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REPORT NUMBER 1036

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Naval Medical Research and Development Command
Research Work Unit M0100.001-1019

Released by:

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3 July 1984

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SUMMARY PAGE

PROBLEM:

To compare the relative merits of red and white light as general night-time ambient illumination on submarines.

FINDINGS:

A review of the literature indicates that although red light is superior to white light in permitting subsequent dark-adaptation, its superiority decreases as the light intensity decreases. At the levels of ambient light found in submarine compartments, the superiority of red light is probably not of practical significance in most situations and in any event can be compensated for by spending an additional minute or two under a no-light condition. Red light, moreover, suffers from a number of disadvantages which can be eliminated by using white light.

APPLICATION:

These findings are pertinent to the question of whether or not to continue the practice of illuminating submarine compartments with red light at night. Recommendations are made concerning the use of subdued white lighting.

ADMINISTRATIVE INFORMATION

This research was conducted as part of the Naval Medical Research and Development Command Work Unit M0100.001-1019 - "Improvement of sonar performance through modification of sonar displays." It was submitted for review on 31 May 1984, approved for publication on 3 Jul 1984, and designated as NavSubMedRschLab Rep. No. 1036.

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ABSTRACT

The literature concerning the effectiveness of red and white light for permitting subsequent dark-adaptation is reviewed. Although red light is clearly superior to white, its advantage decreases as intensity decreases, and at levels of ambient light found in submarine compartments, its superiority over white is probably not of practical significance in most situations. Considering the disadvantages of red light, it is concluded that low-level white light is preferable to red light as general night-time ambient illumination.

After a generation of using red ambient light to illuminate submarine compartments at night, the question has now arisen as to whether red lighting should be discontinued and white light used instead.

Red lighting was instituted during World War II to facilitate dark-adaptation. At that time submarines were powered by electric storage batteries and had to surface each night in order to recharge the batteries. While on the surface, men had to stand watch for enemy ships and it was necessary for the watch-standers to be dark-adapted before coming on deck. More critical was the necessity for men to be dark-adapted at night in the event of a sudden unexpected need to surface. For that reason the crews sought to minimize the time required to dark-adapt.

Another problem was that although the crew wanted to turn off the lights in order to dark-adapt, they needed some light in order to carry out their duties. A solution to this problem was suggested by the difference between the human photopic (daylight) and scotopic (nighttime) luminosity curves (Fig. 1). When the intensity of the ambient illumination decreases, the wavelengths to which the eye is most sensitive changes: at high intensities the eye is most sensitive to 555 nm, whereas at nighttime levels of illumination it is most sensitive to 505 nm. Moreover, Fig. 1 appeared to indicate that at night-time levels the eye becomes relatively insensitive to red light. This led to the proposal that the use of red light would permit men to become dark-adapted while still permitting enough illumination to carry out their duties (1,2). The rationale was that the red light would stimulate only the long-wavelength portion of the photopic luminosity curve while sparing nearly all of the scotopic curve, thus allowing dark-adaptation to proceed or maintaining it if it had already been achieved. A large number of studies soon showed conclusively that the course of dark-adaptation was indeed faster after exposure to red light rather than white (3-16). There were even claims that red light enhanced dark-adaptation compared to the amount of adaptation occurring under no light at all (5,6,17), claims which were quickly refuted (18-22).

Red light was unpopular, however, since it made it difficult to read color-coded charts and proved to be somewhat fatiguing. It was therefore proposed that the same effect could be obtained by having only certain crewmen wear red goggles; only those men who needed to be dark-adapted would thus be inconvenienced, while the rest of the crew could still work in white light (23-25). Red lighting and the use of red goggles became the specified mode of nighttime lighting (26).

The disadvantages of red light have led, however, to a change in the operating procedures regarding the use of ambient lighting at night; the continuous use of red illumination throughout the night is no longer required. But there is no official directive describing the actual procedures that should be followed to obtain an appropriate level of

