filters were constructed using the 21 year-old's characteristics as a baseline. Quartz cells,[39] designed to fit a spectacle-like lens holder were filled with a colored liquid designed to approximate the lens pigmentation. The method of deriving the densities of this solution is as follows: Firstly, two stock solutions of extreme density (1.50 Optical Densities at 403 nm) were made up from two commercially available water-soluble dyes:

Polar Yellow 2G conc.[40]
Neolan Grey RC 200%

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39. Path length of liquid 5.0mm

40. My thanks to Dr. R.S. Sinclair, Department of Chemistry, Paisley College of Technology, Paisley, Scotland, for suggesting these dyes.

both obtainable from CIBA-Geigy Ltd. The Polar Yellow was used to achieve the increase in blue-absorption while the Neolan Grey was used to reduce transmission across the spectrum. Because of the relatively small amounts of solution required and the extreme concentration of the dyes the precise measurement of the concentrations BY WEIGHT was impractical. Therefore concentrations were approximated by dilution with the solvent (in this case water). The absorption characteristics were measured on a UNICAM SP 800 recording spectrophotometer.[41] As the real total optical density measurements should include the factors of the cell, solvent and dye, the second beam of the spectrophotometer was used with no blank in place.[42] Thus, measurements of the experimental cells gave estimates of the total optical density of the filter as a whole. Some concentrations proved to be cloudy due to inhomogeneties in the dye. Filtering would not remove this and so the solutions were centrifuged for 5-7 minutes at 9,000 g's to remove the suspension. The four concentrations of Approximating Filters designed to compensate for the estimated amounts of lens pigment already

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41. This use of this instrument was provided courtesy of the Microbiology Department, University of British Columbia.

42. Generally, when measuring absorbance of chemicals in solution, the characteristics of the cell and the solvent used are balanced out in a second light path in the instrument and nullified in the recording.

extant in the 21-year-old eye are shown in figure 1.9.

The Macular 'Pigment' Simulation Filters

Compensation filters for the so-called macular pigment were constructed on the basis of the estimated values of Bone and Sparrock (1971). Although it can readily be seen that estimates for the macular pigment are quite variable, if it firstly can be assumed that there is a macular pigment, there seems to be evidence for an average density of about 0.5 - 0.6 O.D. Bone and Sparrock's estimation of the 'average' optical density is 0.529 O.D. This value was decided upon in view of its consistency with other estimations and the relatively large sample. Four densities were made based on the assumption that the subjects in this investigation had the mean amount of pigment.[43] These filters would, then add to the existing amount of pigment (at 455nm) by 0.2, 0.4, 0.6, and 0.8 O.D. This would make the maximum macular pigment (experimental plus mean) for a hypothetical eye close to 1.33 O.D. Lutein Xanthophyll ($C_{40}H_{54}(OH)_2$) was dissolved in Chloroform to yield the characteristic two-peaked curve at four concentrations. Due to the nature of

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43. This assumption was made for both the lens and macular pigment. Although it is to be recognized that the lens simulation filters are for 21 year old eyes, the curves in figure 1 point to the relatively small difference in the first 10 years.

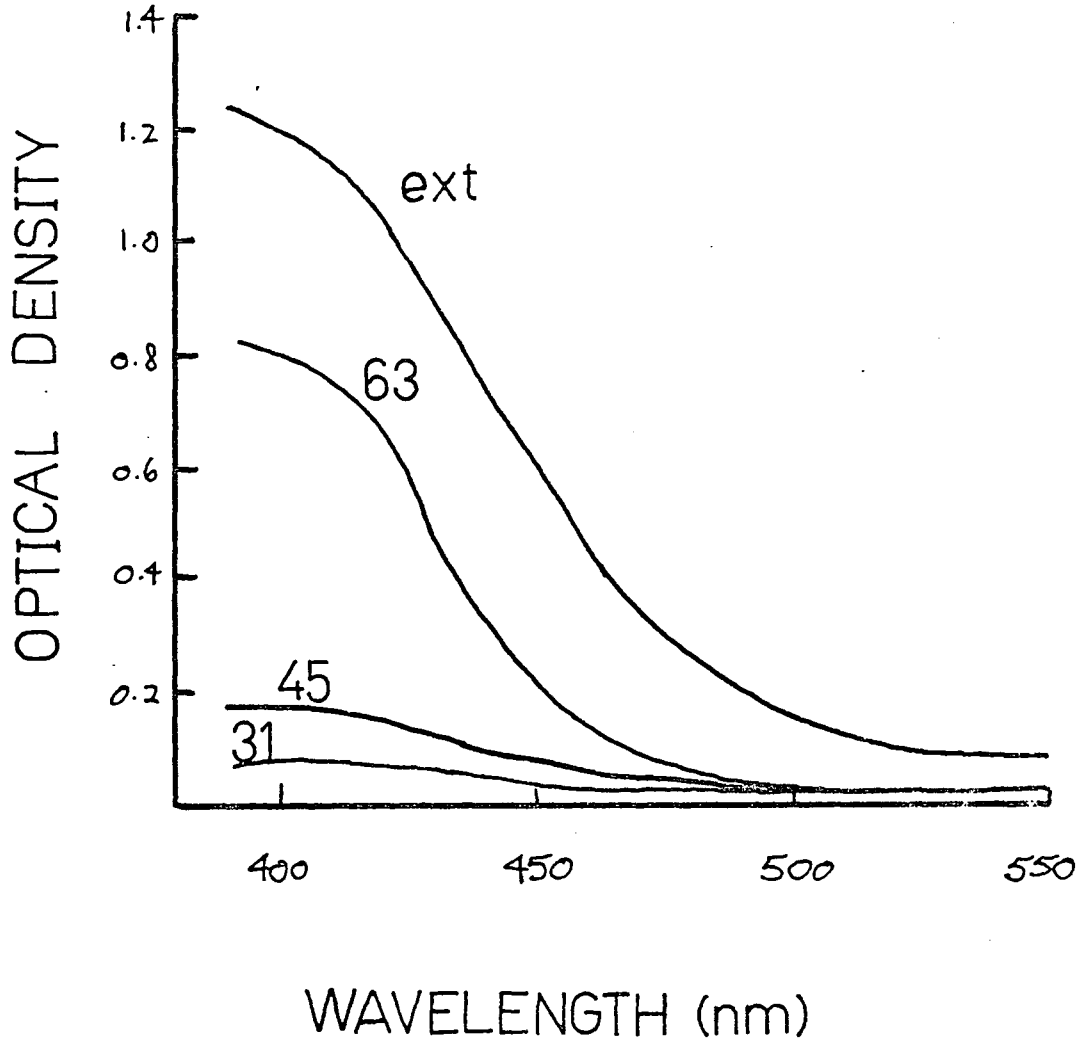

Figure 9 Absorption Characteristics of the Simulated Lens Filters (Approximations of Ages as reported by Said and Weale (1959)).

the crude Xanthophyll used it was impossible to obtain consistent results by weight and therefore, as with the lens approximations, the concentrations were determined by optical density. A stock solution of 1 gram xanthophyll in 100 ml. chloroform was made and filtered 3 times to remove impurities. Dilution of the stock solution to the required densities was achieved with the use of the spectrophotometer mentioned previously. The spectral absorption characteristics for the 4 macular filters are shown in figure 10. Quartz cells of similar nature to the lens-simulation filters were used to house the liquid (path length 2.5mm).[44] Due to the extremely volatile nature of the solvent, the solutions were kept in glass-stoppered flasks. As a precaution against the possibility of both 'lens' and 'macular' filter solutions being subjected to light-produced degradation, samples of all concentrations were left in a fluorescent-source illuminated room for one week and then subjected to spectrophotometric analysis. No observable changes were found in any of the resultant

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44. All spectrophotometric measurements were made with the experimental quartz cells containing their respective liquids. The 2.5mm cells were used for the macular pigment simulation (due to their narrow opening) in an attempt to prevent excessive evaporation during testing. Stoppers of neoprene rubber and several other substances were found to partially dissolve in the chloroform, and therefore no stoppers were used. The cell levels were maintained as full as possible during the experiment by filling with a pipette.

curves. In the experimental situations mentioned in the following part of this paper, the solutions were subjected to tungsten-light only, and then only when the observers were entering or leaving the room. After the experiments were concluded, the solutions were again measured and no changes were found. Figure 11 (a-d) gives the spectral absorption characteristics of the 16 combinations of lens and macular pigment simulating filters which will be used (as well as the filters shown in figure 9 and 10) in the experimental situations described herein. Table 3 gives the brightness values (%) of the least and most dense simulation filters and of the most dense combinations.

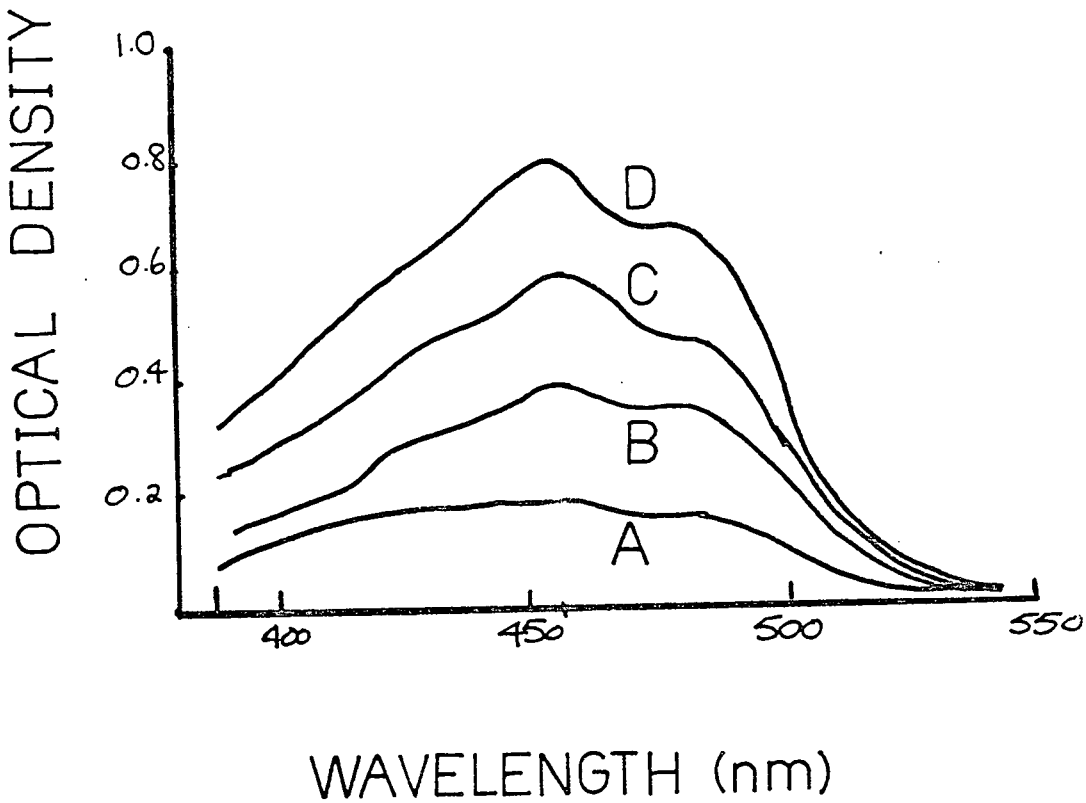

Figure 10 Absorption Characteristics of the Simulated macular pigment filters.

