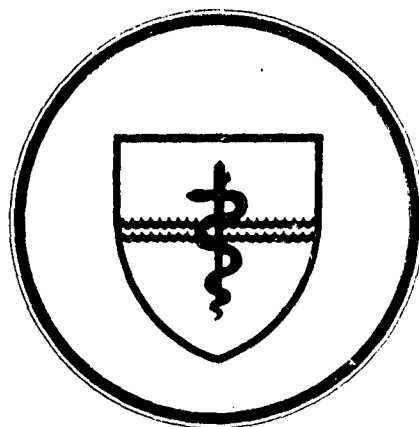


NAVAL SUBMARINE MEDICAL
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REPORT NUMBER 995

THE QUANTITY OF LIGHT PRODUCED BY RED AND BLUE FILTERS
OVER LIGHT FIXTURES IN SONAR CONTROL ROOMS

by

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Naval Medical Research and Development Command
Research Wcrk Unit M0100.001-1012

Released by:

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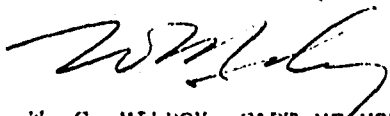
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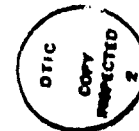
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NAVAL MEDICAL RESEARCH AND DEVELOPMENT COMMAND
Research Work Unit MO100.001-1014

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SUMMARY PAGE

PROBLEM

To compare the light produced by red and blue filters used in sonar control rooms.

FINDINGS

At the low levels used in sonar control rooms, the blue filter produces more light than the red.

APPLICATION

This result explains the popularity of blue and will be helpful in making recommendations for improvements in sonar control room lighting. A nomograph for use in setting lighting levels is presented which allows design engineers, etc., to predict the actual effective brightness of red or blue lights if the photopic luminance is measured.

ADMINISTRATIVE INFORMATION

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ABSTRACT

Red and blue lights of the type used in sonar control rooms were matched in brightness to white light at the low levels of illumination commonly employed in operational conditions. Blue was judged considerably brighter than the red; this difference increased as the light level decreased. A theoretical analysis yielded the same result. The increase in the general level of room illumination should allow the men to see large objects and the room outlines better and helps account for their preference for blue illumination.

INTRODUCTION

Until very recently, submarine sonar control rooms have been provided with red illumination in order to be compatible with other red-lighted submarine control areas. Within the past two years, however, a number of successful trials of blue lighting have been made on operating submarines¹ and these have resulted in an order for all submarines to change from red to blue illumination in their sonar control rooms within the current year.² Our analysis of the popularity of blue lighting suggests at least four possible reasons which we are systematically investigating.³⁻⁵ This paper is a theoretical and empirical assessment of one of these reasons: an increase in the general level of illumination with blue light.

The change from red to blue illumination is made quite simply by removing the red plastic sleeves which cover the fluorescent light bulbs and replacing them with blue. Both are available from the GSA catalogue. Since the two filters have essentially the same percent transmittance, one might conclude that the switch changes only the color of the light and not the overall quantity of light. Interestingly this is not true. The reasons involve both the definition of light and knowledge of the underlying physiology of the eye.

Light is electromagnetic energy but only that portion of the spectrum to which the human eye is sensitive. It is defined, quantitatively, as:

$$L = K \int_{360}^{830} L_{e\lambda} V(\lambda) d\lambda$$

where L is some unit of light, K is a constant depending upon the specific unit, $L_{e\lambda}$ is the spectral radiance in watts/m², $V(\lambda)$ is spectral luminous efficiency for photopic vision from 360 to 830 nm, and λ is the wavelength of the energy. The important parameter here is $V(\lambda)$, a function which describes the sensitivity of the eye to different wavelengths of electromagnetic energy. This function was standardized in 1924 by the Commission Internationale de l'Eclairage (CIE) and has been used as the international basis for light ever since.⁶ All light meters, whether they measure foot candles, candelas per square meter or are calibrated in f-stops for photography, have their spectral sensitivity adjusted as closely as possible to duplicate the $V(\lambda)$ function. This serves the purpose of equating any distribution of electromagnetic energy for its effectiveness for human vision.

