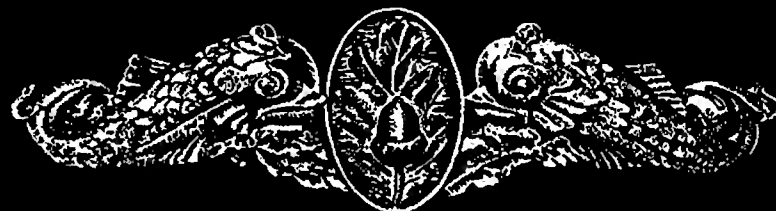


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RELATIVE RED-GREEN SENSITIVITY AS A FUNCTION OF RETINAL POSITION

by

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SUMMARY PAGE

THE PROBLEM

To determine the relative sensitivity to red and green in different parts of the visual field.

FINDINGS

Sensitivity to red, relative to green, is highest at the fovea and decreases as the peripheral angle is increased. The relative sensitivity to green is highest in the near periphery, from 2 to 10 degrees from the fovea. Beyond this point it falls rapidly and is no longer measurable at points where red is still seen.

APPLICATION

Red and green are often employed to color code signal lights and panels of instruments which are used on all naval craft. Since these colors are frequently judged as part of a total picture rather than by an independent foveal judgment of each light, it is necessary to know how these colors will appear when viewed peripherally. The present report contributes some information on this problem.

ADMINISTRATIVE INFORMATION

This investigation was undertaken as a part of Bureau of Medicine and Surgery Research Project MR005.14-1001, Under Subtask (1) Psychophysiological Studies of Visual Factors in Submarine Operation. The present report is No. 27 on this Subtask. It was published in the Journal of the Optical Society, Vol. 52, No. 1, January 1962.

Relative Red-Green Sensitivity as a Function of Retinal Position

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Hue cancellation was employed to obtain sensitivity curves for red and for green by the method of constant stimuli. Data were taken at the fovea, and at points every 2 deg along the lower vertical meridian of the visual field. The results show that sensitivity to red, relative to green, is highest at the fovea, and decreases as the peripheral angle is increased. The relative sensitivity to green is highest in the near periphery, from 2 to 10 deg from the fovea. Beyond this point it falls rapidly, and is no longer measurable at positions where red responses are still obtained.

INTRODUCTION

BOTH casual observations and laboratory measurements (Maxwell,¹ Charpentier,² and Stevens³) have indicated that the hue of a red-green mixture depends upon the size of the stimulus and its location in the visual field. As an observer moves away from a color-mixer disk made up of red and green or as the size of the disk is reduced, its color appears redder. Conversely, as the observer approaches a stimulus of fixed area, or as the size of the stimulus is increased, the mixture becomes greener.

Stevens' interpretation of these observations is that the "functional receptor units vary in density in different parts of the retina; the red is more concentrated at the center of the fovea and less concentrated in the peripheral areas as compared with the blue-green." Wentworth⁴ and Connors and Kelsey⁵ have shown that reports of red can be obtained much farther from the fixation than reports of green, indicating that at least some peripheral areas are more sensitive to red than to green.

The present experiment was undertaken to determine the relative sensitivity to red and green in different parts of the visual field, in order to examine the apparent contradiction of the data of perimetry and of color mixture. To do this, Stevens' method of mixing complementary colors was applied to various discrete points in the visual field.

APPARATUS

The instrument employed was a wide-field colorimeter, designed and built by the Eastman Kodak Company.⁶ Although this instrument can provide a bipartite field, only one half of the viewing screen was utilized in the present experiment. The light source, which was a xenon arc, illuminated a sphere behind the viewing screen. Narrow-band interference and sharp-

cutoff blocking filters determined the wavelengths of the mixture components. A description of the filters is given in Table I. The composition of the mixture was controlled by two adjustable diaphragms which were calibrated to permit small stimulus increments. All luminance measurements were made with the spectra brightness spot meter.

The stimulus field of the colorimeter was masked to 0.77-cm diameter to provide a stimulus of 1° diameter. The masking screen which was matte white, served as a surround and was illuminated to 0.1 ft-L. Peripheral stimulation was accomplished by moving the fixation point to predetermined distances above the stimulus field. Presentation of the stimulus for $\frac{1}{2}$ sec was provided with a rotary shutter controlled by the experimenter. Observations were made with the right eye; the left eye was occluded.

OBSERVERS

Three members of the staff of the laboratory, M. C., J. K., and A. R., served as observers. One is myopic, one hyperopic, and one emmetropic. The ametropes were corrected to 20/20 acuity. All have normal color vision.