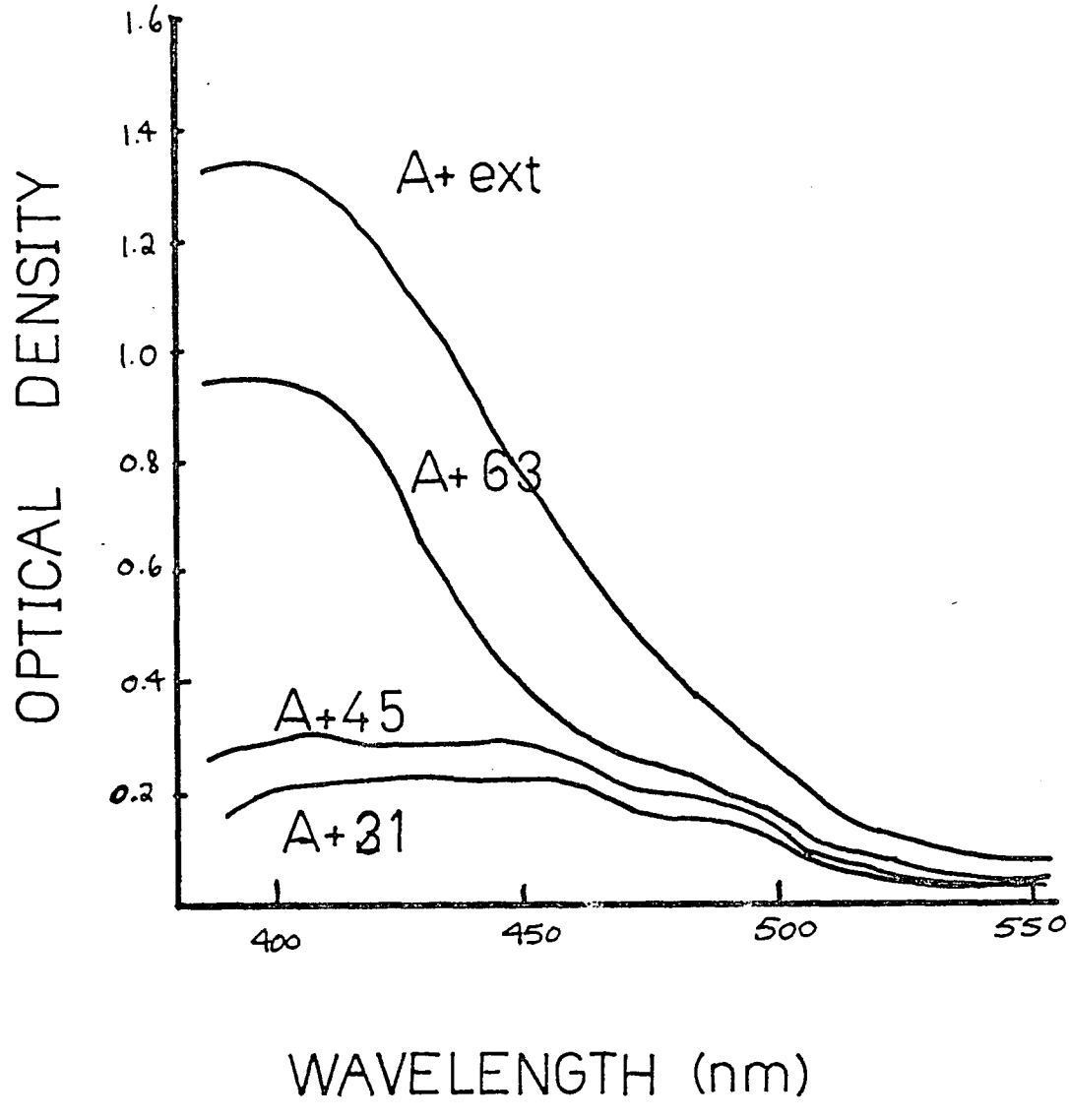

Figure 11a Absorption Characteristics of Macular Simulation Filter 'A' and Experimental lens values

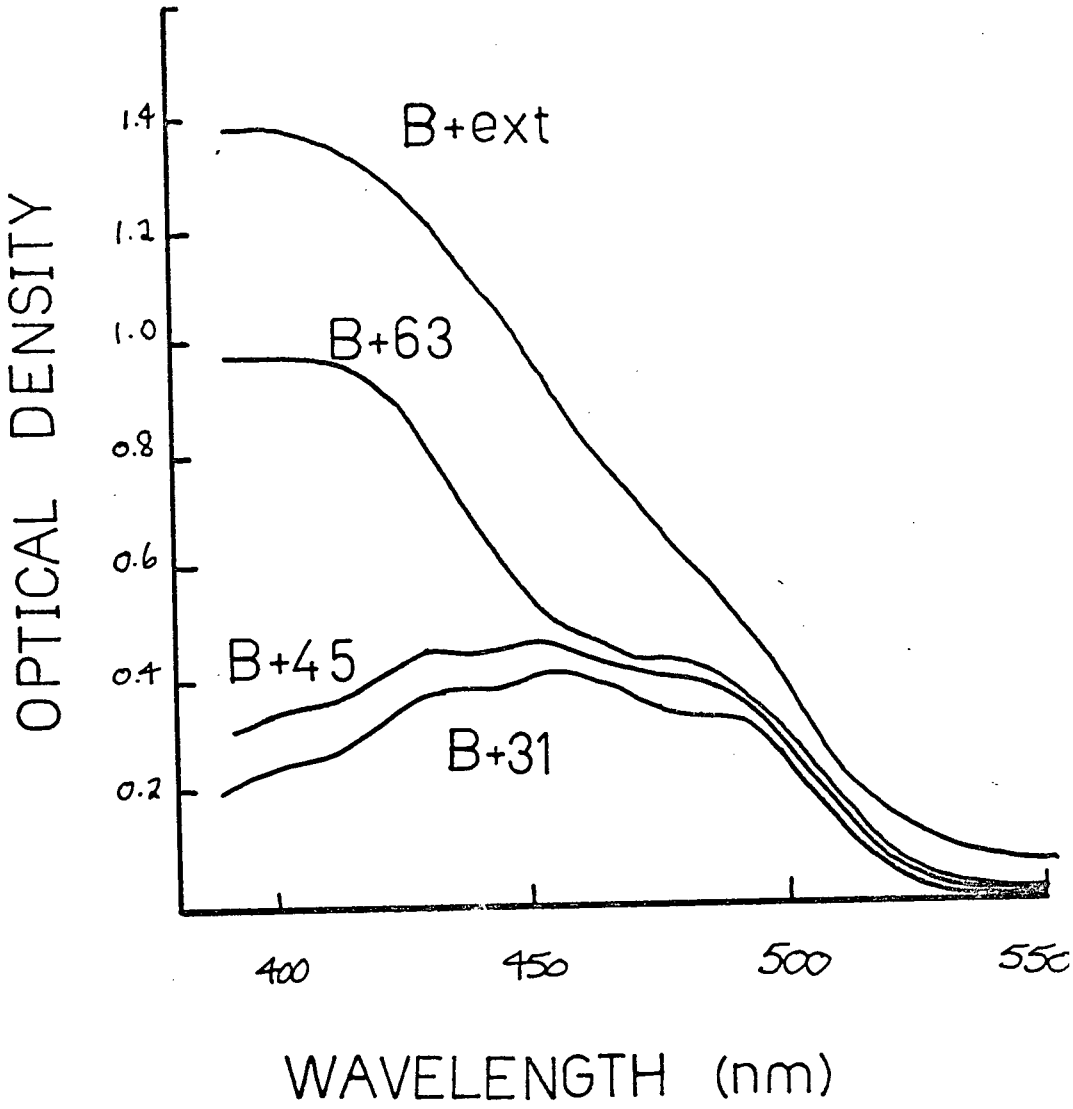

Figure 11b Absorption Characteristics of macular Simulation filter 'B' and experimental lens values.

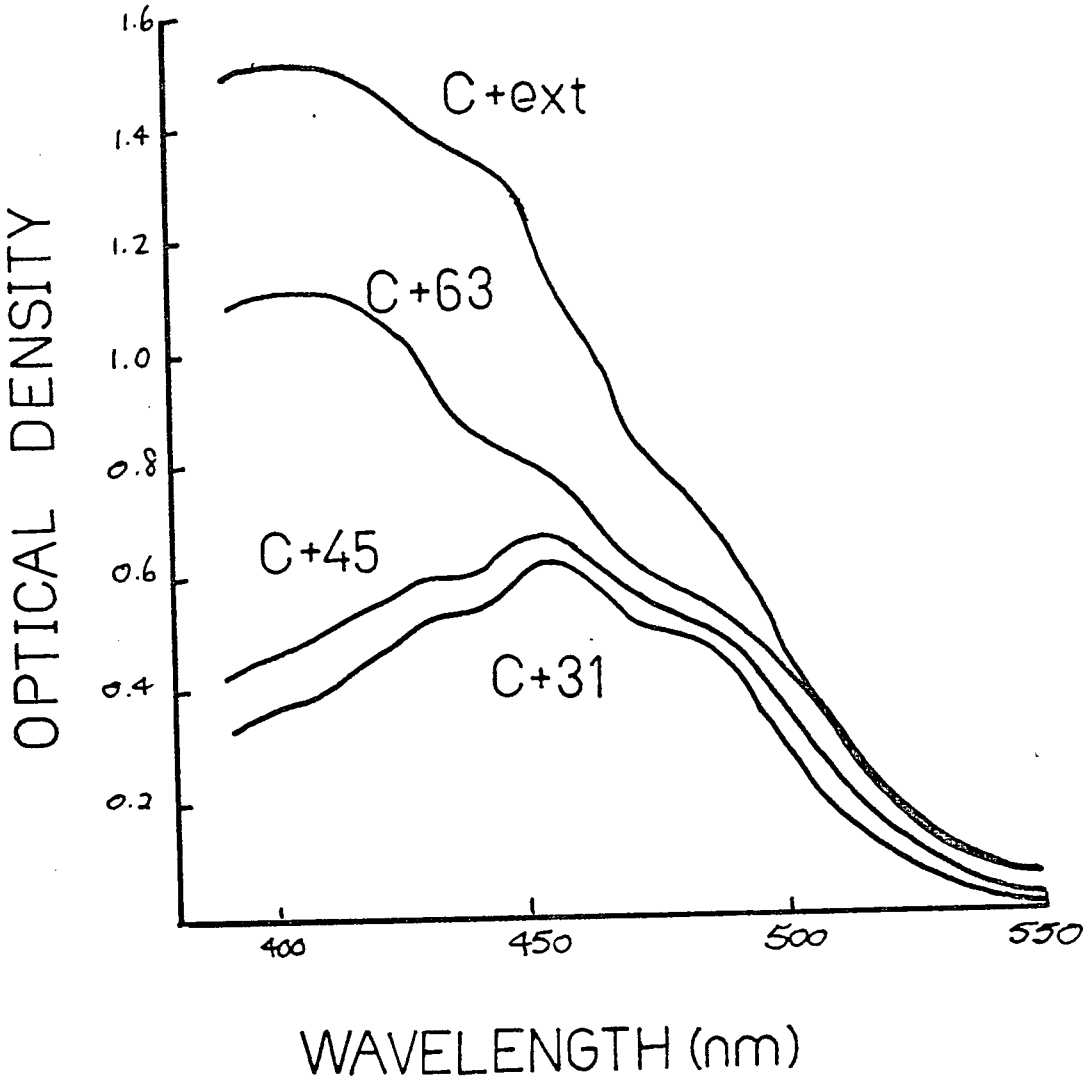

Figure 11c Absorption Characteristics of Macular Simulation filter 'C' and experimental lens value.