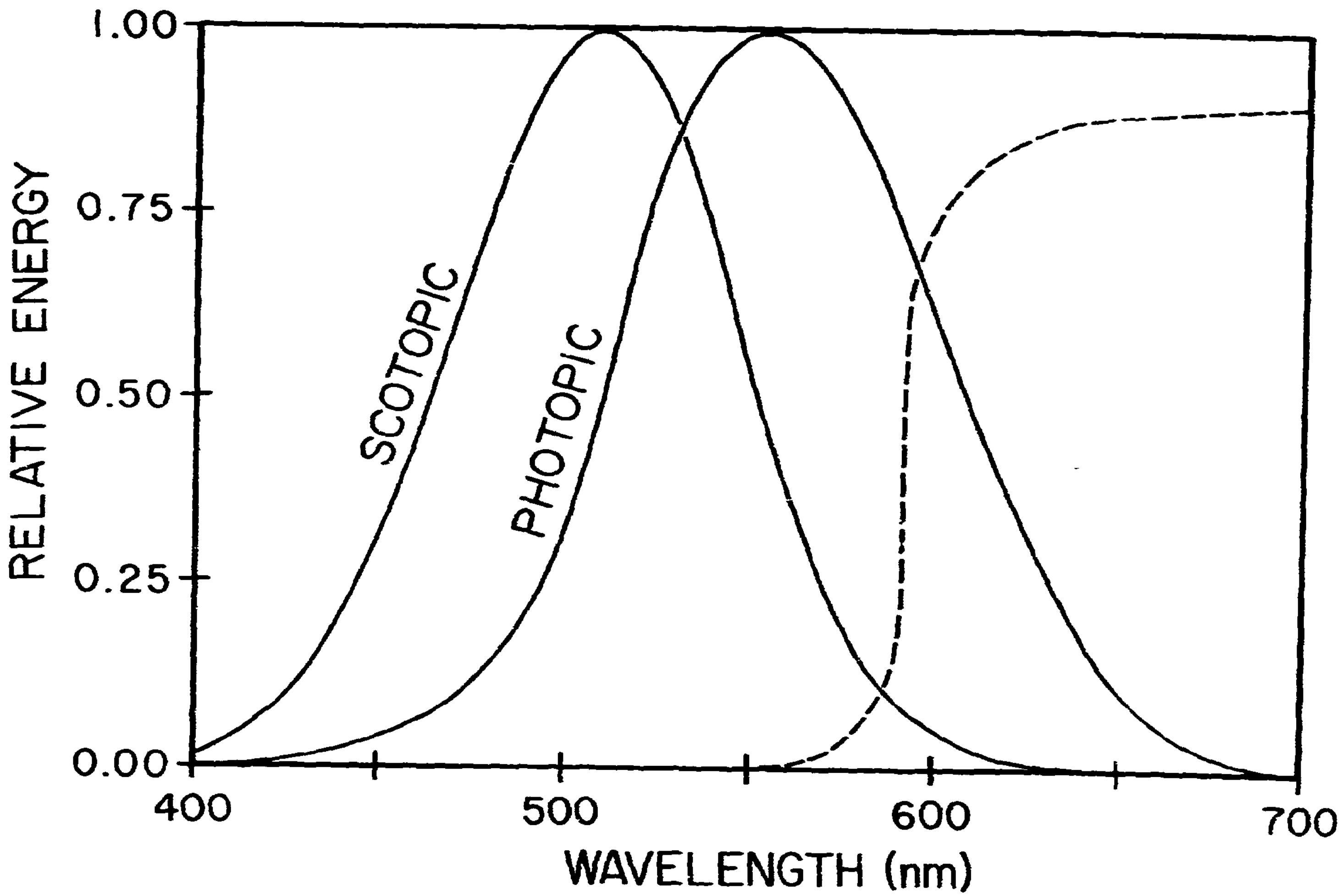

Fig. 1. Luminosity curves of the human eye in arbitrary units with a maximum sensitivity set to 1. The dashed line shows a typica' red filter with a sharp cut-off at around 590 nm.

dark-adaptation prior to coming to periscope depth. These procedures have been left to the discretion of the commanding officer. It appears that most submarines operate in a simil[illegible] fashion, rigging the control room for red 30 minutes before coming to periscope depth and extinguishing all ambient illumination about 10 minutes beforehand. While this change helped to reduce some of the problems with red illumination, it did not eliminate them. More recently, the increased use of color-coded control panels and the imminent use of color-coded CRT displays has resulted in increased questioning as to whether or not red light is the optimal color.

The Magnitude of the Advantage of Red Light

Although it was clear from the outset that dark-adaptation is faster after exposure to red light than to white, the magnitude of this advantage was less publicized. A detailed examination of the relevant studies shows that the temporal advantage conferred by the red light is not great and may not be of practical significance in most cases.

