In 1893 Hering\(^1\) observed that reduction of the field size of an anomaloscope set for the observer's Rayleigh equation caused the mixture field to appear too "red." A new mixture requiring a higher \(G/R\) ratio was necessary. Hering attributed the changes to variation in the density of macular pigment. Quantitative data were obtained by Horner and Purslow\(^9\) using a filter anomaloscope. They showed that the \(G/R\) ratio increased as viewing distance increased (and field size decreased). The effect was 0.07 log unit between a 2° field viewed at 50 cm and a 20 min field viewed at 300 cm. They remarked on intersubject variability but confirmed the finding on 40 observers. They attributed the change to chromatic aberration but, in the second paper, mentioned the Stiles-Crawford effect as an alternative explanation.

These studies show changes in metamers as field size is varied. Such changes may also represent variation of receptoral characteristics.\(^3\) Pokorny, Smith, and Starr\(^4\) explained differences in the unit coordinates for 2° and 10° field sizes by postulating a continuous exponential decrease in effective optical density of the photoreceptors as field size is increased. The direction of change of the \(G/R\) ratios is in the direction predicted by such a variation of effective optical density in the retina. Baker\(^7\) and Alpern and Torii\(^8\) demonstrated that Rayleigh matches are characteristic of pigments in density. Following a bleach, the mixture field appears green. The \(G/R\) ratio must be decreased to maintain a match. The match recovers within 60 to 90 sec.

The present experiment was designed to investigate the Horner and Purslow results using a fixed viewing distance, narrow-band spectral stimuli, and an extended range of field sizes (30' to 10°). A second aim was to estimate the proportion of variability that might be ascribed to receptoral variance, and to examine its range of field sizes (30' to 10°). The \(G/R\) mixture decreases continuously as field size is increased. The data are consistent with the interpretation that the cone visual photopigments decrease exponentially in effective optical density as the field size is increased.

The anomaloscope was used in a manner essentially identical to that of the Nagel anomaloscope.\(^10\) The spectral yellow was variable in luminance; the \(G/R\) mixture was variable from green to red. The primary energies were set so that normal matches would fall near a \(G/R\) of 1.0. The luminances of the \(R\) and \(G\) primaries were similar. The effective field luminance was approximately 5 cd/m\(^2\).

**Observers:** Ten normal trichromats served as observers. They were drawn from laboratory personnel and included naive observers and observers well practiced in making color matches. Their ages ranged from 22 to 36 years.

**EXPERIMENT 1: THE EFFECT OF FIELD SIZE**

**Procedure:** Each observer viewed with his preferred eye. The 2° field was presented first. The observer made 3 "free" matches, a procedure in which he is allowed to vary the luminance of the \(Y\) primary and the \(G/R\) mixture in order to obtain a perfect match. Between settings, the experimenter varied the control knobs. After the free matches, the experimenter established a match range by setting various \(G/R\) ratios and asking the observer to state whether the ratios constituted a match. The observer was allowed to make minute adjustments of the \(Y\) control during this procedure. Observers could not achieve a perfect match with the 8° and 10°×10° fields. They were instructed to set the \(G/R\) ratio so that the mixture half-field appeared neither more "reddish" nor more "greenish" than the spectral half-field. Each observer was cautioned not to stare continuously at the field but rather to use a glance technique in which he looked away every 10–12 sec.

Following the initial settings for the 2° field, the other field sizes were presented in varied order, with a brief break between field sizes. At the end of the procedure, matches were rechecked for the 2° field.

**Results and Discussion:** The dial readings were converted into \(\log G/R\). In population studies,\(^1\) the normal mean is assigned a value of 0, with a range between the 2nd and 98th percentiles of ± 0.15. Positive \(\log G/R\) ratios reflect an increase in \(G\) primary, negative ratios an increase in \(R\) primary, needed for the match. \(\log G/R\) ratios for the 10 observers are shown in Fig. 1 as a function of field size. All observers require more red in their match as the field size is increased.