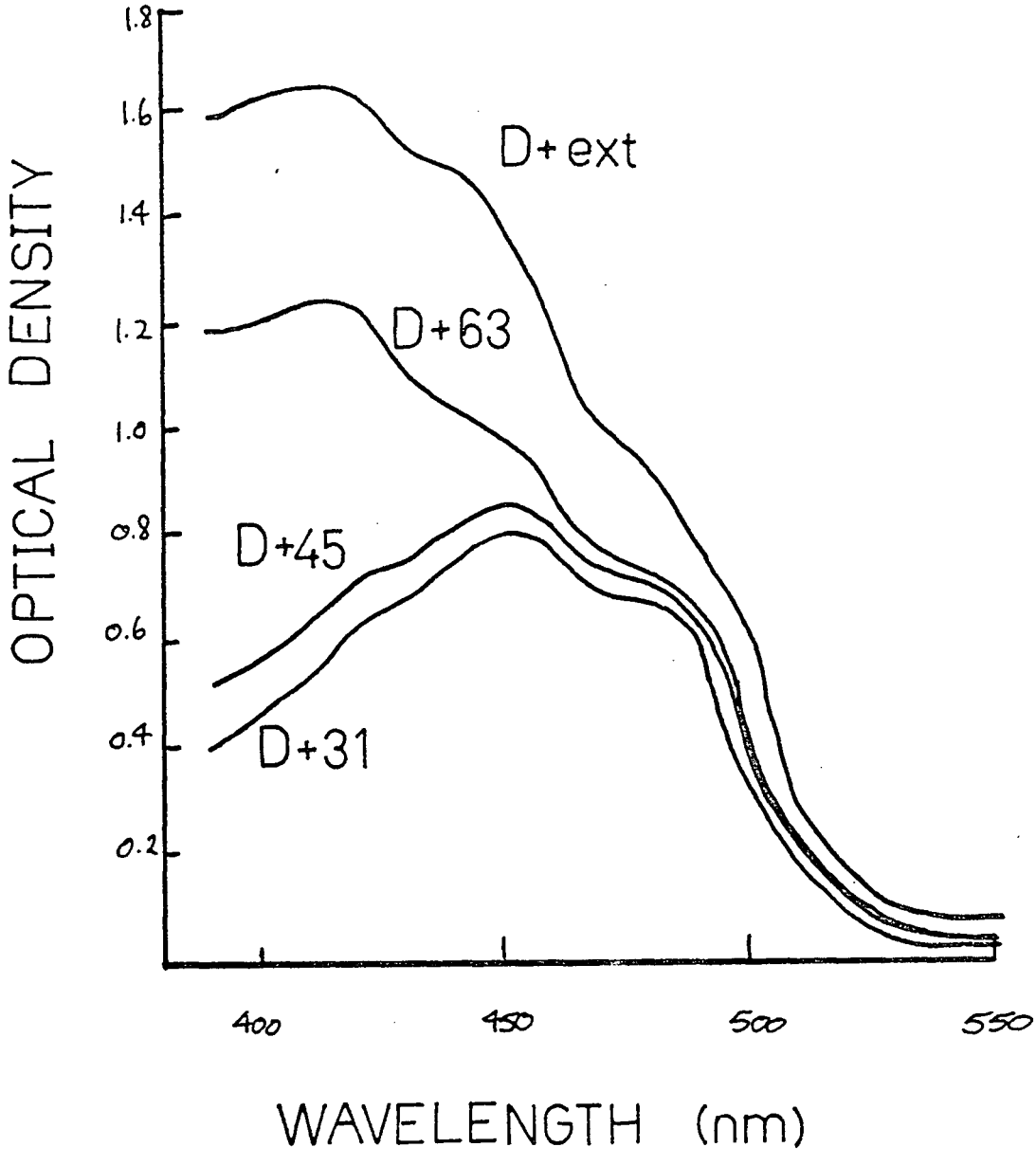

Figure 11d Absorption Characteristics of Macular Simulation filter"d" and experimental lens values.

Table III

Brightness Values of the Least and Most Dense Experimental Simulation Filters.

		Y%
(LENS)	EXT	85
	31	94
(Macular pigment)	D	88
	A	93
	EXT + D	74.8

Table IV

Simulation Conditions for Experiment I

		Macular Simulation					
	(Space)	A	B	C	D	OLens	O Macular
Len Simulation	31	31+A	31+B	31+C	31+D	D	31
	45	45+A	45+B	45+C	45+D	C	45
	63	63+A	63+B	63+C	63+D	B	63
	EXT	EXT+A	EXT+B	EXT+C	EXT+D	A	EXT

METHOD

Twelve observers between 22 and 25 (mean age 23.0) were selected from a group who volunteered to be subjects for this study and were randomly assigned to one of four experimental groups. Testing took place at the University of British Columbia, Psychology Department between July 5th and August 4th, 1972. All subjects were screened for gross color vision defects with the Ishihara and American Optical H-H-R Pseudoisochromatic plates[45] and for near acuity with the C.W. DIXEY ACUITY CARD. Only Ishihara or AO H-R-R scores of zero were treated as acceptable for observers as were acuity scores indicative of N5 vision. Upon initial screening of subjects, two observers failed to meet these criteria and were replaced. All testing; premeasures and experimental measures were done with the right eye only. If the subject wore corrective lenses for the near acuity test, these lenses were worn throughout the experiment. After approximately ten minutes in reduced illumination, each observer was tested on the three equations of the Pickford-Nicholson anomaloscope and the Farnsworth-Munsell 100-hue test to determine baseline measures. As a precaution against possible detrimental effects produced by the lenses alone on performance, four subjects, one from each group, were

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45. Illumination of 100 equivalent lux.

tested under two additional conditions:

1. 5.0mm quartz cell (water-filled)
2. 2.5mm quartz cell (chloroform-filled)

Both of these groups showed no significant or systematic deviations from their baseline rates. As these initial testing conditions were counterbalanced among the four subjects, learning effects were negligible. All subjects were fitted with a spectacle device in which the left eye was occluded and the right eye side adapted to hold two quartz cells. All subjects were then tested under the six conditions summarized in Table IV. For the purpose of analysis, the conditions where there is only one SIMULATIONS FILTER being used, are conceptualized as using zero amounts of the other filter density. In the experimental situation, subjects always had two cells in front of their right eye and were not informed of the densities in each cell. Under each of the six conditions, 8 tests were made:

Box 1 100-hue test
Box 2 100-hue test
Box 3 100-hue test
Box 4 100-hue test
Red-Green Equation Anomaloscope
Yellow-Blue Equation Anomaloscope
Blue-Green Equation Anomaloscope
Pseudoisochromatic Plates (Dvorine and Ishihara)

The order of presentation of these tests and the macular pigment simulation filters were counterbalanced so that no two subjects under any of the six conditions received the filters or the sequence of tests under each of them in the same order. Forty-eight measures (six conditions x eight measures) were taken on each of the twelve observers during the experimental session. The 100-hue and the Pseudoisochromatic plates were done under an approximation of Illuminant 'C' at 100 equivalent lux, while the three anomaloscope equations were set in accordance with Lakowski's (1971) measurements of model I which are summarized below:

R-G Equation 1.9 nits (candelas per square metre)
Y-B Equation 3.0 nits
B-G Equation 2.2 nits

The retinal illumination for the anomaloscope at these levels is between 30 and 50 Trolands (1 degree subtense). As the anomaloscope settings had to be changed many times during an experimental session, the brightness of the matching field was determined each time with the use of an S.E.I. Exposure Photometer.

RESULTS

The data collected from the eight response categories in this experiment can be seen as measures on three discreet

tests: the Anomaloscope, the Farnsworth-Munsell 100-hue test and the Pseudoisochromatic Plates. Each of the three categories will be dealt with seperately, and as a consequence the assumption must be made that there are no significant interactions between them. Because of the small number of subjects per group, descriptive statistics were employed, instead of inferential types. Group means and standard deviations for results have been presented in either tabular or graphic form.

The Anomaloscope

The Control Condition

Table IV gives the mid-points and standard deviations for the three equations of the Anomaloscope for the NORMAL-NO LENS and Control groups.[46] The red-green equation clearly shows the least variance of the three, while the other two vary slightly more. The means of each equations Mid-Points will be used as the Standard Mid-Points for comparison.

The Means and Standard Deviations for single filter conditions are presented in Table V. The latter two equations, and especially the yellow-blue, are strongly affected by the denser values of both lens and macular pigment simulation filters. The Mid-Points and Ranges (2x standard deviations) are, respectively, more erratic and enlarged than the controls. These do not appear to be directed shifts towards one anomaloscope filter or the other, and, contrary to what would be expected from the physical properties of the simulation filters, larger proportions of blue do not seem to be indicated.

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46. The Mean and Standard Deviation are calculated on the lowest and highest acceptable scores for each subject Therefore; the Mean can be seen as the midpoint and the Standard Deviation can be seen as one-half of the Range.

Table V

Anomaloscope Mid-Points and Standard Deviations for the Control Conditions.

	GROUP				
	I	II	III	IV	Zero density cells control
Red-Green Equation					
$\bar{X}$	40.5	42.1	41.0	38.8	40.5
SD	0.9	1.9	1.2	1.6	0.4
Yellow-Blue Equation					
$\bar{X}$	38.4	43.5	40.8	41.5	41.1
SD	1.9	3.0	1.5	3.4	3.5
Blue-Green Equation					
$\bar{X}$	43.0	40.5	42.5	44.8	42.1
SD	3.3	1.7	2.1	2.9	0.5

Totals (for comparison purposes)

	Mean Mid-Point
Red-green	40.6
Yellow-blue	41.1
Blue-Green	41.7

Table VI

Anomaloscope Mid-Points and Standard Deviations for Single Filter Conditions.

	A	B	C	D	31	45	63	EXT
Red-Green Equation								
X	39.5	41.1	40.3	40.3	40.5	41.1	41.1	39.8
SD	1.2	2.4	2.3	1.8	0.9	2.9	2.7	1.8
Yellow-Blue Equation								
$\bar{X}$	43.5	42.0	47.0	34.8	37.1	44.0	41.5	40.6
SD	4.4	3.8	10.4	14.7	6.8	13.0	9.7	15.2
Blue-Green Equation								
$\bar{X}$	43.0	43.0	43.0	38.0	40.5	39.5	45.0	43.0
SD	5.4	5.4	11.4	14.5	6.1	9.0	6.4	5.4

Table VII

Anomaloscope Mid-Points and Standard Deviations for Two-filter Conditions.

(a) Red-Green Equation

			Lens Simulation			
			31	45	63	EXT.
Macular Simulation	A	$\bar{X}$	40.1	42.4	41.4	39.3
		SD	1.8	2.0	1.1	0.7
	B	$\bar{X}$	40.2	41.3	41.0	40.0
		SD	1.3	2.3	0.8	1.9
	C	$\bar{X}$	40.7	41.3	41.7	39.7
		SD	1.4	2.1	1.3	1.5
	D	$\bar{X}$	40.7	41.0	41.2	39.8
		SD	1.5	2.5	1.6	1.1

(b) Yellow-Blue Equation

			Lens Simulation			
			31	45	63	EXT
Macular Simulation	A	$\bar{X}$	38.8	52.0	39.7	38.8
		SD	10.2	15.1	12.6	20.4
	B	$\bar{X}$	39.2	45.7	41.0	31.3
		SD	11.9	9.2	8.2	23.4
	C	$\bar{X}$	36.8	44.8	32.3	40.7
		SD	17.6	11.8	24.2	6.7
	D	$\bar{X}$	38.3	30.7	35.2	31.2
		SD	19.6	23.1	26.2	26.9

(c) Blue-Green Equation

			Lens Simulation			
			31	45	63	EXT
Macular Simulation	A	$\bar{X}$	43.7	36.5	46.2	43.5
		SD	9.7	8.9	8.3	4.9
	B	$\bar{X}$	46.8	47.0	44.3	40.2
		SD	8.9	10.6	15.0	12.1
	C	$\bar{X}$	44.7	45.7	35.2	45.8
		SD	12.7	12.2	25.6	11.5
	D	$\bar{X}$	37.2	41.8	45.0	43.8
		SD	24.0	16.0	19.0	11.3

Table VI presents the mean mid-points and matching ranges for the Two-Filter Conditions. The red-green equation remains unaffected by the experimental procedure. Every condition remains close to the control mid-point with low matching ranges. The yellow-blue equation shows more erratic mid-points and increased matching ranges with increasing filter density. The most dense four combinations show mid-point shifts toward the yellow side of the equation with the matching ranges encompassing up to 54 Anomaloscope units: almost three-quarters of the total possible range of the instrument. The blue-green equation shows mid-point shifts toward the blue filter and matching ranges do not show as large increases as did the yellow-blue equation.

The Farnsworth-Munsell 100-Hue Test

The means and standard deviations of each of the four boxes are presented, for the single cell condition in Table VIII(a).

It appears from these data that increases in macular simulation density tends to affect Box three scores strongly; Box one and four scores slightly and Box two scores hardly at all. The lens simulation filters tend to affect Box three scores strongly, Box one and four scores slightly, and Box two scores hardly at all but note, as a Function of

Decreasing Filter Density and not increasing density as in the macular simulation. This finding can be attributed to subject bias as the 31 and D groups were the same subjects (see Table IV).

The two-cell condition means and standard deviation are presented in Table VIII (b). Again, Box three seems to be affected most by increases in filter density. All experimental groups show a general tendency to higher scores with increases in filter density with the D-lens simulation conditions affecting color discrimination most.

Pseudoisochromatic Plates

The scores of the pseudoisochromatic plates showed no mistakes for any of the subjects under any filter condition in Experiment I.