The critical point is that the relative advantage of red over white for subsequent dark-adaptation is a function of the intensity of the initial adaptation exposure. A number of studies have shown that as the intensity level of the initial adaptation decreases, the rates of dark-adaptation after red or white light become more similar. In other words, the advantage of red-adaptation over white is reduced as the intensity of the adapting light decreases. As will be detailed below, this is true whether what is measured is the ability to detect a spot of light or to perceive fine detail, and it holds whether what is being measured is initial dark-adaptation from a light-adapted state or the interruption of dark-adaptation and subsequent readaptation.

For example, Hecht and Hsia (11) compared the course of dark-adaptation after exposure to three levels of brightness of red or white. After adapting to around 350 mL* of illumination, it took about 15 minutes longer to dark-adapt after exposure to white light than to red; when the initial illumination was around 30 mL, it took about 10 minutes longer with white light; and when the initial illumination was around 3 mL, it took about 2 minutes longer after the white (Fig. 2).

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* The units of light measurement used in the articles cited are retained in this review. 1 foot-candle (ft-C) = 3.4 millilamberts (mL); 1 foot-Lambert (ft-L) = 1.1 millilamberts. A ft-C is a unit of light-emittance; a ft-L is a unit of reflectance. When the relecting surface reflects 100% of the light falling on it, then 1 ft-C = 1 ft-L.