This system has functioned successfully for most applications for fifty years, but there are some instances in which it fails; these all involve the use of $V(\lambda)$ in cases for which it does not adequately represent the spectral sensitivity of the human eye.⁷

One major misuse of the $V(\lambda)$ function is for low light levels which are not in the range of daylight or photopic vision. At nighttime or scotopic levels of illumination, the spectral sensitivity of the eye shifts toward the shorter wavelengths, as shown in Fig. 1. The use of $V(\lambda)$ values to evaluate the electromagnetic energy when scotopic or night vision values apply results in sizeable errors. The contributions of the short wavelengths (violets, blues, and blue-greens) are under-

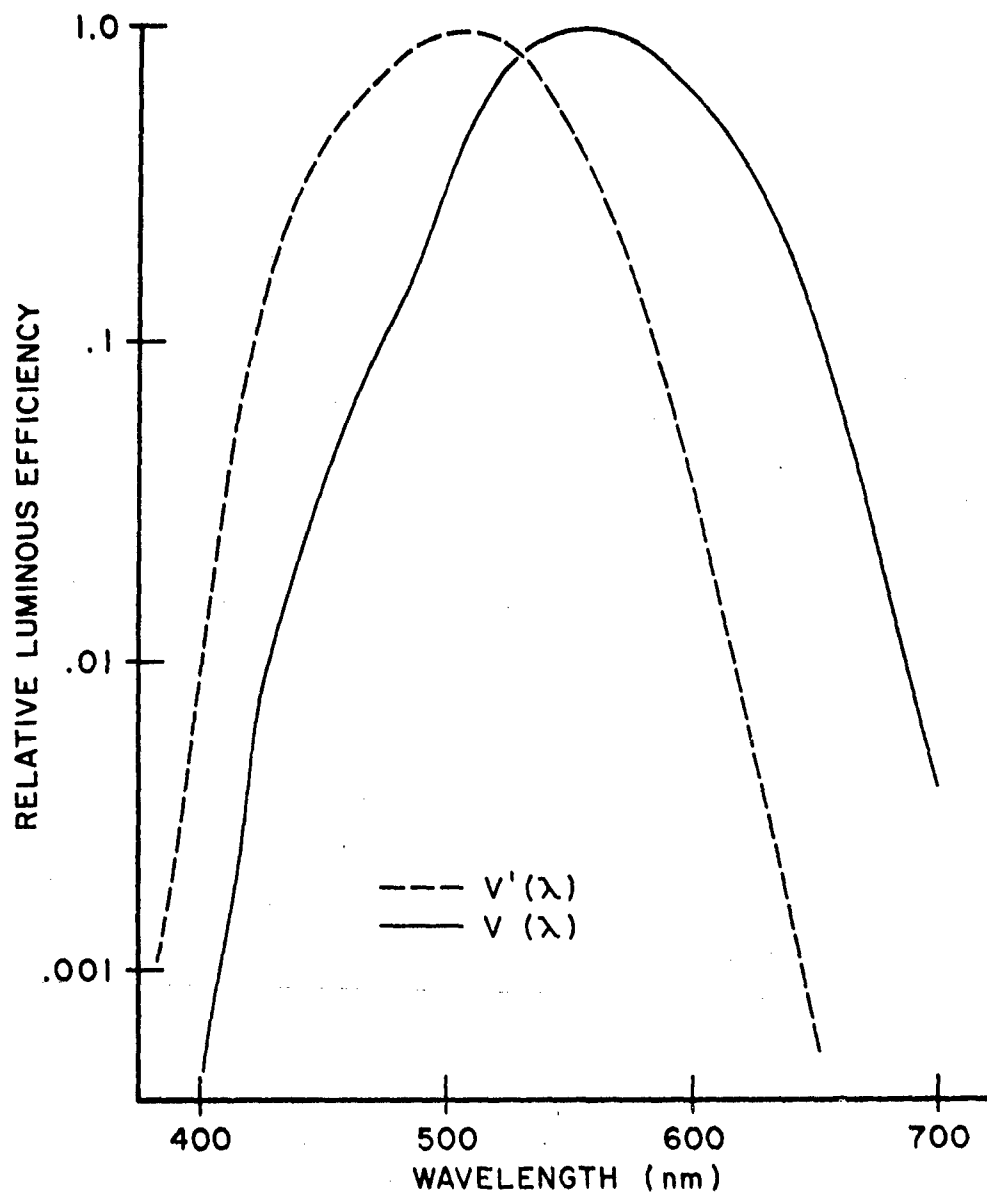


Fig. 1. A comparison of the spectral luminous efficiency functions for photopic, daylight vision, $V(\lambda)$, and scotopic or night vision $V'(\lambda)$

estimated and they appear much brighter than measurements indicate, while long wavelengths (yellows and reds) are overevaluated and appear dimmer.⁸

This problem was recognized years ago by the CIE and a scotopic luminous efficiency curve, $V'(\lambda)$, was established in 1951.⁹ This function should be used to evaluate electromagnetic radiation at low light levels, in a manner completely analogous to the use of $V(\lambda)$ at high. Unfortunately, too few people recognize the problem and there are only a few light meters that are equipped to measure scotopic levels. The result is that almost all measurements of light are done with $V(\lambda)$ meters, whether appropriate or not.

In between photopic and scotopic levels of illumination, there is a wide range of levels, covering several log units, over which spectral sensitivity shifts gradually and irregularly from photopic to scotopic.^{10,11} There is no standard procedure for evaluating electromagnetic energy in this region, although there have been several systems¹²⁻¹⁴ proposed and the CIE expects to standardize one in the future.¹⁵ It is this range, commonly referred to as mesopic, that is the subject of this report.