PROCEDURE

When the right proportions of the red and green stimuli were mixed, complete cancellation of both red and green was obtained and the stimulus field appeared gray if viewed directly. At other proportions of the components, the stimulus was reported as red or green. Discrimination limens were determined for red and for green in the mixture.

The *method of constant stimuli* was employed to determine these limens at the fovea and at every 2 deg away from the fixation point along the lower vertical meridian of the visual field. This procedure was con-

TABLE I. Description of stimulus components.

Filters	Dominant wavelength	Percent purity	Max. lum. in ft-L	Half-width
Red	677	97	0.190	13 m μ
Green	496.9	97	0.163	12 m μ

¹ J. C. Maxwell, "On the theory of compound colours and the relations of the colours in the spectrum," *Phil. Trans. Roy. Soc. London* 150, 57-84 (1860).

² M. Charpentier, "Sur une condition physiologique influençant les mesures photométriques," *Lumière électrique* 21, 165 (1886).

³ S. S. Stevens, *Am. J. Psychol.* 46, 70 (1934).

⁴ Hazel A. Wentworth, *Psychol. Monographs*, 40, 183 (1930).

⁵ Mary M. Connors and Patricia A. Kelsey, *J. Opt. Soc. Am.* 51, 874 (1961).

⁶ D. L. MacAdam, *J. Opt. Soc. Am.* 40, 589 (1950).