**Effect of field size on red—green color mixture equations**

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logG/R ratios change most rapidly for small field sizes, leveling off above 4°. The spread of individual observers is approximately 0.18 log unit for field sizes greater than 30 min and 0.205 for the 30 min field.

Chromatic aberration

Horner and Purslow ascribed their result to chromatic aberration. We found chromatic fringes evident as the field size was reduced below 2°. A red fringe surrounding the mixture field may have interacted with the match settings for the 30° and 1° fields. To check this possibility, we introduced a 2 mm artificial pupil containing an achromatizing lens designed to compensate for chromatic aberration of the eye. Two observers (VP and JP) repeated experiment 1. The data were within experimental variance.

Rod intrusion

The effect of rod intrusion, on a large-field Rayleigh match at 5 cd/m², is desaturation of the mixture field. The desaturation appears more marked with a 100-fold reduction of luminance and the mixture field appears "pinkish." If a desaturant is allowed, a match may be made and the R/G ratio will depend on the choice of desaturant. We ascertained on four observers that at 5 cd/m², neither the use nor choice of desaturant affected the G/R ratio. Thus, rod intrusion was not a major source of contamination of the G/R ratios. Further, had rod intrusion affected the G/R ratios, we might have expected greater interobserver variability in setting the G/R ratio at the 8° and 10° x 10° fields as evident, for example, in the Stiles and Burch 10° data. However, the logG/R range was the same for the 8° and 10° x 10° fields as for the 2° field, supporting the notion that rod intrusion did not interact with the G/R setting. We note that any effect would have been opposite in direction to the trend of data shown in Fig. 3.

EXPERIMENT 2: THE VARIABILITY CONTRIBUTED BY INERT OCULAR PIGMENTS

Procedure: The 2° aperture stop was used. Each observer made two sets of matches, one at the standard Rayleigh wavelength of 589 nm and one at a wavelength of 575 nm. Free matches and match widths were established as described above. The data were converted to logG/R.

Results and Discussion: Columns 1 and 2 of Table I show the results of log G/R for the 589 and 575 nm fields. The matches for 589 nm vary around 0, those for 575 nm around 0.427. Column 3 shows values obtained by subtracting log G/R at 589 nm from log G/R at 575 nm. The effect of inert ocular pigments on log G/R is to multiply the retinal match by the factor T670/T545, where T670 is the transmission factor for the inert pigments at the 670 nm primary and T545 is the transmission factor for the inert pigments at the 545 nm primary. The matches are not affected by transmission factors for the test wavelength. Subtracting log G/R at 589 nm from log G/R at 575 nm for each observer removes the effect of the observer’s inert pigments. The range of variation in the column 3 values reflects receptor variability and repeatability variance. In comparison, the range of variation in the column 1 and 2 matches reflects, in addition, variation contributed by inert pigments.

Moreland discussed the role of inert ocular pigments in accounting for interobserver variability in Rayleigh matches. The macular pigment does not absorb at wavelengths above 540 nm and would not contribute to variability in this study. The inert ocular pigment that may affect Rayleigh matches is that in the lens. Moreland suggests that lens variation in observers ranging in age from 20 to 60 years might account for 0.1 log unit of published log G/R ranges. His calculation was based on Said and Weale’s data suggesting a linear change of lens density with age. Coren and Girgus suggest that a second degree polynomial is a better fit to the age data. Use of the polynomial would

![FIG. 1. Log G/R ratios for ten observers plotted as a function of the field of view.](image-url)
increase Moreland's expected log G/R range due to age to 0.18. Our observers ranged in age from 20 to 36 years, which would predict no more than a 0.1 variation in log G/R due to differences in age. Examination of Table I shows that the ranges in columns 1-3 are 0.185, 0.205, and 0.075, respectively, confirming that the major portion of the interobserver range at 2° (about 0.1) may be ascribed to population variation in inert lens pigment.

We can calculate the variance of the match at 589 nm expressed as percent green normalized at 575 nm for comparison with data of Stiles. The standard deviation was 0.008 compared with Stiles' report of an average deviation of 0.0075 in the same spectral region.