Light levels in sonar control rooms are usually kept low in order not to interfere with detection of dim targets on the CRTs. A survey of lighting in the sonar shacks of twelve different submarines was conducted under normal operating conditions. Illumination falling on the CRTs, both red and blue, ranged from less than .01 foot candle (fc) to .28 fc when measured photopically ($V\lambda$).³ These values

all lie within the mesopic range. Here we know that measurements do not give an accurate evaluation of the quantity of light, but we have no accepted procedure for correcting the measures. For this reason, an empirical investigation was made of the effectiveness of the red and blue lights used in sonar rooms: subjects were asked to make brightness matches between the red and blue and a standard white at various low levels in the mesopic range. In addition, a theoretical analysis of the effectiveness of red and blue light at mesopic levels is provided.

APPARATUS AND PROCEDURE

The subject viewed a split-half, circular field of 12 degrees diameter. The apparatus which provided this field consisted of a large box, divided into two separately illuminated halves. The interior of the box, which the subject viewed, was painted flat white. Illumination in the box was provided by daylight fluorescent lamps which could be fitted with colored sleeves of red or blue plastic. The quantity of illumination in each half was varied by black cloth filters and shades out of the subjects' view.*

The red and blue filters were obtained from the GSA catalogue and thus are the same as employed on submarines. Their spectral transmittances were measured on a Cary Spectrophotometer, Fig. 2, and their CIE chromaticity values for daylight fluorescent lights calculated; these are shown in the CIE diagram in Fig. 3. The actual transmittances of the filters vary of course with the light

* The author wishes to thank Dr. James Worthey for the use of the apparatus which he designed and built.