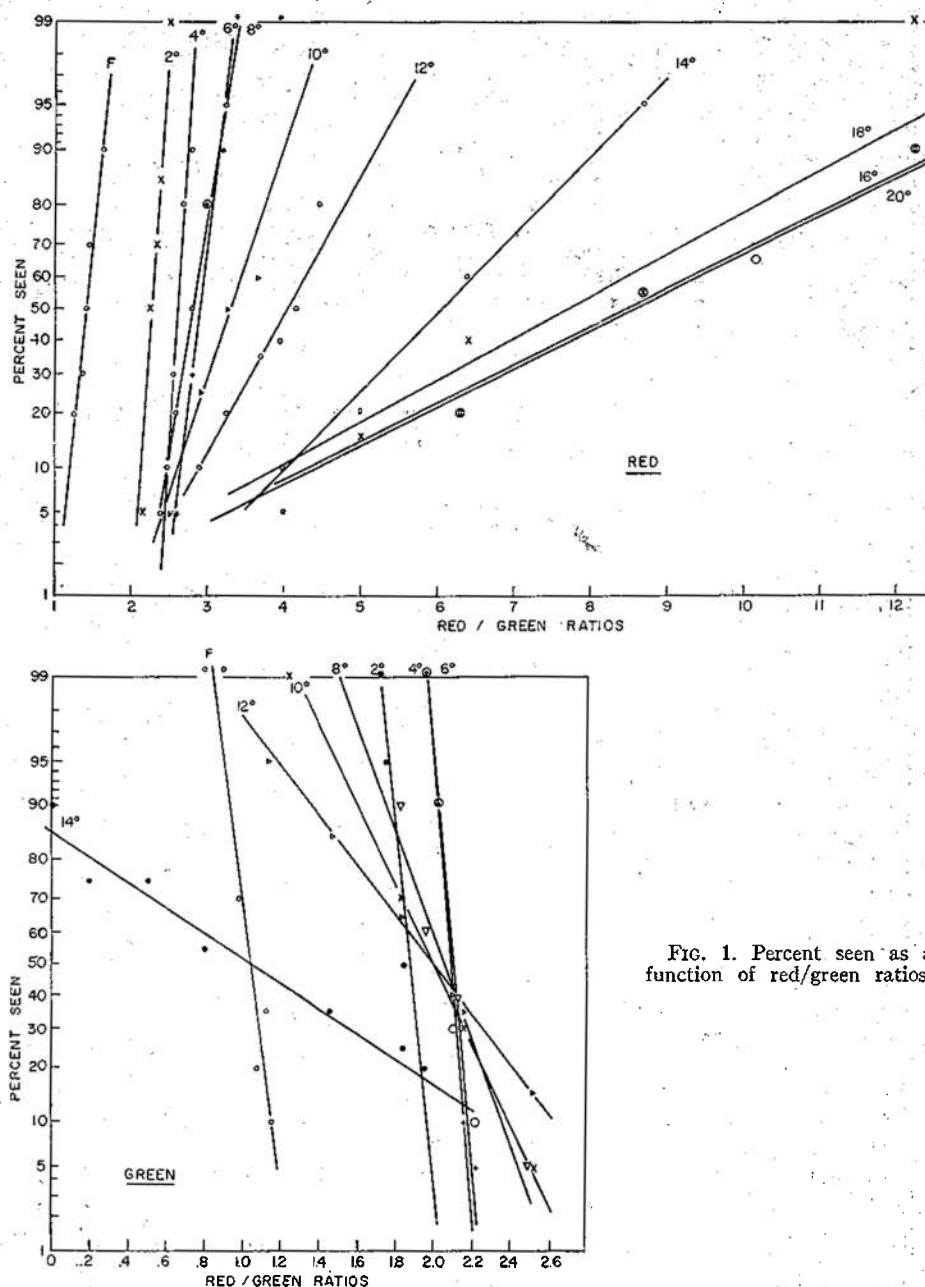


FIG. 1. Percent seen as a function of red/green ratios.

tinued until the color could no longer be seen, influenced both by the decreasing sensitivity of the retina and the limitations of the apparatus. Each frequency-of-seeing curve was based on the percent-seen of red (or green) as a function of the red/green ratio. Twenty readings were taken at each ratio, providing 100 judgments for each curve.

The observer's task was to report if the stimulus appeared red, or not red; green, or not green. The green was set at 0.056 ft-L and the various red/green ratios were obtained by adding different amounts of red. In order to extend the range beyond 8° from fixation the absolute amount of green was reduced. At this point,

sensitivity to green was high enough so that the absolute amount of green was not a limiting factor in the liminal determinations. However, sensitivity to red had decreased to the extent that the reduction in green was necessary to obtain the higher red/green ratio. Beyond 14° from fixation, sensitivity to green had become so low that green could not be seen even with the maximum green stimulus (0.163 ft-L); but, by increasing the amount of red to the maximum (0.19 ft-L) the red range was further extended and liminal determinations were made by varying the green.

To ensure that the ratio limens were independent of these stimulus changes, data were taken at 8° from

TABLE II. Limens for green in terms of red/green ratios.*

Degrees from fovea	M. C.		Observers		A. R.		Mean	
	Limens	σ	J. K.	σ	Limens	σ	limens	σ
0	1.04 (0.114)	0.07	1.07 (0.116)	0.14	1.73 (0.133)	0.15	1.28	0.12
2	1.89 (0.162)	0.07	1.89 (0.162)	0.14	2.03 (0.170)	0.10	1.94	0.10
4	2.10 (0.174)	0.06	2.06 (0.171)	0.08	2.12 (0.175)	0.10	2.09	0.08
6	2.12 (0.175)	0.06	1.95 (0.165)	0.12	1.78 (0.156)	0.20	1.95	0.13
8	2.06 (0.171)	0.22	1.98 (0.167)	0.23	1.89 (0.162)	0.26	1.98	0.24
10	2.05 (0.092)	0.30	2.07 (0.092)	0.57	1.94 (0.165)	0.34	2.02	0.40
12	2.00 (0.090)	0.50	1.76 (0.083)	0.76	1.11 (0.118)	0.31	1.62	0.52
14	1.03 (0.061)	1.02						

* Ratios computed from components in ft-L. () Total luminance of stimulus in ft-L.

fixation under three different conditions, two levels of green (0.056 ft-L and 0.030 ft-L) with red added; and one level of red (0.055 ft-L) with green added. The three conditions yielded comparable limens in terms of red/green ratios.

RESULTS

The complete data for one observer are given in Fig. 1. Percents seen of red (and green) are plotted as a function of the ratio of red to green in the mixture. These data demonstrate the method by which the limens and the standard deviations were obtained. This figure shows that both the liminal values and the slopes of the distributions vary with position in the visual field.

Table II gives the limens (i.e., the ratios that just appear green) for all observers in terms of red/green ratios. As the peripheral angle is increased, the ratios first rise and then fall. The higher ratios, those between 2° and 10° from fixation, indicate the positions where