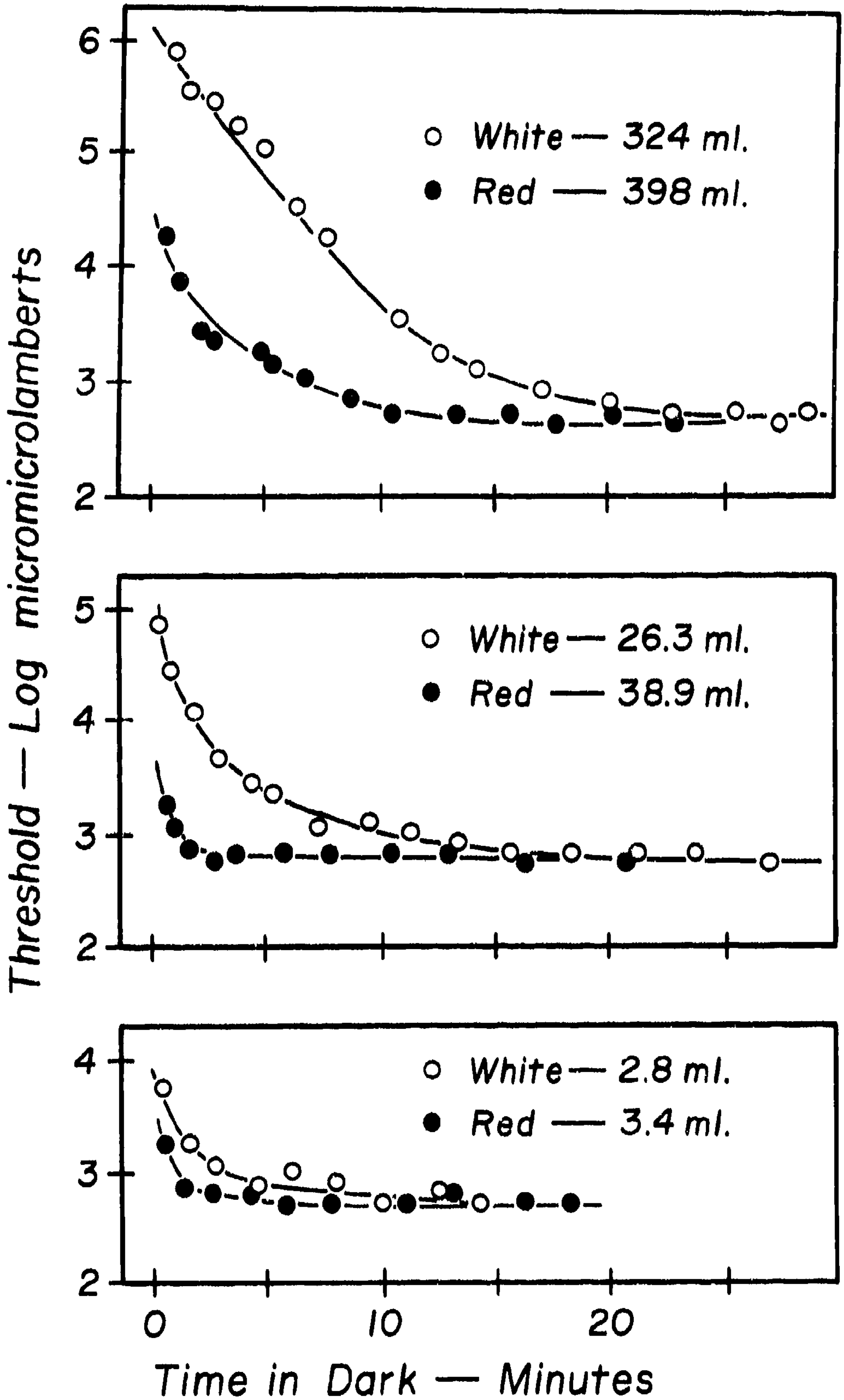

Fig. 2. Dark-adaptation following adaptation to red or white light at three brightness levels. Dark-adaptation is always faster after red light than after white light of comparable brightness, but the difference between the two curves decreases as the intensity of the lights decreases. (Taken from Hecht and Hsia, 11).

Hulburt (14) measured the times needed to dark-adapt after exposure to equally bright red and white lights at four intensities. He reported that after exposure to 100, 10, 1, or 0.1 fC, it took longer to adapt after exposure to white by 14, 5, 1, and 1 minutes, respectively.

Peskin and Bjornstad (12) adapted their subjects to various colors and then measured the time taken to dark-adapt. They reported that the time taken to reach twice the final threshold was 10.25 minutes longer after exposure to about 130 mL of white than red, but only 2 minutes longer after exposure to 5 mL of each color.

Ferguson and McKellar (8) tested scotopic acuity (rather than detection) after adaptation to various colors. They found that after adaptation to 0.5 ft-C of white, it took 15 seconds longer to perceive the break in a low contrast Landolt-C than after red-adaptation. After exposure to 10 ft-C of white, it took one minute longer to see that target than after exposure to red.

Luria and Schwartz (27) also tested scotopic acuity after exposure to white or red light. They found that after exposure to 22 ft-L, it took an average of 3.9 minutes longer to reach maximum scotopic acuity after stimulation by white light rather than red; after exposure to 3.4 ft-L, it took 3.6 minutes longer after stimulation by white; and after exposure to 0.19 ft-L, it took only 1.5 minutes longer after the white light (Fig. 3).

Luria and Kinney (28) studied the effects of brief exposure to light on dark-adaptation, measuring the time taken to readapt. When dark-adapted subjects were exposed to 20 seconds of light at an intensity of 6 ft-L, it took about 2.5 minutes longer to readapt if the light was white rather than red; if the 20-second exposure was at an intensity of .06 ft-L, then the time taken to readapt was only about 1.5 minutes longer with white (Fig. 4).

It is clear that the difference in time taken to dark-adapt after exposure to white rather than red light becomes relatively small when the stimulation prior to dark-adaptation is of low intensity. Indeed, the differences are so small that Lowry (29) concluded after his study that after exposure to 3 ft-C of illumination, there is no difference in the time taken to dark-adapt after red or white. Sheard (30) agreed with Lowry, stating (p. 483), "However, I have obtained just as rapid dark-adaptation and secured as great a degree of night vision through the use of neutral filters which transmitted relatively low amounts of incident light...the use of neutral filters was as satisfactory as that of red goggles..." Hecht and Hsia (11) argued that Lowry's (29) results were due to the pitfalls which occur in trying to equate lights of different colors at low intensities. They believed that Lowry's red and white lights did not stimulate the cones equally, and the results were therefore "irrelevant to the phenomenon they were designed to clarify" (See also Kinney, 31).