Table VIII

Means and Standard Deviations for 100 hue test (By Box)

(a) Single Cell Conditions 100 Lux

		Box 1	Box 2	Box 3	Box 4
A (only)	$\bar{X}$	5.0	5.7	7.0	4.0
	SD	4.5	4.0	4.2	3.3
B (only)	$\bar{X}$	5.3	4.0	6.7	5.3
	SD	1.9	5.7	3.8	1.9
C (only)	$\bar{X}$	8.0	4.0	8.0	5.0
	SD	8.6	3.3	8.6	7.1
D (only)	$\bar{X}$	11.0	5.3	13.3	10.7
	SD	5.1	3.7	5.0	6.8
31 (only)	$\bar{X}$	7.7	8.0	13.7	10.3
	SD	8.2	0.	8.2	4.9
45 (only)	$\bar{X}$	10.0	3.0	11.3	4.0
	SD	4.3	1.4	2.5	3.3
63 (only)	$\bar{X}$	4.0	6.7	2.7	2.7
	SD	5.7	5.0	1.9	1.9
EXT(only)	$\bar{X}$	5.3	4.0	5.3	2.7
	SD	1.9	3.3	1.9	1.9

(b)

		Box 1	Box 2	Box 3	Box 4
A-31	$\bar{X}$	5.3	8.0	12.7	7.3
	SD	5.0	11.3	9.6	7.7
A-45	$\bar{X}$	4.0	6.3	8.3	5.3
	SD	5.7	4.7	9.1	1.9
A-63	$\bar{X}$	13.3	4.3	13.3	12.7
	SD	5.0	3.3	6.8	6.3
A-EXT	$\bar{X}$	5.7	5.0	13.0	12.0
	SD	4.0	1.4	3.7	6.7
B-31	$\bar{X}$	4.0	10.7	18.7	2.7
	SD	5.7	10.0	13.6	1.9
B-45	$\bar{X}$	6.7	6.3	15.7	5.3
	SD	9.4	5.8	17.4	5.0
B-63	$\bar{X}$	10.7	16.0	15.0	6.3
	SD	1.9	7.3	9.2	4.0
B-EXT	$\bar{X}$	4.7	5.3	9.7	11.0
	SD	5.9	3.8	8.0	10.6

		Box 1	Box 2	Box 3	Box 4
C-31	$\bar{X}$	4.0	5.7	15.0	9.7
	SD	3.3	5.4	6.1	11.0
C-45	$\bar{X}$	6.7	12.3	25.3	9.0
	SD	5.0	10.2	30.3	7.8
C-63	$\bar{X}$	10.7	7.0	6.3	9.0
	SD	5.0	5.4	6.3	6.7
C-EXT	$\bar{X}$	7.7	4.3	14.3	9.7
	SD	2.9	0.5	6.3	1.7
D-31	$\bar{X}$	6.7	14.0	24.7	14.3
	SD	3.8	7.3	4.1	9.0
D-45	$\bar{X}$	14.7	12.3	19.3	16.3
	SD	11.5	11.1	8.1	6.0
D-63	$\bar{X}$	12.0	14.3	17.0	11.7
	SD	5.7	4.5	4.2	7.6
D-EXT	$\bar{X}$	8.3	7.3	20.7	15.7
	SD	5.9	5.2	12.2	8.3

EXPERIMENT II

To investigate the additional effects of changes in illumination of luminance on color vision test scores, a study was conducted based upon an adaptation of the finding of several authors. The simulation filters reported in Experiment I were used in concert with reductions in illumination to determine whether simulated macular and lenticular absorption plus reductions in the amount of light reaching the eye would effect color vision test scores from young subjects in a systematic manner. Verriest's (1963) age norms for the 100-hue test show gradual increases in the blue-green and red regions of the test with increases in age and with reductions in illumination. He concluded from these, as well as other findings, that in case of acquired blue-yellow discrimination deficiency:

> ...the retina would become less sensitive to light so that its sensory conditions would shift.... the blue-yellow discrimination defect observed would be due to a "mesopisation" of the vision. If this explanation were true, the discrimination would improve if the illuminance were increased and would become worse if the illuminance were decreased.[47]

As can be seen from the results of Experiment I, simulated changes of both lens and macular absorption do

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47. Verriest (1963) pg 194-195

not adequately account for the ageing changes observed by Verriest on the 100-hue profiles but together with reductions in illumination of the hue discrimination tests and screening plates, these changes may be more drastic. The anomaloscope matching data for the yellow-blue and blue-green equations shows some deviation from normality along the lines of an ageing population as reported by Lakowski (1962). Looking at these results in view of Verriest's conclusions, the questions of INCREASES in the luminance of the anomaloscope might produce reductions in the variability of the ranges and mid-points found in Experiment I.

Modifications to the Pickford-Nicholson Anomaloscope (Model III)

In order to achieve the brightness levels required for the investigations of experiment II, modifications were made to the Pickford-Nicholson Anomaloscope used throughout this experiment. These modifications were made in the summer and early fall of 1971 by the author.[48]

The Pickford-Nicholson Anomaloscope has been described by Lakowski (1971) as a simple colorimeter. It is basically an additive colorimeter which contains a source of illum-

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48. My thanks to Keith Waldron, technician, Psychology Department, U.B.C. for his help in the modifications of this instrument.

inant 'A' light, two sets of filter holders and shutters and two integrating chambers, each opening to a single half of the same bipartite field. Three sets of filters are in the Pickford-Nicholson Anomaloscope and with them, theoretically, all classical forms of color vision defect can be tested (Lakowski, 1971):

Equation	Standard	Defect
Red - Green -	Yellow	Protan - Deutan
Yellow - Blue -	Neutral	Tetartan
Blue - Green -	Blue-Green	Tritan

The modifications reported allow the testing of subjects on the three equations generally used at luminances of at least 1 log unit higher than those reported by Lakowski and possibly two log units higher with an illuminant which is higher in color temperature than S_a at 2850°K. The instrument was modified with respect to its source and its light mixing environments in the following manner. The original source and its socket was removed from the lamphouse assembly and the lamphouse and integrating chambers were sprayed with a Barium Sulphite paint mixture which was adapted from that reported by Middeton and Saunders (1954). The paint was diluted in approximately 1 part acetone and the liquid was then applied to the surfaces of the integrating chamber and the lamphouse. The acetone subsequently

dried leaving the barium sulphate - carbonxymethyl-cellulose mixture adhered to the walls. Each of the integrating chambers had one 90° corner made into a 45° corner to increase the brightness of the light reaching the comparison apertures. The lamphouse was then fitted with a lamp holder assembly consisting of a raised asbestos plate which had holes drilled in it and pins fitted for electrical contact with the lamp. Reflectors were placed behind the source in the axis of each of the two apertures. The source was a 24 volt, 150 watt quartz-halogen lamp manufactured by Philips. As illuminant 'A' is required for the correct color rendition of the filters at previously mentioned levels (Lakowski 1971) the lamp was run at approximately 13 volts to render the source effectively 2850°K. A 24 volt transformer was used to replace the 12 volt model found in the instrument as well. Monitoring plugs were placed at the rear of the instrument to check the applied voltage at the socket of the source. In order to cool the source and surrounding filters etc., an exhaust fan assembly was fitted to the bottom of the anomaloscope which forced air through the lamphouse and out the top. During the experimentation, a Variac line transformer was used to control the voltage to the transformer, while a voltmeter was used to monitor the source. As can be seen from figure 12 (a), the light leaving both apertures is

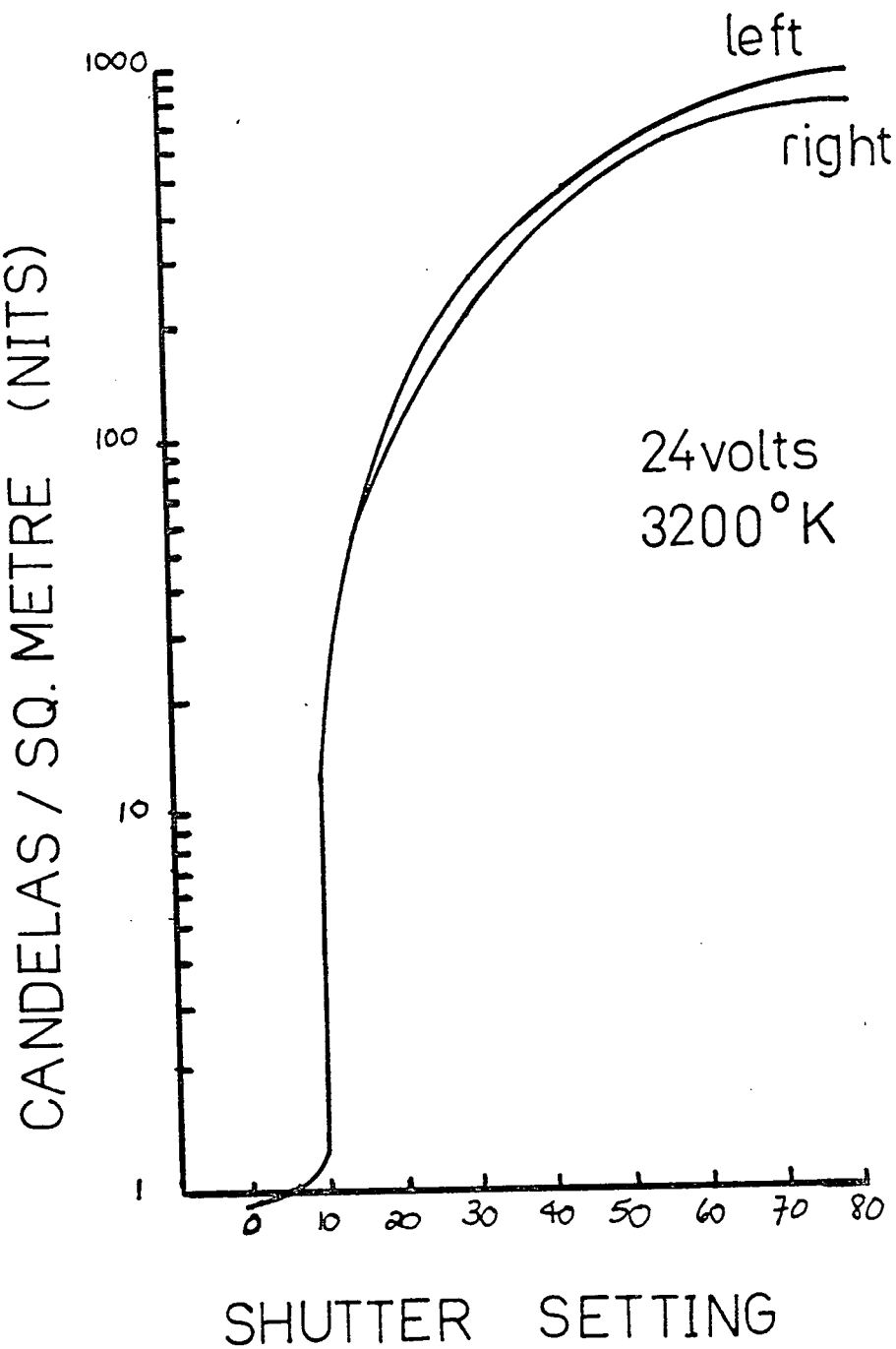

Figure 12a Aperture luminance is a function of shutter setting.