TABLE III. Limens for red in terms of red/green ratios.*

Degrees from fovea	M. C.		Observers		A. R.		Mean	
	Limens	σ	J. K.	σ	Limens	σ	limens	σ
0	1.42 (0.136)	0.16	1.62 (0.147)	0.25	2.19 (0.179)	0.32	1.74	0.24
2	2.28 (0.184)	0.10	2.40 (0.190)	0.10	3.00 (0.224)	0.14	2.56	0.11
4	2.62 (0.183)	0.12	3.09 (0.229)	0.11	3.04 (0.226)	0.29	2.92	0.17
6	2.89 (0.218)	0.21	2.82 (0.214)	0.18	2.61 (0.202)	0.30	2.77	0.23
8	2.79 (0.212)	0.26	3.20 (0.235)	0.70	3.08 (0.228)	0.35	3.00	0.44
10	3.28 (0.128)	0.46	3.70 (0.141)	0.21	3.68 (0.140)	0.45	3.55	0.37
12	4.05 (0.152)	0.88	3.10 (0.123)	0.65	5.50 (0.098)	1.60	4.22	1.04
14	6.10 (0.221)	1.60	1.72 (0.082)	1.78	8.25 (0.129)	2.90	5.36	2.09
16	8.50 (0.212)	2.70	1.90 (0.290)	1.80	9.30 (0.094)	2.65	6.57	2.38
18	7.75 (0.215)	2.50	6.00 (0.222)	3.30	20.70 (0.199)	9.00	11.48	4.93
20	8.90 (0.211)	2.65			22.30 (0.199)	6.20		

* Ratios computed from components in ft-L. () Total luminance of stimulus in ft-L.

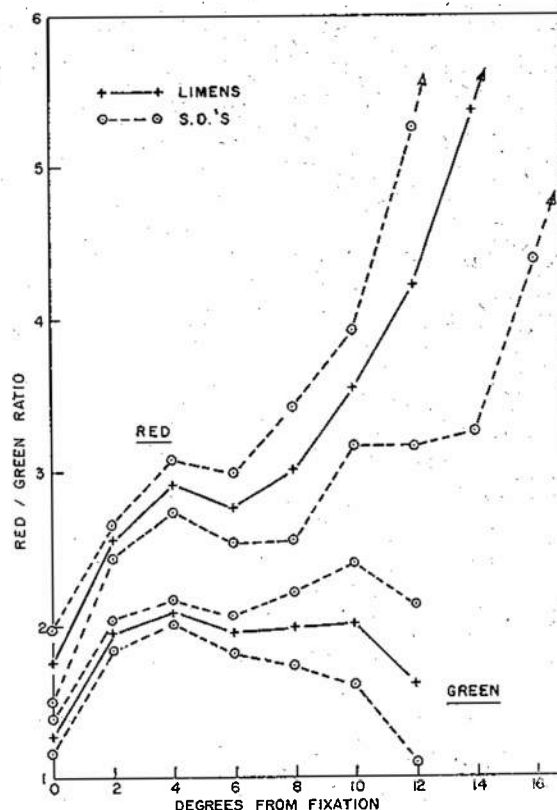


FIG. 2. Averaged limens and standard deviations of three observers as a function of position in the field.

proportionately less green is needed for the stimulus to appear green. Beyond 14° from fixation, none of the observers was able to perceive the stimulus as green, even with the red removed and the maximum green stimulus presented.

Table III gives comparable data for red. For all observers, the red/green ratios are smallest at fixation and increase with increasing distance from fixation. An interesting interruption in this trend is found in the data of J. K. There is a sudden decrease in the red/green ratios at 14° and 16° from fixation where green responses could not be obtained. Beyond 16° from fixation another reversal occurs and a high percentage of red is necessary for the stimulus to be perceived as red.

Another indication of changing function is seen from the standard deviations of Tables II and III. For both red and green the standard deviations of the distributions are slightly higher at the fovea than at 2° or 4° from fixation. Beyond 4° the slopes of the curves become successively less steep, the standard deviations increasing to 10 to 20 times their foveal values.

The average limens for red and for green and the standard deviations are presented in Fig. 2. This affords a direct comparison of the effectiveness of the stimuli with change of position. This graph reveals the following points. First, the appearance of a given ratio varies with location. One demonstration of this phenomenon