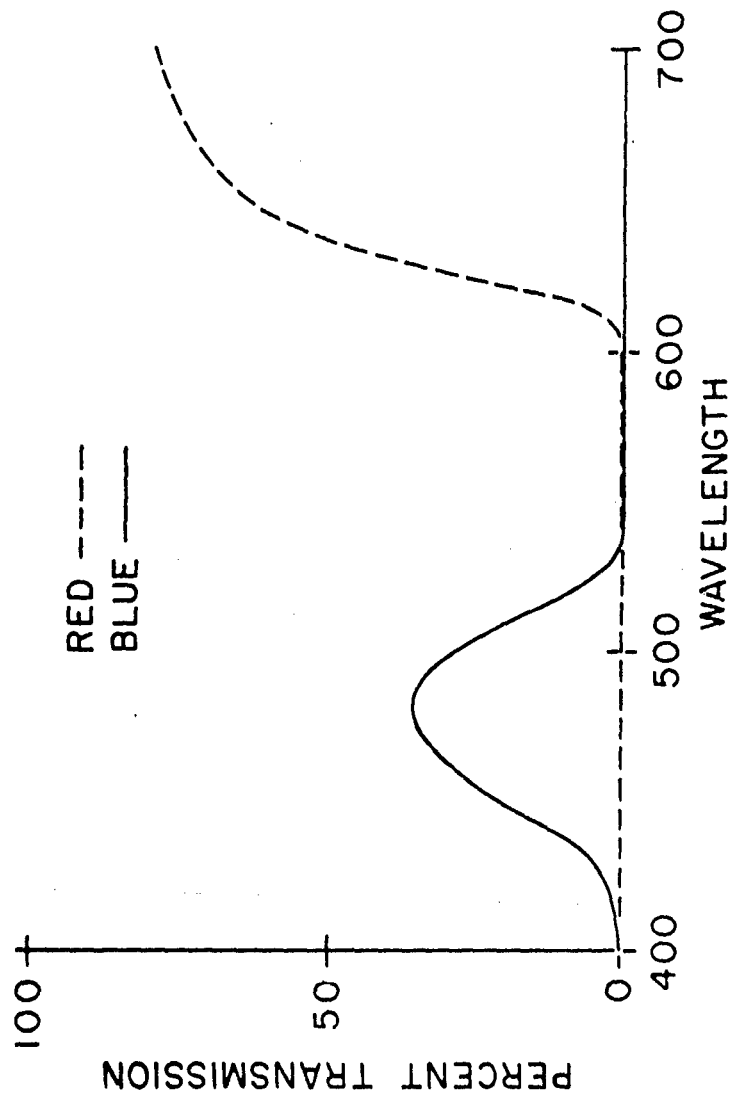


Fig. 2. Spectral transmittance of the red and blue filters

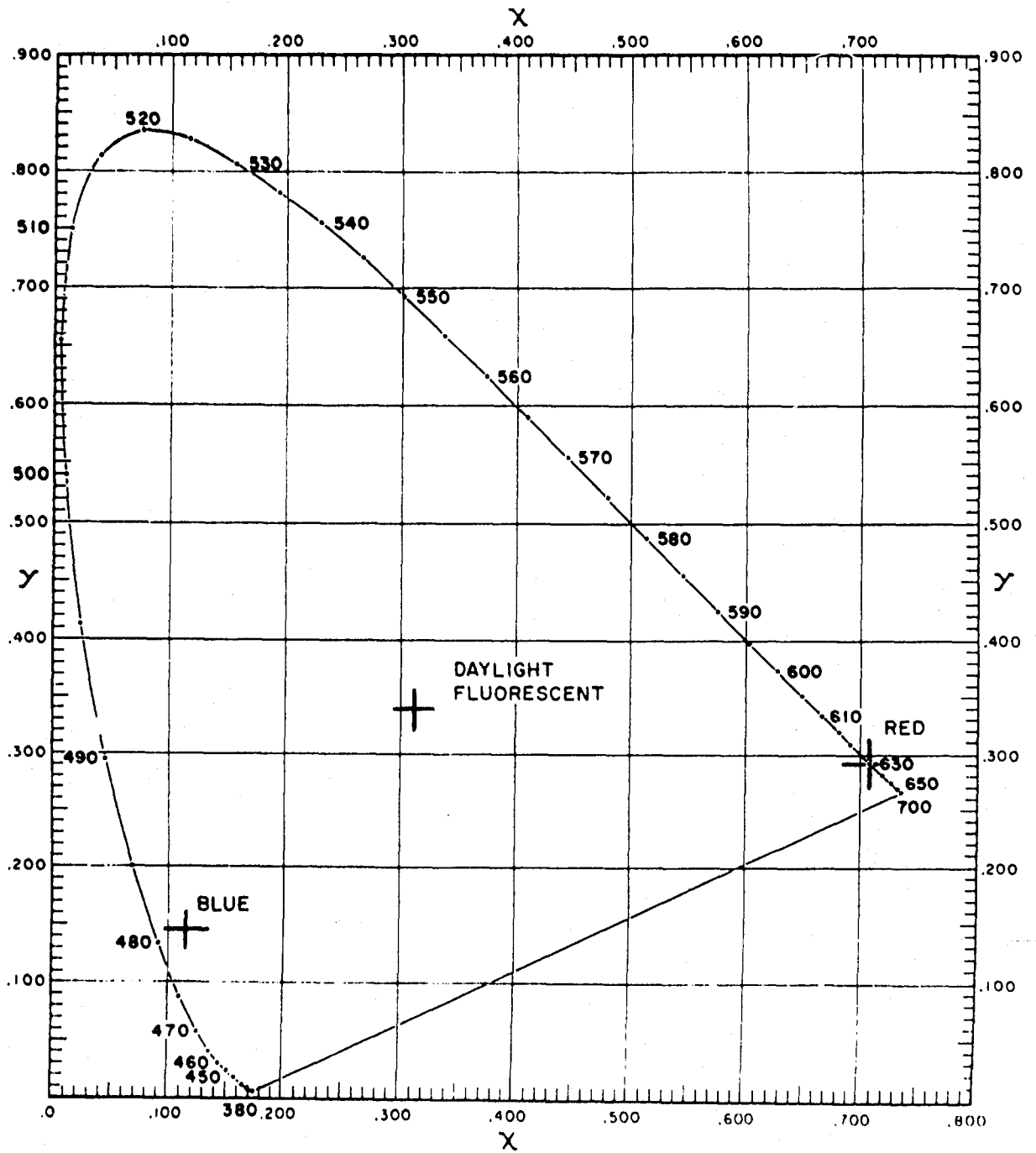


Fig. 3. The CIE chromaticity coordinates of the red and blue filters used with daylight fluorescent lamps

source with which they are used. For an equal energy source, both the red and blue transmit four percent of the light. For a daylight fluorescent lamp, the transmittances are .016 for red and .037 for blue; for cool white fluorescent, the comparable values are .019 and .024. Daylight fluorescent and cool white are both commonly found aboard submarines.

Subjects made brightness matches between the white standard in one half and red or blue illumination in the other. The amount of red or blue illumination was adjusted, employing the method of constant stimuli, while the subject reported whether the color was brighter or dimmer than the white. The luminance at the point of equality, half-way between the lighter and darker judgments, was then measured using a Spectra-Pritchard photometer. This photometer is equipped to measure not only standard photopic luminance, but also scotopic levels. Both measures were made of each brightness match.

Three levels of the white standard were employed covering two log units. The highest, 1.5 foot-Lamberts (fL) (5 cd/m^2) is at the low end of the photopic vision. It is much brighter than that employed in sonar shackles during normal operations. The two lower levels, approximately 0.1 fL and 0.01 fL, represent the levels normally found in operating submarines;³ they are completely within the realm of mesopic vision. The precise values of the white standard are given in cd/m^2 * because

* 1 fL = 3.426 cd/m^2

theory and standard practice employ the metric units. The three levels were 5 cd/m^2 , $.38 \text{ cd/m}^2$, and $.048 \text{ cd/m}^2$, when measured photopically.

Five subjects made the matches. They adapted for five minutes to the brightest light, 10 minutes to the middle one, and 20 minutes to the lowest one.