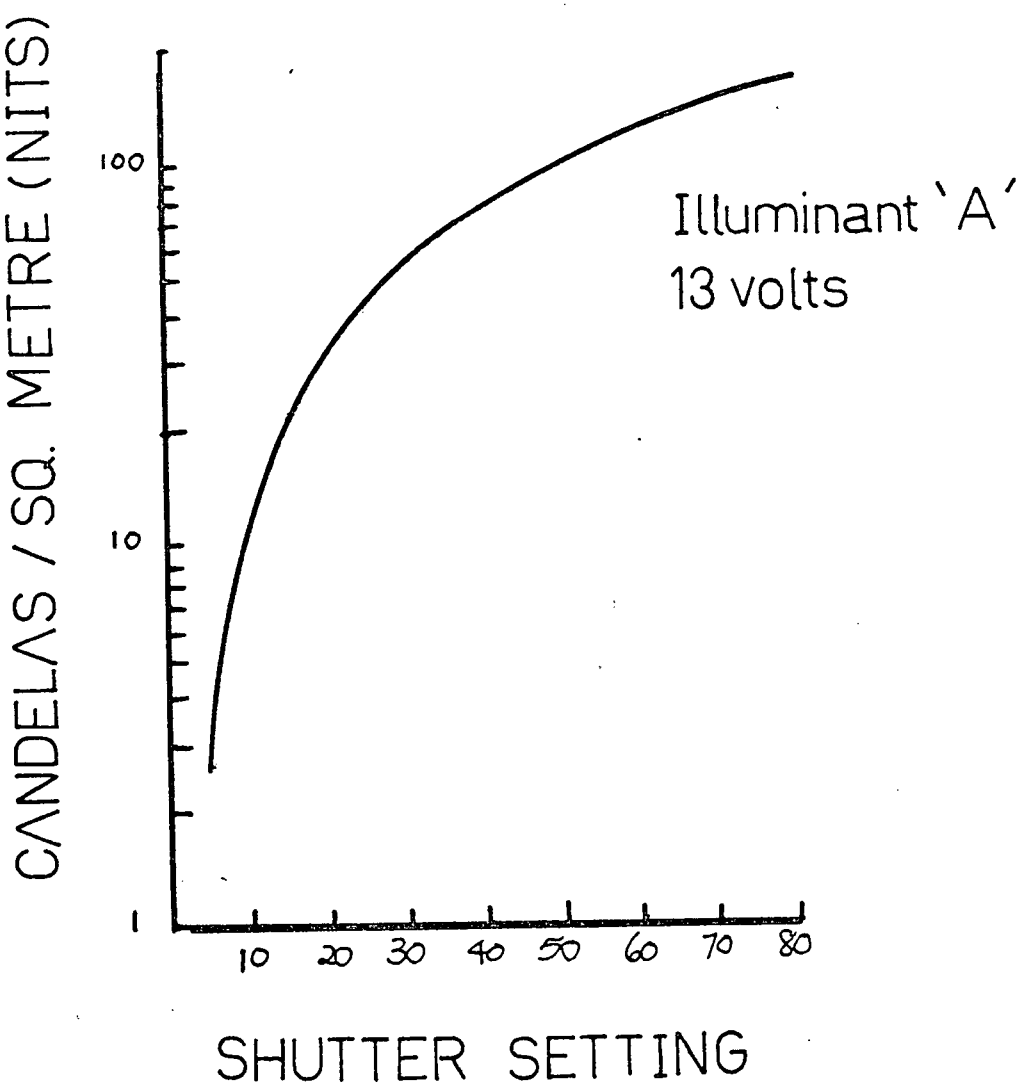

Figure 12b Aperture luminance is a function of shutter setting.

quite uniform in terms of brightness.[49]

The anomaloscope filters used in this experiment were those with spectral characteristics as reported by Lakowski (1971) for model I. Energy distributions for these filters at the Aperture modified anomaloscope are presented in Figure 13.

METHOD

The twelve volunteer subjects reported in Experiment I were dark adapted for 10 minutes and then tested monocularly (right eye) under an approximation of Illuminant 'C' masked to deliver 2.0 lux over a 30 x 10 cm area. The observers wore two liquid filters in front of the right eye in the manner reported in Experiment I. The filters were placed in 4 mutually increasing pairs which represented conditions ranging from 31 years old lens plus low macular pigment to extreme lens plus extreme macular pigment. As Verriest (1963) notes, the normal subject becomes 'wholly tritanopic' when the illuminance falls below 0.2 lux. As a precaution, all subjects were tested with the Panel D-15 test without the simulation filters at 0.42 lux to determine whether any

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49. These measurements were made on the same source used in this experiment, which was burned approximately 10% of its burning life (50 hours at 24 volts) before these measurements were taken.

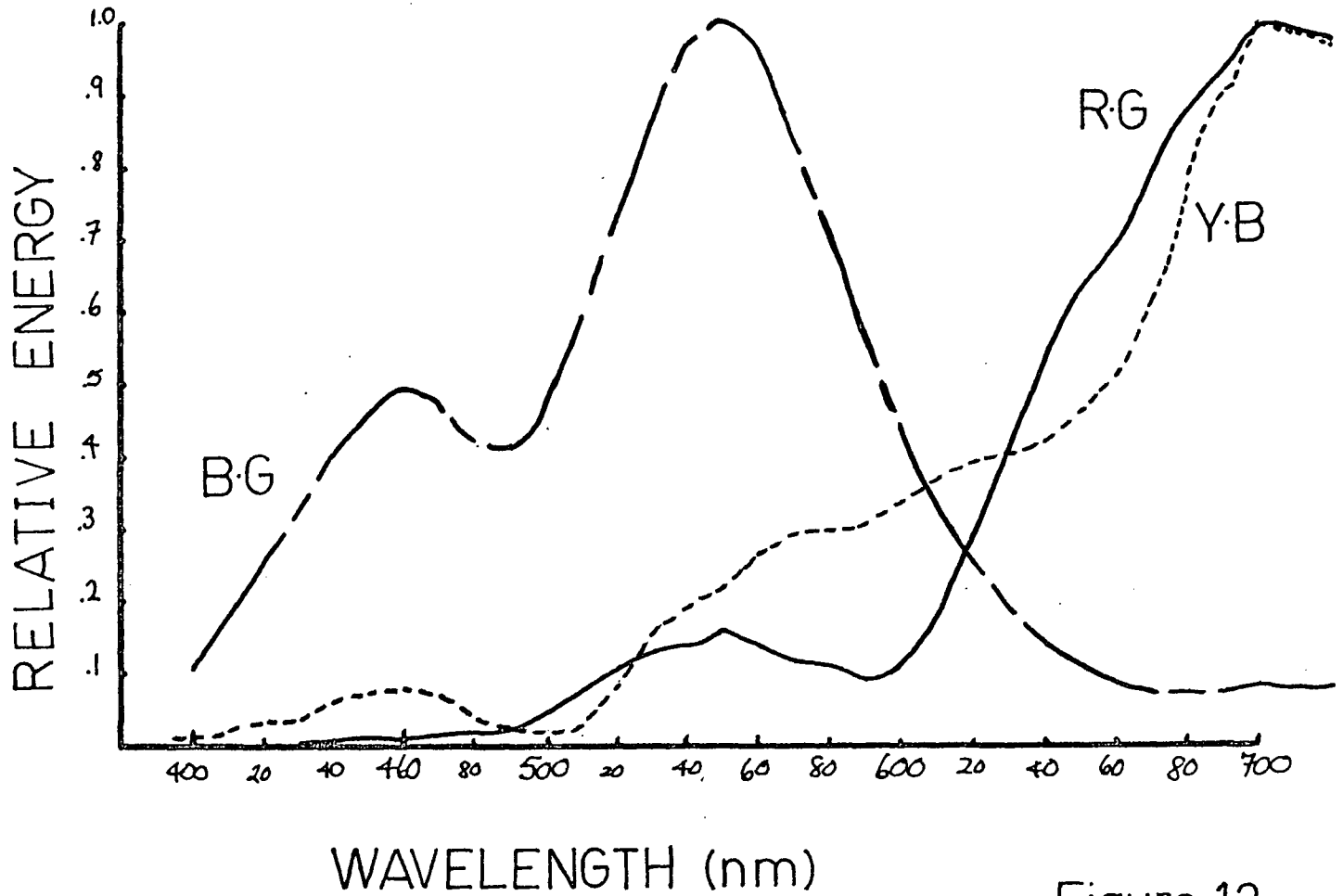

Figure 13

Spectral characteristics of Anomaloscope filters (Model I) at aperture.

would show 'wholly tritanopic' characteristics. Two neutral density filters (combined Y%-21) were used to achieve the reduction in illumination. Although some observers made tritanopic confusions, the magnitude of error cannot be seen as large enough to classify them as wholly tritanopic. The mean-score diagram for this control condition is presented in figure 14. The neutral density filters plus the Experimental filters were then placed in the subjects view[50] and each was tested on the complete 100-hue, Panel D-15, and Dvorine and AO H-R-R pseudoisochromatic plates. Subjects were required to hold the neutral density filter throughout the experiment. The maximum density pair of filters (ext lens + D macular) represent a reduction of 27% (Y% = 73), therefore, the lowest level of illumination achieved under the reduced illumination and filter conditions is 0.31 equivalent lux. The same observers with their respective lens and macular simulating filters (without the Neutral Density filters) were also tested on the three anomaloscope equations at 10 times the luminance for each equation as reported in Experiment I. All above mentioned tests were presented in a counterbalanced order to eliminate

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50. Subjects were required to hold the neutral density filters in front of their right eye.

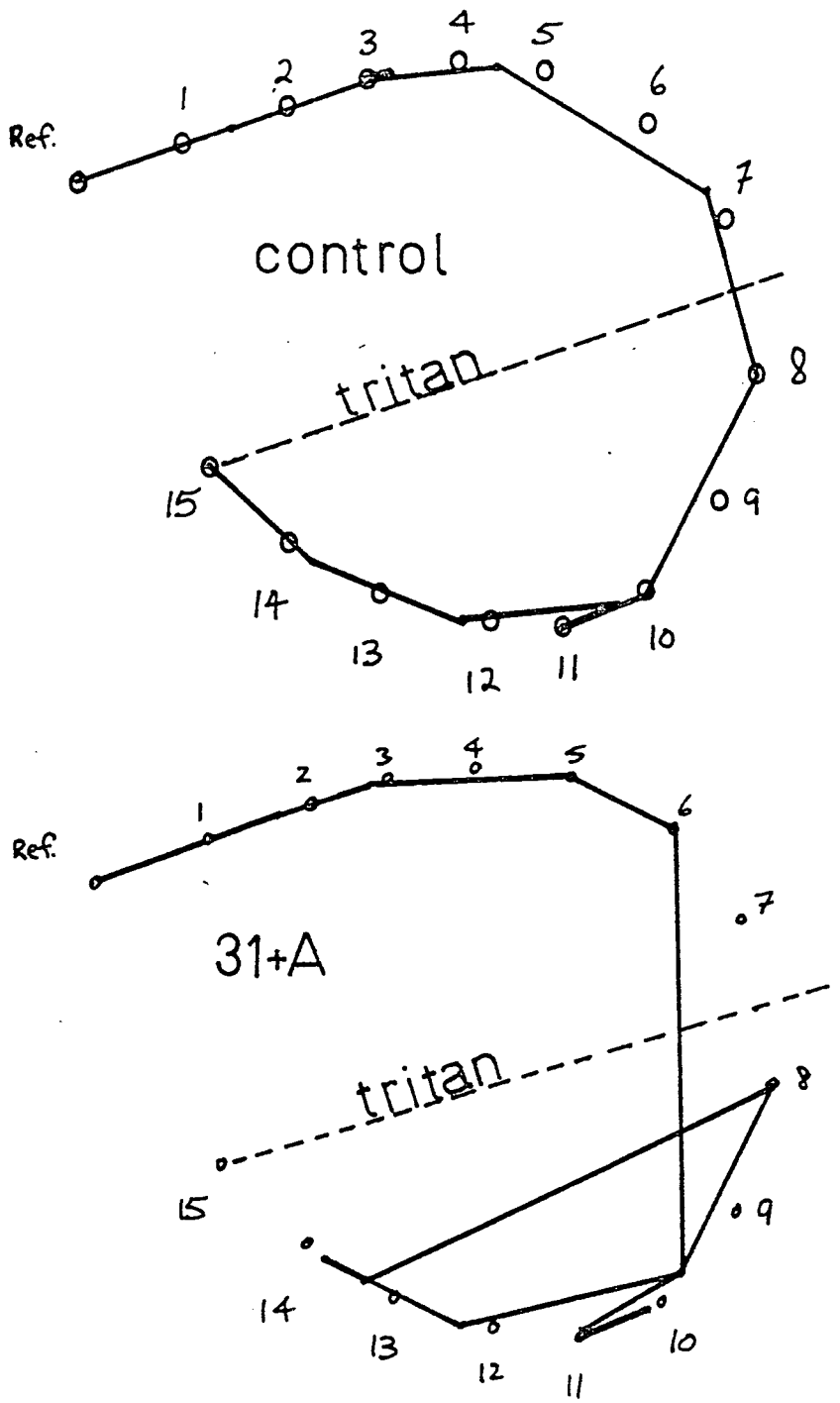


Figure 14a Panel D-15 Mean Scores

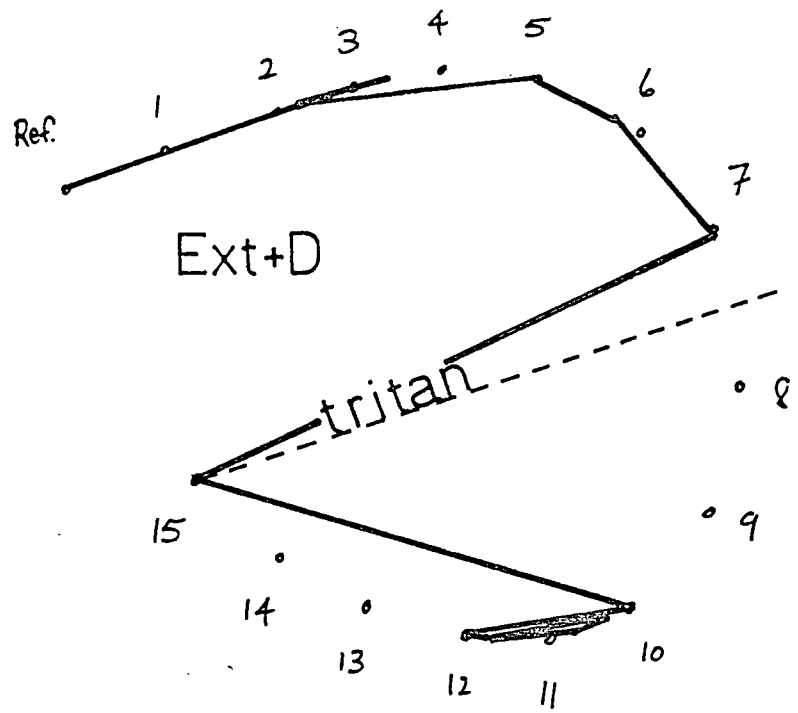


Figure 14 b Panel D-15
Mean Scores

learning effects. As in Experiment I, no two subjects received any of the tests in the same order.