EXPERIMENT 3: RECOVERY FROM BLEACH

Procedure: A silicon photocell (UDT PIN10) was used to sample the fraction R in the R/G output. The photocell output was amplified and displayed on a chart recorder. A 3200 °K light of luminance 6000 mL was used to present a uniform bleach over the visual pupil. The pupil constricted to about 2 mm giving an estimated 60,000 tds, providing a substantial bleach.

The upper 3 traces are red runs; the lower are green runs.

We used the procedure described by Alpern and Torii: Following the bleach, the observer viewed either the 2° or the 8° field and attempted to track the recovery following one of two criteria—tracking between "too red" and "match" or tracking between "too green" and "match." Three repetitions were made for each criterion.

Results and Discussion: The sets of recoveries, superimposed on each other, are shown in Fig. 2. The fraction R in the match is shown as a function of time. In panel (a) are shown the data for the 2° field and in panel (b) the 8° field. For the 2° field, the upper three traces are the red runs, the lower three traces are the green runs. For the 8° field, the sets of traces are not clearly separated. The solid line shows the midpoint of the steady-state match (experiment 1). The arrows show the fraction red predicted for dilute pigments assuming optical densities of 0.45 for LWS, 0.35 for MWS for the 2° field. We have chosen to reproduce the actual tracings of the chart recorder to demonstrate the variability of the technique. The widening of match width noted by Alpern and Torii is evident in the 2° field recoveries but not in the 8° field recoveries; the red runs for the 2° and 8° fields are quite different, while the green runs are similar. The sets of green runs for the 2° and 8° fields are initially overlapping but draw apart at full recovery. The data support the hypothesis that for observer VP, the 2° field is characterized by visual pigments in higher densities than those characterizing the 8° field. However, the variability is too great to allow estimation of optical density or pigment kinetics for either field.

We were also able to demonstrate informally that the field size effect for four other observers reflected pigments in different densities: The observers state that the mixture field for a match made at 10° appears too red when viewed with the 2° field stop. Following a bleach, this mixture field viewed with a 2° stop appears initially greener than the spectral yellow, passes through the 10° match at about 45-60 sec, and then appears too red at full recovery.

THEORETICAL TREATMENT

While the inert pigments do contribute to interobserver variability, we would not expect them to interact with the field size for a given observer. We therefore reduced the matches for all field sizes by subtracting the Table I column 2 match for each observer and adjusting matches to set the mean log G/R at 2° to zero. Means and standard deviations were computed and are shown in Fig. 3. Error bars are ± one standard deviation. The solid line is a theoretical prediction for log G/R, calculated for an observer whose visual pigments show a continuous exponential decrease in effective optical density as field size increases. The effective densities are those derived previously. We assume that effective optical density for the long-wavelength sensitive pigment varies as

\[
OD_{LWS} = 0.25 + 0.8825 e^{-d/1.333}
\]

and that for the middle wavelength varies as

\[
OD_{MWS} = 0.15 + 0.8825 e^{-d/1.333}
\]

where d is the diameter of the viewing field in degrees. These equations pre-
dict effective optical densities of 0.45 for LWS, 0.35 for MWS for the 20 field. The prediction passes within one standard deviation of the observed results for all field sizes. However, the average data fall below the prediction for the 30' and 10' fields and above the prediction for 40, 80, and 100 x 100 fields suggesting that the exponential should be more compressed. For example, $OD = k + 0.75 e^{-d/1.333}$ would provide a better fit for the $G/R$ mixture data.

We conclude that these data provide experimental confirmation that the effective optical density of the visual photopigments decreases continuously as field size increases.

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3In contrast, studies of chromatic cancellation [S. S. Stevens, "The relation of saturation to the size of the retinal image," Am. J. Psychol. 46, 70-79 (1934); M. M. Connors and J. A. S. Kinney, "Relative red-green sensitivity as a function of relative position," J. Opt. Soc. Am. 52, 81-84 (1962)] and other spectral sensitivity studies with change in retinal position may additionally be affected by variation in the relative populations and sensitivities of the receptor classes.