RESULTS OF THE EMPIRICAL STUDY

The average measurements of the red and blue fields judged to be equal in brightness to the white field are given in Table I. These values illustrate a number of the problems inherent in the measurement of light. Thus the photopic quantities of red and blue never are the same as that of the white; in a perfect system of measurement they should be, since the task was to equate them to the white. The reasons for the discrepancies vary with light level.

At the highest level, the photopic measured quantities of red (3.55 cd/m^2) and blue (1.40 cd/m^2) are less than that of the white (5.0 cd/m^2). This reflects two well-known phenomena.⁷ First, monochromatic or pure colored light at photopic levels appears brighter than neutral or white lights when both are evaluated by the luminous efficiency curve (V_λ) of the light adapted eye. This fact, first noted by Helmholtz over 100 years ago, stems from the physiology of human color vision; it is causing increasing problems in photometry as color light sources, such as CRTs, become common. A second phenomena affects only the blue values and reflects the fact that sensitivity to short wavelengths (blue or violet) is greater in a large field of view than in a small one. Thus the blue

Table I. Photopic and scotopic luminance measures of white, red, and blue fields judged to be equally bright (mean values are cd/m^2).

White Standard	Photopic ($V(\lambda)$)		Scotopic ($V'(\lambda)$)	
	Red	Blue	Red	Blue
5.0	3.55	1.40	0.63	6.90
0.38	0.38	0.18	0.05	1.01
0.048	0.072	0.013	0.015	0.11

light is more effective than the measurements indicated because light meters are made to conform to the $V(\lambda)$ function which was based on a relatively small, two degree field. Neither of these phenomena is of great importance in sonar control rooms, however, since their major effects are at photopic levels of illumination, and gradually decrease with decreasing light level.

It is at the lower two, mesopic levels where the change in spectral sensitivity becomes influential. At the lowest level of $.048 \text{ cd/m}^2$, the photopic value for red light is one and a half times the value for white while that for the blue is too small by a factor of nearly four. This is a direct reflection of the shift in spectral sensitivity toward the shorter wavelengths; thus the red wavelengths are overevaluated by the use of $V(\lambda)$ while the blue are underevaluated.

This result has direct application to the lighting of the sonar control room. Most individuals measuring these red and blue lights with a photopic based meter would make the reasonable assumption that

this red was over five times as bright as the blue, when in actuality they are equally bright. Furthermore, if they wanted to have blue light equal to the red in the sonar room, they would increase the blue to $.07 \text{ cd/m}^2$; this would of course make it appear five times brighter.

At the intermediate level of $.38 \text{ cd/m}^2$, the mesopic spectral sensitivity has not shifted so far toward the shorter wavelengths and the changes are not so pronounced. In fact the red light actually measures photopically the same as the white. This fortuitous event results from cancellation of the overevaluation of the long wavelengths with changing spectral sensitivity by the underevaluation of the brightness of monochromatic red light.

Measures of the scotopic luminance of the same lights are also given in Table I. These values would not be available to most lighting engineers since most light meters are not equipped to evaluate the radiant energy for scotopic spectral sensitivity. Nonetheless, the scotopic luminances are instructive. For red, the scotopic luminances are much lower than

the photopic, because the rods are insensitive to long wavelengths, while for blue the reverse is true. The scotopic luminances moreover, since they are based upon the sensitivity of the rods, are a good predictor of the effects on dark adaptation. The blue light, being much brighter than the red, stimulates the rods more and is much more detrimental; at the low level the blue (.11 cd/m²) is almost 10 times as destructive of night vision as is red (.015 cd/m²).

THEORETICAL ANALYSES

There is as yet no international standard for measuring light in the mesopic region, as mentioned previously. However, there are a number of systems that have been proposed; any one of these does a better job than simply using photopic measures. One approach, recommended provisionally,¹⁶ is to measure both the scotopic and photopic luminances (S and P) for a ten degree field and combine them by means of a nonlinear formula which expresses the luminance L. The original formula, devised by Palmer,¹² was:

$$L = (MS + P_{10}^2)M + P_{10}$$

where L, S, P and M are expressed in cd/m², M has a value of .06 cd/m² and P₁₀ indicates the photopic value for a ten degree field. This was recently expanded to an improved version:¹⁷

$$L = \sqrt{MS} + P_{10} + \frac{M}{2} - \frac{\sqrt{(\sqrt{MS} + P_{10} + M)^2 - M^2}}{4}$$

The formula and its refinements were devised to predict brightness matches in the literature and all

are fairly successful. They must, of course, emphasize the photopic measures at high mesopic intensities and the scotopic at low mesopic levels.