RESULTS:

The Anomaloscope

Table IX shows the mid-points and standard deviations for the three equations at 10 times the luminance reported in Experiment I. There is a distinct decrease in the ranges of both the yellow-blue and blue-green equations under the extreme conditions and, in addition, the mid-points appear to be shifted slightly towards the blue filter values of each pair. As in the previously noted findings, the mid-points and ranges for the red-green equation remain respectively central and small.

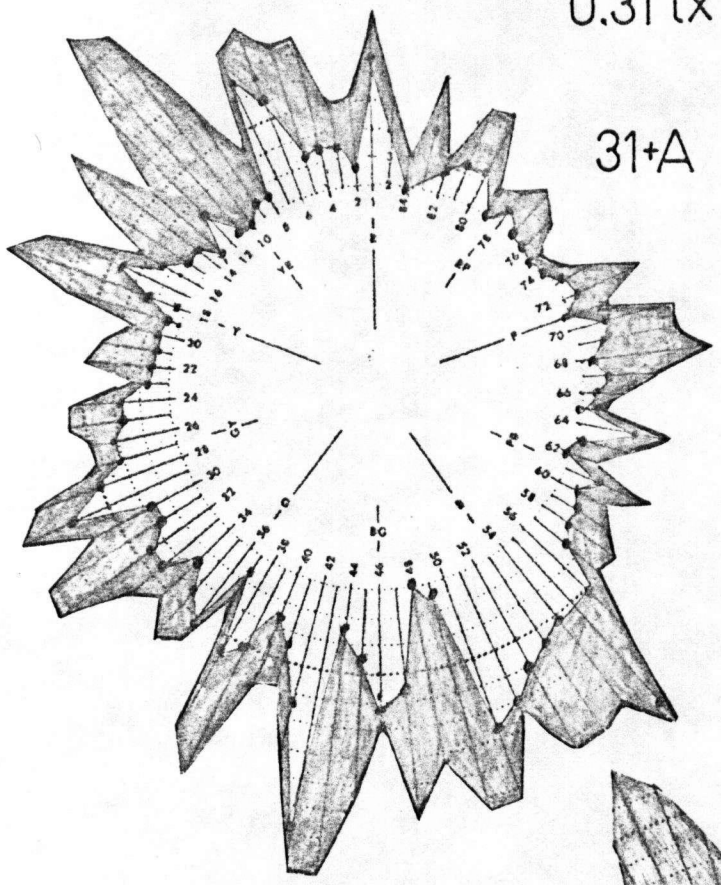
The Farnsworth-Munsell 100-hue Test

Table X gives the mean and standard deviation of the box scores of the 100-hue test performed under very low illumination with the experimental filters. The increasing filter densities affect Box one and Box three the most, although as can be seen by Figure 15 there are high error scores at the beginning and end of every box in the high density conditions.

344.5

0.31 lx

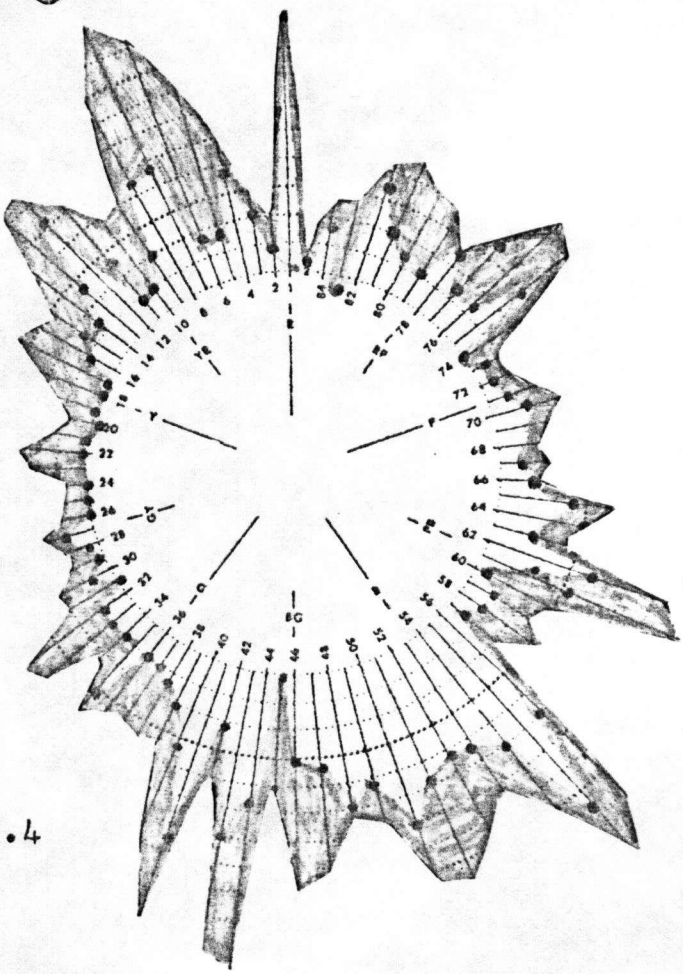
31+A



100-hue profiles for reduced illuminated condition

Figure 15a

45+B



Outer Profile = Mean.
Inner Profile -1 Standard Deviation

363.4

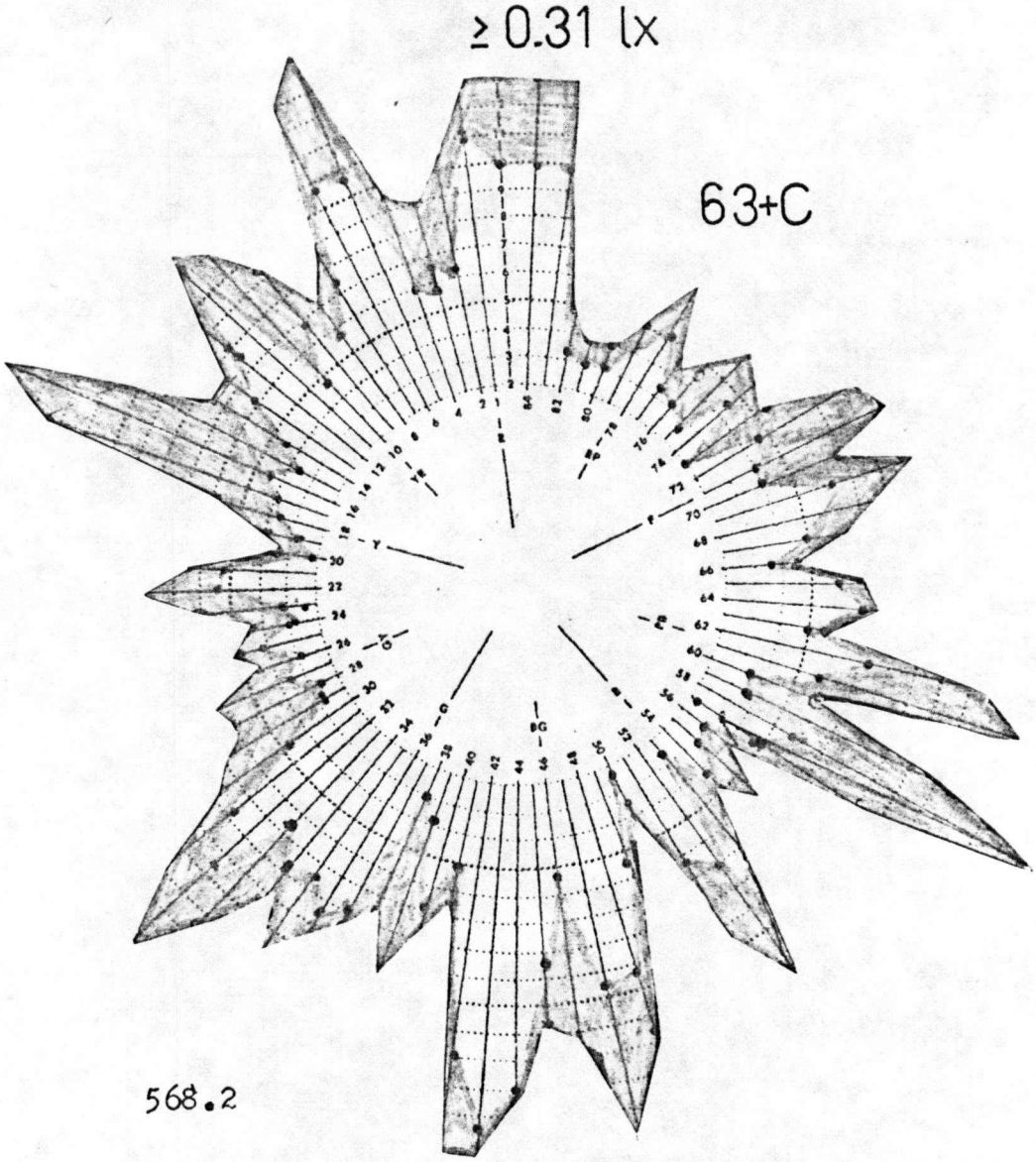


Figure 15 b

≥ 0.31 lx

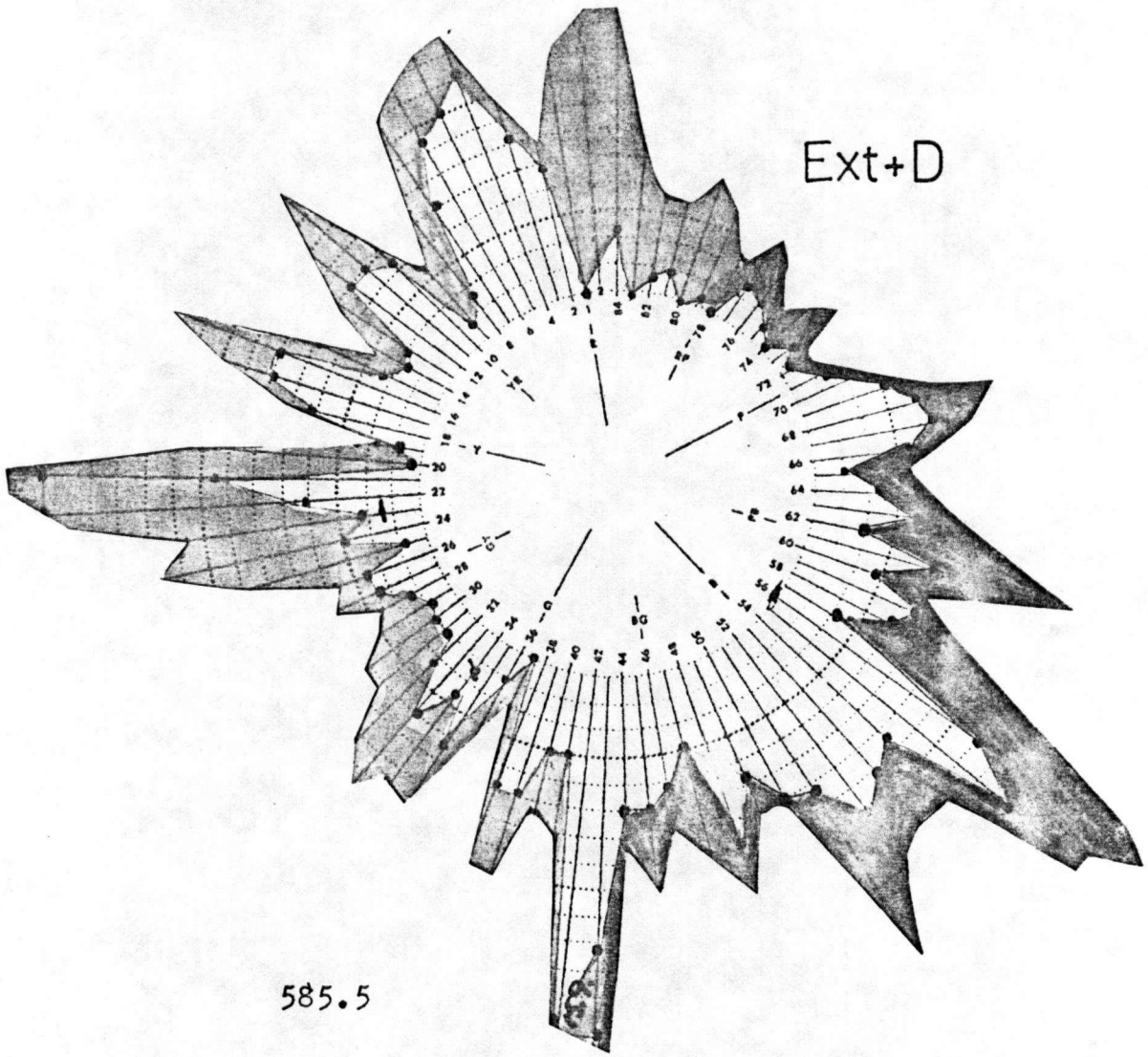


Figure 15c

Table IX

Anomaloscope Mid-Points and Standard Deviations for 10X Luminance of Exp. 1. (Two filter conditions.)