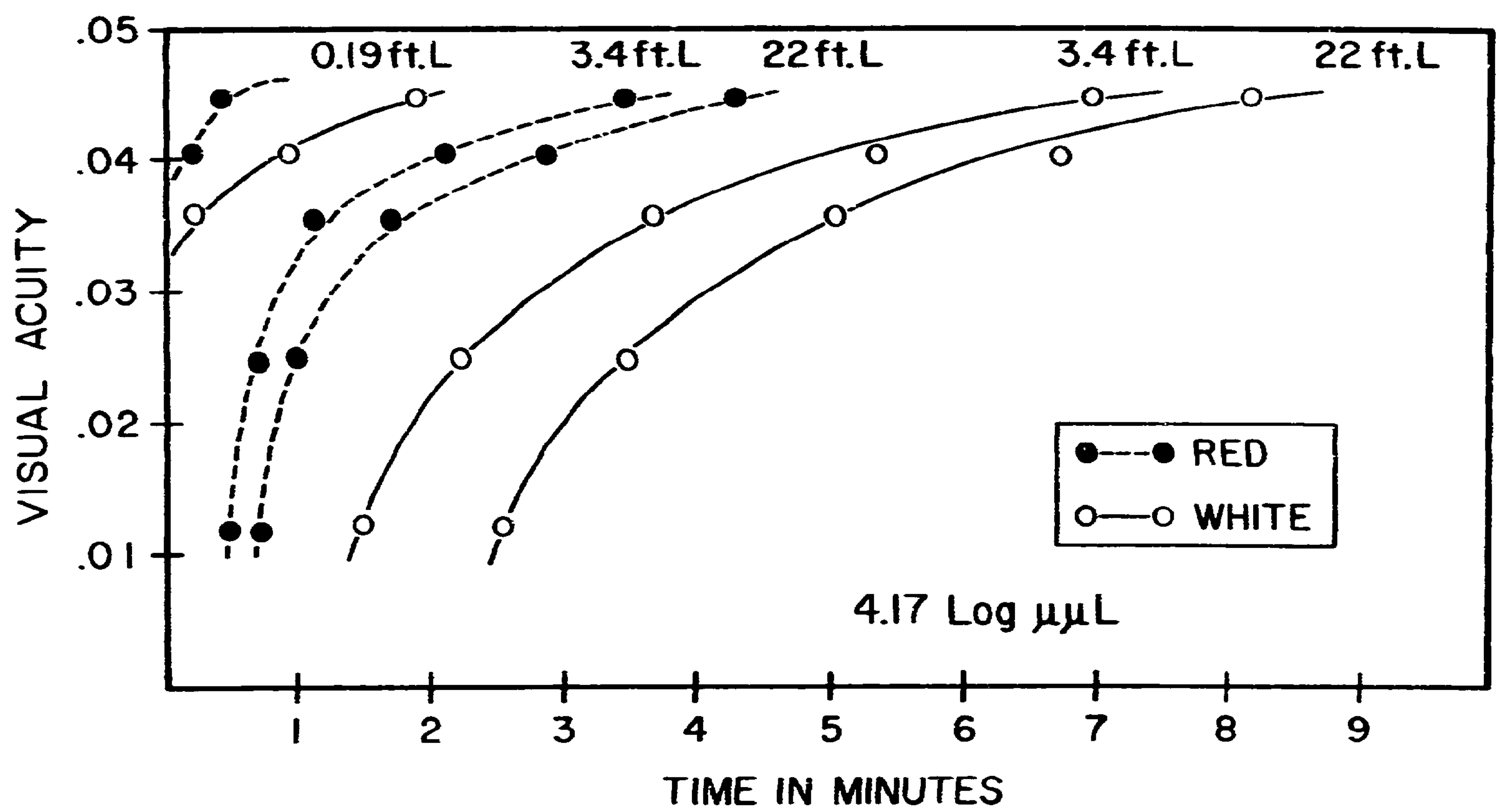

Fig. 3. Average time to see targets at a brightness of 4.17 log uuL after initial adaptation to three intensities of either red or white. The difference in time taken to reach a given level of visual acuity after red- compared to white-adaptation decreases as the intensity of the pre-adaptation light decreases. (Taken from Luria and Schwartz, 27).