This type of analysis has been done for the brightness matches listed in Table I. Table II gives the effective, mesopic luminance, calculated from Palmer's improved formula, for those matches. If the formulae worked perfectly and there were no errors of measurement or judgment, the values for red and blue would always equal the white, to which they were matched. At the mesopic levels (.38, .048 white standard), the agreement is quite good and represents a large improvement over the original, photopic values in Table I. At the brightest level, 5 cd/m², the increased brightness of the colored lights at photopic levels is still evident; the formula does not address this specific problem.

Table II. Effective, mesopic luminance of the equally bright fields (cd/m²) (a)

White Standard	Red	Blue
5.0	3.3	2.2
0.38	0.30	0.35
0.048	0.048	0.046

(a) The cd/m² for the white standard are the measured, V(λ) based, photopic luminances. The red and blue luminances have calculated with Palmer's improved formula¹⁷ using the measured photopic, V(λ), and scotopic V'(λ) luminances. The blue photopic

luminance has been adjusted for a 10° field.

In order to extend the analysis to the entire range of mesopic intensities, photopic and scotopic luminances of the red and blue lights were measured over several log units of attenuation and the effective mesopic luminance calculated. The results, shown in Fig. 4, allow one to predict the actual effective mesopic luminance or brightness of the red or blue lights if one knows their measured, photopic luminance. If, for example, one measured the red light with an ordinary luminance meter, and the value was $.1 \text{ cd/m}^2$, the effective mesopic luminance, read from the intersection with the "red" line is $.06 \text{ cd/m}^2$. Blue, measuring the same $.1 \text{ cd/m}^2$ gives $.22 \text{ cd/m}^2$ or 3.7 times as much light. At $.01 \text{ cd/m}^2$, the red and blue effective mesopic luminances are $.0038 \text{ cd/m}^2$ and $.032 \text{ cd/m}^2$, respectively. The blue is thus 8.4 times as effective.

DISCUSSION

Previous measures, in sonar control rooms, made with normal photopic meters, had yielded values of red and blue light varying from 1 cd/m^2 (.28 fc) to about $.01 \text{ cd/m}^2$. Both brightness matches and theoretical calculations of the relative effectiveness of the blue and red light at these levels show the blue to be much more effective than the red in providing general illumination. Blue gives about twice as much light at the upper limit and nearly 10 times as much at the lower. This fact was noted by a number of sonar operators, in a previous study⁵. Unsolicited remarks such as "You can

see what you're doing" and "You can at least see the equipment" were made for blue, but never for red illumination. One remarked "You can see, but still not well enough to see the logs." These remarks emphasize one aspect of blue illumination. Since the increased brightness stems from the increased importance of rod or scotopic vision, the advantage is in the ability to see large objects, room outlines, etc. There is no advantage for cone or photopic vision: acuity and color vision suffer as they do in low level red illumination.

SUMMARY

Both the empirical comparison and the theoretical analysis show that the blue filters used in sonar control rooms give more light than the red when employed at low levels of illumination. At the upper end of the range of illumination levels found under operational conditions in the sonar control room, the ratio of blue to red is about two; at the lower end there is nearly ten times as much blue light as red. This is due to the shift in the spectral sensitivity of the eye toward scotopic or rod vision at low levels. It means that the men have more light to see large objects and the general room outline and it undoubtedly accounts, at least in part, for the preference for blue. It does not, of course, mean the men have more light for reading or seeing fine detail; if red and blue measure the same photopically this aspect of vision will be the same.