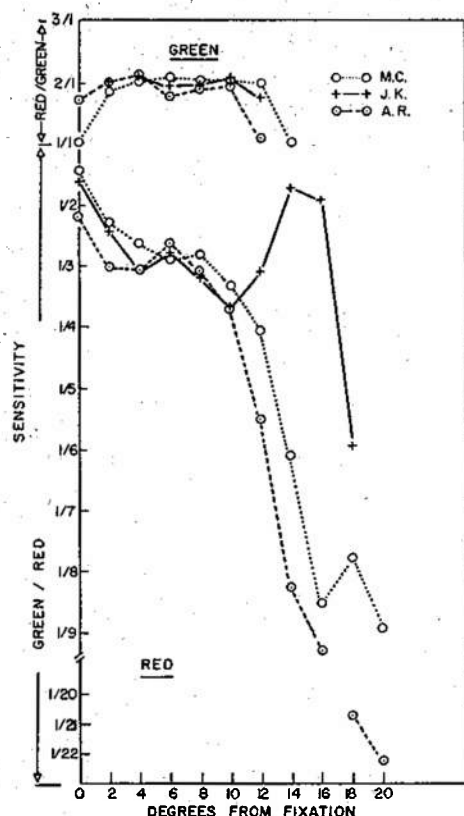


FIG. 3. Sensitivity curves for red and green for three observers. The spacing of the units on the ordinate are not linear, numerically, but have been adjusted to keep equal proportions of red and green; i.e., 3 to 1 of red/green is equal spatially to 1 to 3 of green/red.

is that a ratio which is perceived as red at the fovea will be called green in the near periphery. Second, as the periphery is approached, the range of ratios perceived as neither red nor green increases greatly until green is no longer reported and a red/green ratio of 11/1 is needed for perception of red.

A different procedure has been employed in Fig. 3. The limens for green remain in terms of red/green ratios, while the limens for the red have been converted to their reciprocals, green/red ratios. By recasting the data in this manner, it is possible to make comparisons between red and green and to infer patterns of sensitivity. For all observers, the relative sensitivity to red decreases irregularly from fovea to periphery. The relative sensitivity to green follows an even closer pattern among observers, showing less than maximum sensitivity at the fovea, rising to a plateau in the near periphery, and dropping rapidly to zero by 16° from fixation.

DISCUSSION

There is no contradiction between the findings of Stevens and those of Wentworth and Connors and Kelsey regarding the relative sensitivity to red and to green at the fovea and in the periphery. However, the interpretations of retinal sensitivity immediately suggested by these findings are at variance.

An examination of the patterns of sensitivity found for all observers in the present experiment resolves the apparent contradiction of the previous studies. The red-sensitivity curve is highest at fixation, lowering as the peripheral angle is increased. The green curve reaches a peak in the near periphery, falls rapidly, and green is no longer seen at a smaller peripheral angle than the red. Therefore, the phenomenon described by Stevens of increasing the size of the mixture and having it take on a green tone is explained by the addition of the more green-sensitive near-peripheral regions. This explanation does not involve the necessity of assuming a continuing increase in sensitivity, nor a proportionate (to red) increase in sensitivity to green in the far periphery (where Wentworth and Connors and Kelsey have shown green sensitivity to be greatly diminished). Since Stevens' investigation included a radius of only 10° from the fovea, the reduced sensitivity to green in the far periphery was not reflected in his results.

There were several advantages in determining the changing ratios of sensitivity from the two directions (relative sensitivity to red and to green). First, in asking an observer to judge a cancellation, it is necessary that the stimulus can be made to appear similar at each retinal position. In our experience, these wavelengths which appeared equally bright and saturated and canceled to a white at the fovea were often seen as yellow in the periphery. This fact compounds the observer's difficulty in making judgments. Second, by plotting both the red and the green functions, the areas of cancellation (those ratios which are neither red nor green) are found to be, not a constant, but a variable correlated with peripheral angle.

Because of the interdependence of red and green in a given ratio, no statement can be made of the absolute sensitivity to either component. However, a comparison of the total curves for red and for green reveals their lack of concomitance and indicates that sensitivity to both colors must be changing with peripheral angle.

The dramatic shift in red/green sensitivity between the fovea and the near periphery suggests the influence of macula pigmentation. The absorption characteristics of the macula would lead to ratio changes in the direction found in this experiment.

Numerous authors (Maxwell,¹ Parsons,⁷ LeGrand,⁸ Jaeger⁹) have indicated that differences in pigmentation may account for variations in color-mixture functions among normal observers. A further indication of the effect of the macula in the present experiment can be seen from the fact that individual differences among the three observers are greater at the fovea than they are at 4°-6° in the periphery, where the macula is no longer an influencing factor.

⁷ J. H. Parsons, *An Introduction to the Study of Colour Vision*, (Cambridge University Press, London, 1924), 2nd ed., pp. 43-44.

⁸ Y. Le Grand, *Light, Colour and Vision* (John Wiley & Sons, Inc., New York, 1957), p. 322.

⁹ W. Jaeger, *Die Farbe* 4, 205-206 (1955).