		31+A	45+D	63+D	EXT+D
Red-Green Equation	$\bar{X}$	41.0	40.3	40.5	39.8
	SD	1.5	1.4	0.5	1.2
Yellow-Blue Equation	$\bar{X}$	40.0	47.3	38.8	42.6
	SD	11.3	11.2	16.1	6.0
Blue-Green Equation	$\bar{X}$	40.0	40.3	46.7	44.8
	SD	7.2	6.4	8.5	5.2

Table X

Means and Standard Deviations for 100-hue Test

(Two-Filter Conditions) 0.3 Lux

		Box 1	Box 2	Box 3	Box 4
31+A	$\bar{X}$	103.7	70.3	112.0	68.3
	SD	40.9	16.7	23.5	22.4
45+B	$\bar{X}$	107.7	94.0	119.0	51.3
	SD	69.9	33.4	9.1	30.3
63+C	$\bar{X}$	164.0	138.0	163.3	100.0
	SD	50.5	28.0	65.0	3.7
EXT+D	$\bar{X}$	159.0	134.3	188.7	88.3
	SD	29.7	17.6	21.9	44.9

The Panel D-15 Test

As can be noted in Figure 14, there is a tendency to confuse the caps in a manner characteristic of the TRITAN Defect. The mean-score diagrams 31-A and EXT-D indicate the profiles of the least and most dense experimental filter groups under low illumination. There appears to be an increase in the TRITAN ERROR between these two conditions and, as evidenced by the EXT-D profiles, all observers in this group paired caps 7 and 15, thus indicating a fairly strong tritan classification.

The Pseudoisochromatic Plates

In Experiment II subjects made confusion mistakes in both the Dvorine and AO H-R-R tests. Frequency histograms of these mistakes are presented in Figure 16. The Dvorine test seems to be affected most at plates 9 and 10, although plates 12 and 13 are also generally confused. These two plates seem to be more often confused by observers wearing the denser simulation filters. The AO H-R-R test scores show a tendency towards blue-yellow confusion. Plates 17 and 18 tend to be weighted toward the tritan classification in the low-density groups and towards the tetartan classification in the high-density group. The author observed that subjects generally made more use of brightness and form cues at these levels of illumination and it is believed that correct responses were given to some of the AO H-R-R plates by the perception of form and contrast rather than colour. (The frequency for group 63-C is based on two instead of three observers, as one subject did not complete the AO H-R-R test or the Panel D-15).

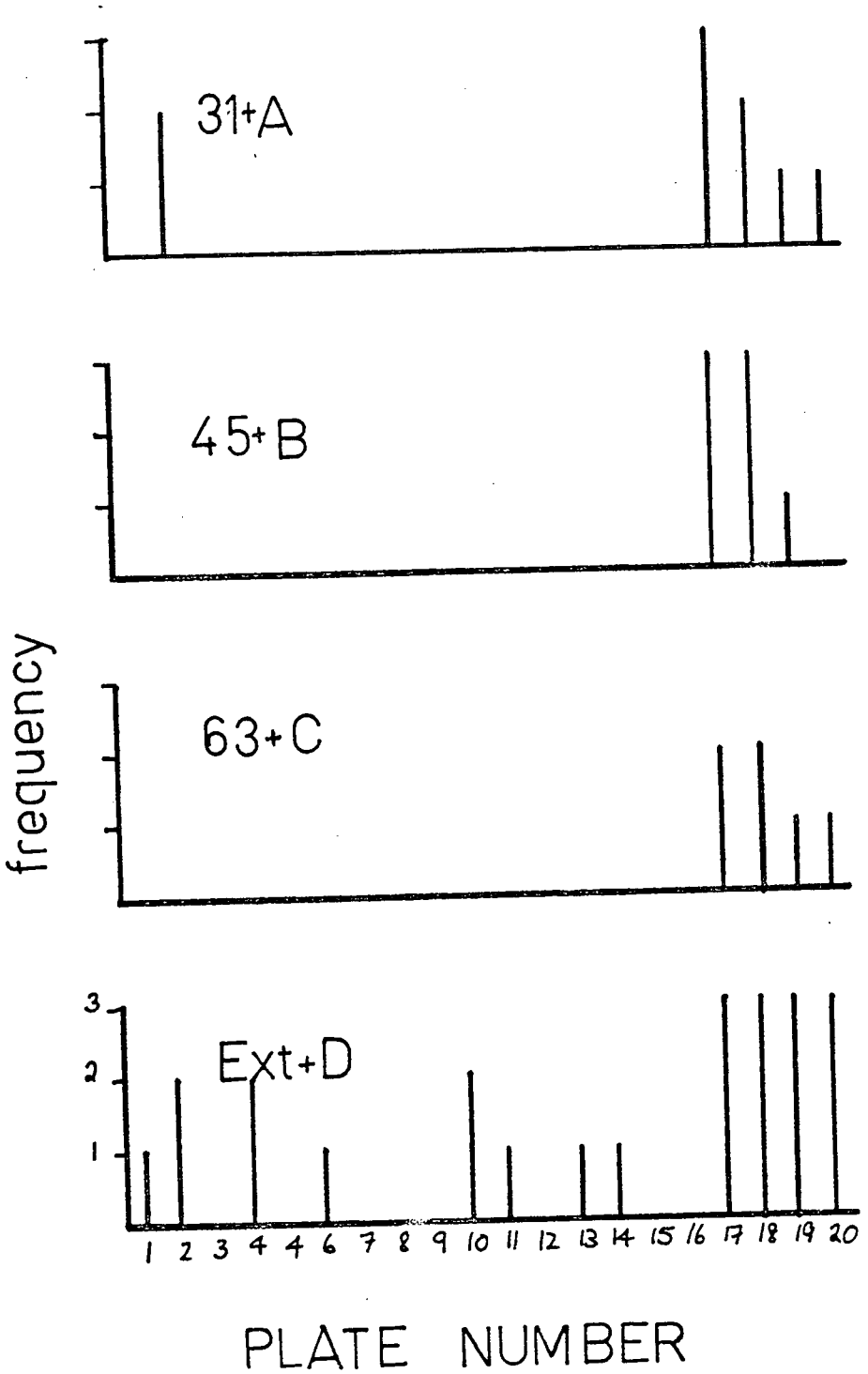


Figure 16a Frequency Histograms for Confusion Errors on the AO H-R-R test (0.31 Lux)

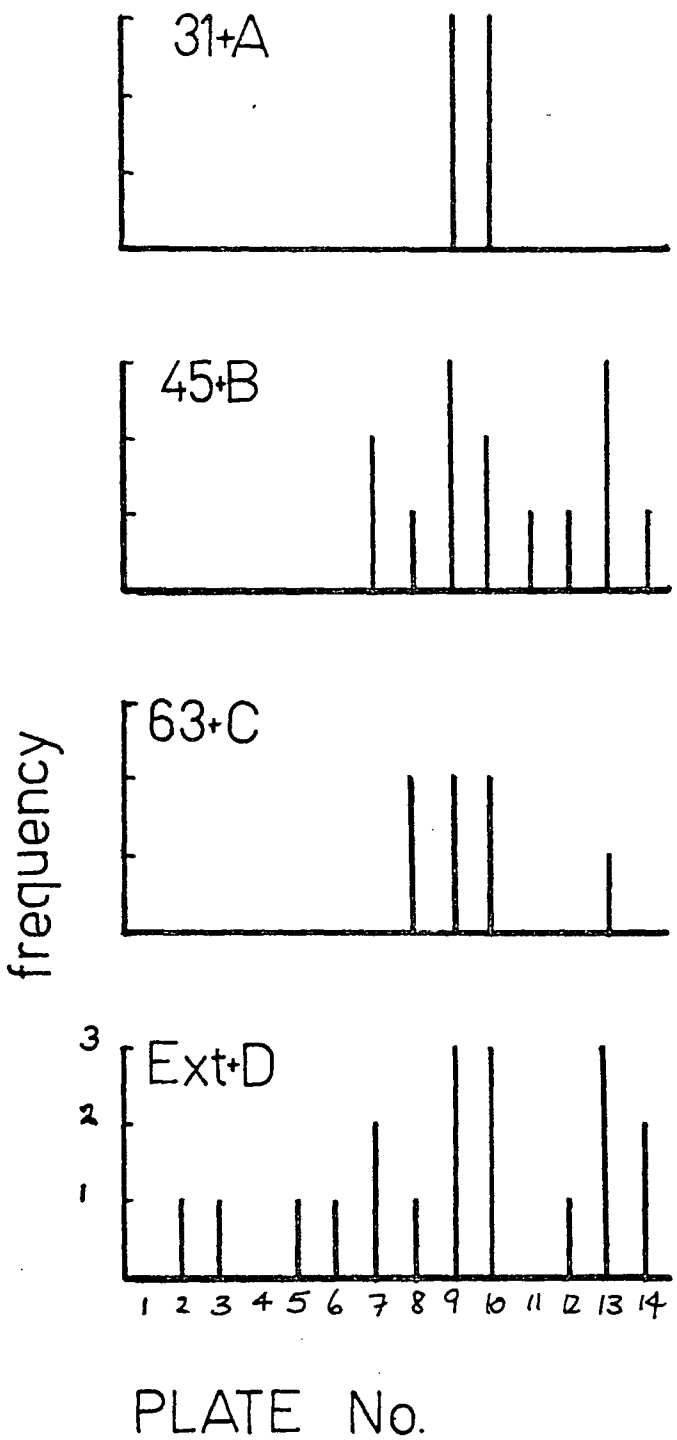


Figure 16b Frequency Histograms for Confusion Errors on the Dvorine Test (0.31 Lux)

DISCUSSION

It would appear from the data collected in Experiment I that the combinations of lens and macular pigment simulation filters produce changes in color vision which resemble those changes which have been attributed to ageing processes. The color matching data shows a general widening of the yellow-blue and blue-green matching ranges. The Yellow-Blue equation seems to be affected most with mid matching points not tending to shift towards the blue as one might expect from the experimental filter characteristics. In-Stead there appears to be a general description of color matching ability. Part of the widening and possible mid-point shifts can be explained by the fact that there are actually fewer discernable differences on the yellow side of the equation than there is on the blue. The increased 'macular pigment' simulation filters seem to affect the yellow-blue and blue-green equations more than did the lens filters. This finding might be interpreted as indirect evidence for the existence of increases in macular pigment due to ageing.