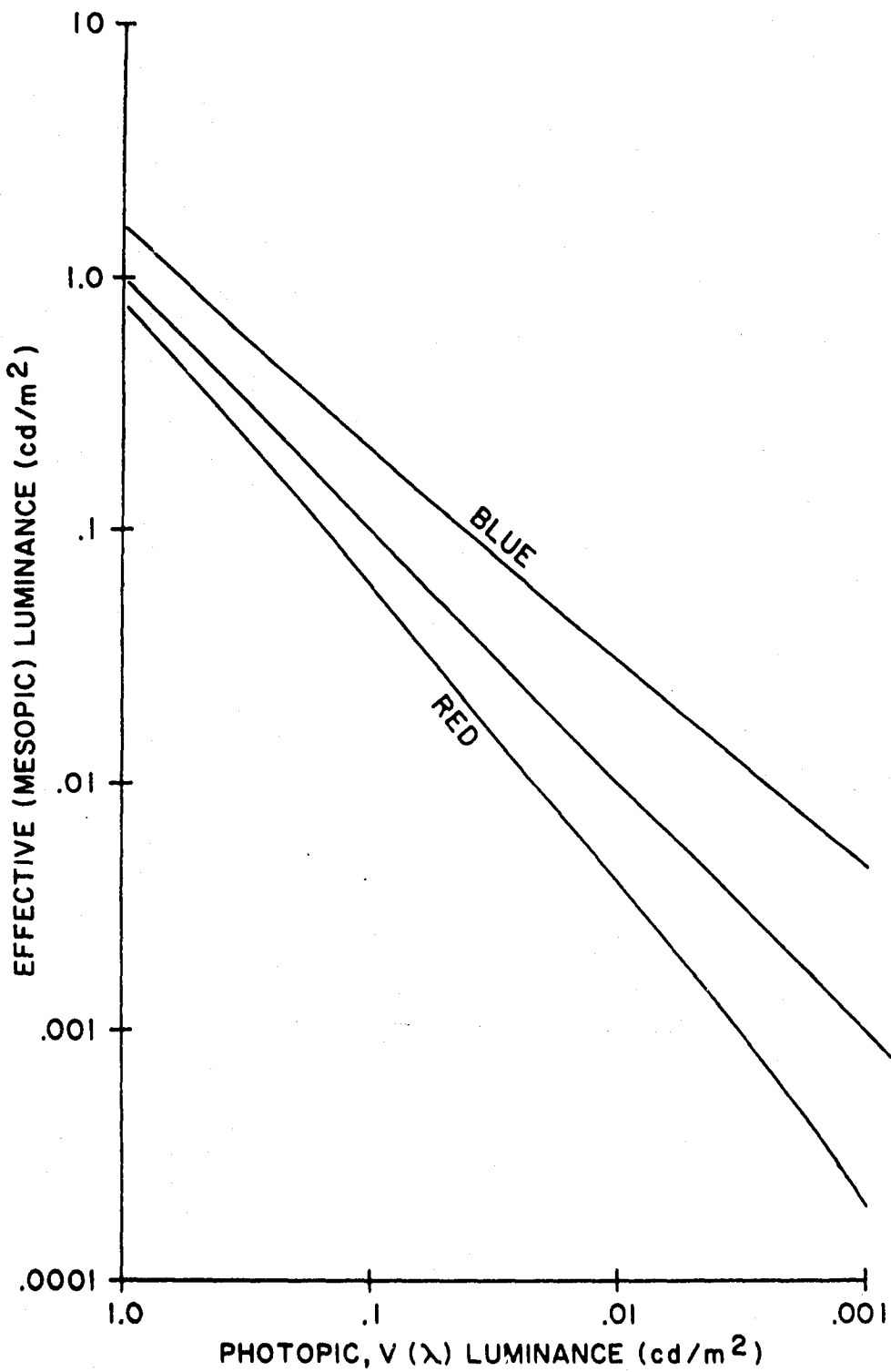


Fig. 4. The effective mesopic luminances of red and blue light filters with daylight fluorescent lamps as a function of photopic luminance

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