Many subjects accepted matches down to 100% yellow filter in the yellow-blue equation (0 on the anomaloscope setting). No one accepted totally blue matches. Colour

naming of the anomaloscope 'primaries' by the observers with the denser experimental filters proved to be quite difficult. The blue-green equation in particular caused notable colour-naming difficulties, many observers exchanging notable colour-naming difficulties, with many observers exchanging names for the primary filters shown. As gradual increases in the matching ranges can be seen to be associated with increases in filter densities it is not improbable that in the ageing population, increased matching ranges, along these same lines could be produced by gradual selective decreases in ocular transmissivity. However, as can be clearly seen in this study these hypothetical ocular changes do not completely account for the extent of widening of the matching ranges involving blue light found in those age populations which correspond to the four experimental groups mentioned herein. This point becomes more evident when the colour discrimination and confusion data are noted. Figure 17 gives 100 hue mean-partial error scores for the four experimental groups under conditions of mutually increasing filter density pairs. Comparing this figure with Verriest's age data (Fig. 6a) one may note the correspondence between the two lower density conditions. However, there seems to be more error in Verriest's data on the increased age groups than can be accounted for by ocular changes alone;

at least as simulated in the present study. However, the direction of change appears to be correct. If reductions in the total amount of light were made as well, further correspondence might be attained. Experiment II attempted to combine thes imulated reductions in ocular transmissivity with further reductions in illumination in an investigation of colour vision. Because the colour matching data of Experiment I was as anticipated it was felt that the color matching task could conceivably be seen as already at a reduced level. Increases in the luminance of the instrument produced two changes in the response of the experimental observers:

1) Increased luminance decreased the size of the matching ranges, especially the yellow-blue equation.

2) Increased luminance produced a tendency toward shifting the mid-point towards the blue 'primary'.

This finding seems to support Verriest's notion of the possibility of a 'mesopisation' process taking place in the visual system, at least from a physical standpoint. The performance of observers under the increased luminance condition clearly shows improvement. It would seem that the responses become more predictable in the physical terms of the simulation filter characteristics under this increase. It would be interesting to see these mid-points and matching ranges measured on ageing observers at the increased luminance.

If the 'mesopisation' process was to be seen as a reasonable hypothesis, improvement should be noted at the higher of the two brightness levels. Matching ranges should decrease but, as well, the mid-matching point should shift towards the blue 'primary'.[51] Colour discrimination data under low illumination and experimental filters point to an 'early' classification of the Tritan defect and further non-specific degradation after that. The profiles of conditions under low lumination are presented in Figs. 15 (a-d). Although Verriest (1963) reports that complete tritan confusions do not occur until 0.2 Lux; the observers in the present study were scoring in a manner which would classify them as Tritan at a minimum of 0.31 lux with the use of the experimental filters. The first two conditions appear to be tritanopic while the latter two appear anarchic. This breakdown in color discrimination takes place at a level of 0.31 lux and higher. This would tenuously implicate reductions in illumination and strong lens-macular pigmentation as a possible contributor to acquired yellow-blue deschromatopsia. The results of the Pseudoisochromatic Plates in Experiment II

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51. The extent of this shift could be used as an estimate of the spectral characteristics of the ocular media. Presumably, the measurement would take into account the relative threshold for different wavelengths.

raise some other interesting questions. With increasing filter density there are increased error scores on both the Dvorine and AO H-R-R tests. The four most common confusion errors as seen in Figure 16 are Plates 17 and 18 of the AO H-R-R and Plates 9 and 10 of the Dvorine. It is felt that the experimental conditions employed in this section affect not only color discrimination but pattern recognition as well. In random presentations of the Dvorine plates for example, the 'heavily pigmented' observer might still be able to differences in colour but not identify the figure. As noted earlier, the AO H-R-R test editions used in this study showed some parts of figures which were slightly discernable by form contrasts with the surround. The set number of geometrical figures used increases the observer's chances of correct guessing; for example a straight line perceived in the Plate usually means either a triangle or a square etc. It would seem from the observations of the author that responding to a stimulus in a manner which requires some form of verbal recognition of the meaningfulness of the stimulus is conceptually more difficult than simple manipulation of the stimulus parameters as in the 100 hue test. Many subjects 'saw' differences at the reduced illumination levels but were unable to state what these differences were. Of course anything, but

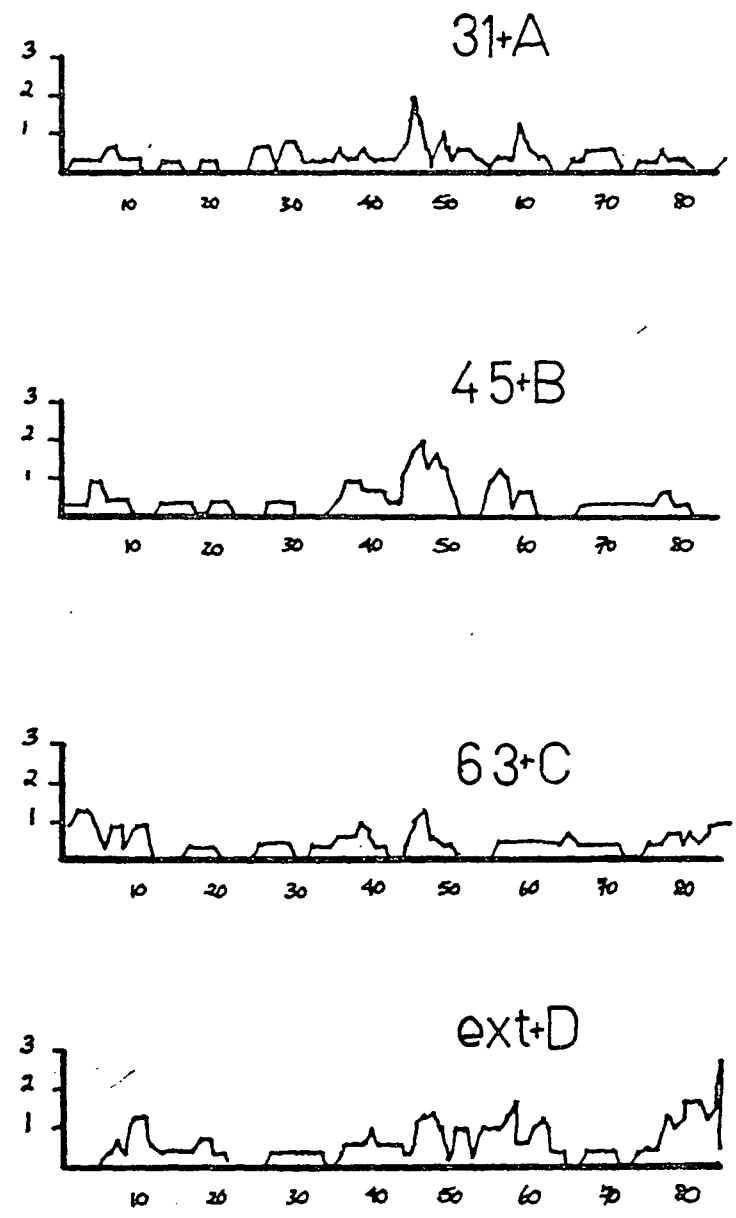

Figure 17 100 hue profile for 4 mutually increasing pairs of simulation filters 100 lux.

but the correct figure response is treated as a mistake in the PIC tests and therefore some potentially useful information is lost as a result of this scoring procedure.

In terms of the generalizability of these findings to ageing processes, it seems that both selective absorption of light and reductions in illumination are needed to express the ageing parameters in physical terms. Senile decreases in colour discrimination have been produced at levels which are slightly higher than previously reported but with experimental simulation filters which simulate lens and macular pigmentary changes.

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Appendix A

Simulation Filter Characteristics
Optical Density vs. Wavelength (single cell conditions)

	A	B	C	D	31	45	63	EXT
390	.1	.14	.25	.34	.07	.18	.84	1.24
400	.13	.18	.3	.4	.07	.17	.81	1.21
410	.15	.20	.35	.48	.06	.16	.76	1.15
420	.16	.28	.42	.58	.06	.14	.66	1.05
430	.18	.33	.48	.64	.05	.12	.48	.9
440	.18	.34	.51	.72	.04	.10	.32	.84
450	.19	.39	.59	.78	.03	.08	.22	.6
460	.19	.38	.59	.76	.02	.06	.12	.44
470	.16	.36	.5	.68	.01	.05	.09	.34
480	.16	.36	.49	.68	.01	.04	.08	.26
490	.14	.32	.42	.60	.01	.04	.06	.18
500	.09	.22	.28	.36	.01	.04	.05	.16
510	.05	.10	.14	.18	.01	.03	.05	.12
520	.03	.05	.07	.08	.01	.02	.05	.10
530	.02	.02	.03	.03	.01	.01	.05	.09
540	.02	.02	.02	.02	.01	.01	.05	.08
550	.01	.02	.01	.01	.01	.01	.05	.08

Appendix A continued (two cell conditions)

	A-31	A-45	A-63	A-EXT	B-31	B-45	B-63	B-EXT
390	.17	.28	.94	1.34	.21	.32	.98	1.38
400	.20	.30	.94	1.34	.25	.35	.99	1.39
410	.21	.31	.91	1.30	.26	.36	.96	1.35
420	.22	.30	.82	1.21	.34	.42	.94	1.33
430	.23	.30	.66	1.08	.38	.45	.81	1.23
440	.22	.28	.50	1.03	.38	.44	.66	1.12
450	.22	.27	.41	.79	.41	.47	.51	.99
460	.21	.25	.31	.63	.40	.44	.50	.82
470	.17	.22	.25	.50	.37	.41	.45	.70
480	.17	.20	.24	.42	.33	.40	.44	.62
490	.15	.18	.20	.32	.33	.36	.38	.50
500	.10	.13	.14	.25	.23	.26	.27	.38
510	.06	.08	.10	.17	.11	.13	.15	.22
520	.04	.05	.08	.13	.06	.09	.10	.15
530	.03	.03	.08	.11	.03	.04	.08	.11
540	.03	.03	.07	.10	.03	.03	.07	.10
550	.02	.02	.06	.09	.02	.02	.07	.09

Appendix A cont'd.

	C-31	C-45	C-63	C-EXT	D-30	D-45	D-63	D-EXT
390	.32	.43	1.00	1.49	.41	.52	1.18	1.58
400	.37	.47	1.11	1.51	.47	.57	1.21	1.61
410	.51	.51	1.11	1.50	.54	.64	1.24	1.63
420	.48	.56	1.08	1.47	.64	.72	1.24	1.63
430	.53	.60	.96	1.38	.69	.76	1.12	1.54
440	.55	.61	.83	1.35	.76	.82	1.04	1.54
450	.62	.67	.81	1.19	.81	.86	1.00	1.38
460	.61	.65	.71	1.03	.78	.82	.88	1.20
470	.51	.55	.59	.84	.69	.73	.77	1.02
480	.50	.53	.57	.75	.69	.72	.74	.94
490	.43	.46	.48	.60	.61	.64	.66	.78
500	.29	.32	.33	.44	.37	.40	.41	.52
510	.15	.17	.19	.26	.19	.21	.23	.30
520	.08	.10	.12	.17	.09	.10	.13	.18
530	.04	.04	.08	.12	.04	.04	.08	.12
540	.03	.03	.07	.10	.03	.03	.07	.10
550	.02	.02	.06	.09	.02	.02	.06	.09

Appendix A cont'd.

	C-31	C-45	C-63	C-EXT	D-30	D-45	D-63	D-EXT
390	.32	.43	1.00	1.49	.41	.52	1.18	1.58
400	.37	.47	1.11	1.51	.47	.57	1.21	1.61
410	.51	.51	1.11	1.50	.54	.64	1.24	1.63
420	.48	.56	1.08	1.47	.64	.72	1.24	1.63
430	.53	.60	.96	1.38	.69	.76	1.12	1.54
440	.55	.61	.83	1.35	.76	.82	1.04	1.54
450	.62	.67	.81	1.19	.81	.86	1.00	1.38
460	.61	.65	.71	1.03	.78	.82	.88	1.20
470	.51	.55	.59	.84	.69	.73	.77	1.02
480	.50	.53	.57	.75	.69	.72	.74	.94
490	.43	.46	.48	.60	.61	.64	.66	.78
500	.29	.32	.33	.44	.37	.40	.41	.52
510	.15	.17	.19	.26	.19	.21	.23	.30
520	.08	.10	.12	.17	.09	.10	.13	.18
530	.04	.04	.08	.12	.04	.04	.08	.12
540	.03	.03	.07	.10	.03	.03	.07	.10
550	.02	.02	.06	.09	.02	.02	.06	.09