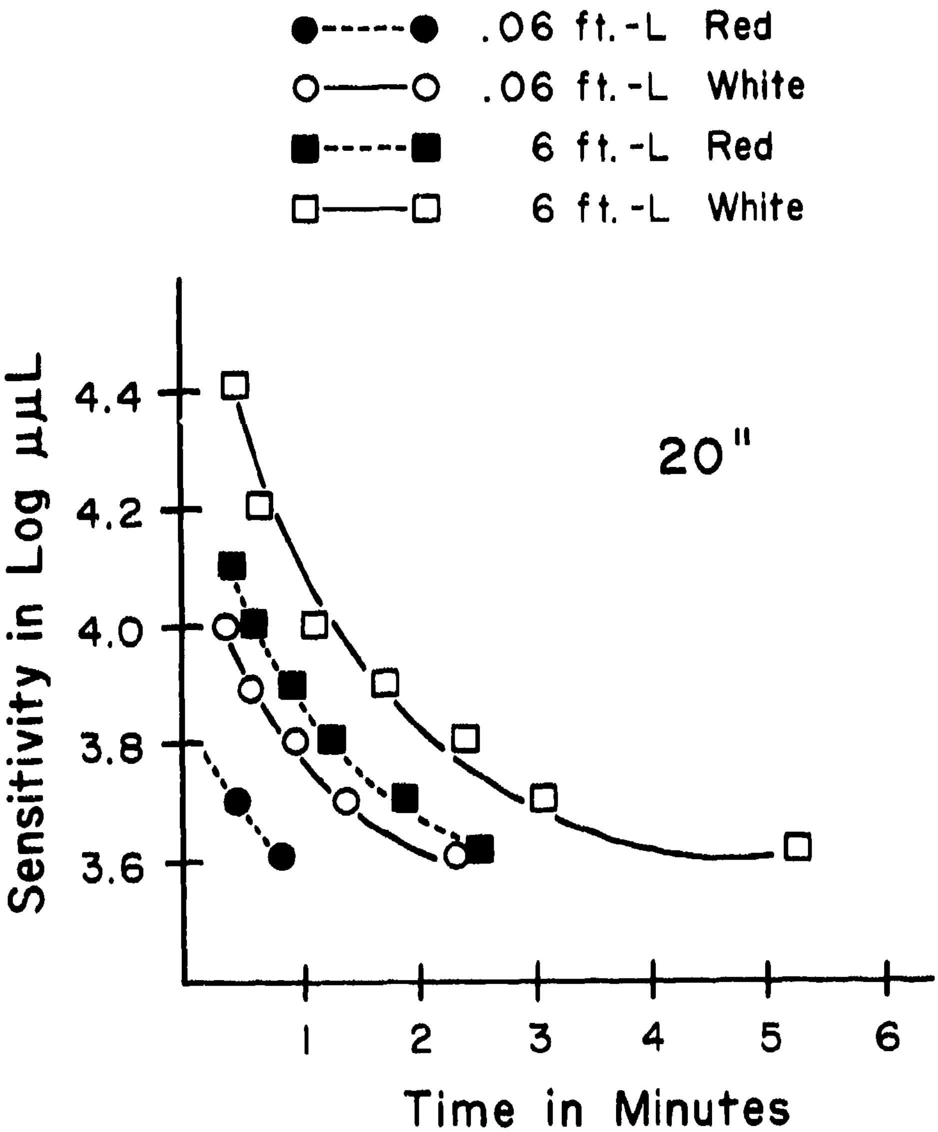

Fig. 4. The times required to regain complete dark-adaptation after exposure to two intensities of either red or white light for 20 seconds. The difference in readaptation time between the red and white lights is less for the lower intensity. (Taken from Luria and Kinney, 28).

Why is Red Light Not More Effective?

One would imagine from Fig. 1 that a sharp cut-off filter at about 600 nm would indeed allow almost complete dark-adaptation while transmitting enough light to the cones to allow reading and the like. Why then is the relative advantage of red lighting surprisingly small?

The reason for the mistaken expectations is that the two luminosity curves shown in Fig. 1 are arbitrarily plotted with the highest points on each curve assigned the same value and the rest of the points correspondingly scaled. This is a misleading way to plot the curves, for although each curve shows the relative sensitivity to the various wavelengths for either the rods or the cones, it completely distorts the relation between the sensitivities of the two curves. As Cornsweet has pointed out (32, p. 147), "plotting them this way loses important information, and gives the false impression that the cones are actually much more sensitive than the rods in the long wavelength end of the spectrum."

The correct way to compare the two luminosity curves is shown in Fig. 5, from which we see that the cones are less sensitive than the rods only below the long wavelength end of the spectrum; in the red wavelengths, the rods and cones are actually equally sensitive. Or as it is often put, there is no photochromatic interval in the red end of the spectrum. Figure 6 makes it clear why the relative effectiveness of red light is much less than it is widely thought to be.

Red-Adaptation and Dark-Adaptation

The reason for the continued use of red light on submarines remains the desire to facilitate dark-adaptation. Although it may not be necessary for submarines to surface every night, emergencies may arise which make it necessary to surface quickly at night. The periscope operators and other members of the crew will want to be dark-adapted when the submarine comes to the surface or to periscope depth. It is for this reason that red light is used at night. Is it still necessary?

First, it must be made clear that red-adaptation is not dark-adaptation (16,19,20,30,34). Complete dark-adaptation can be achieved only in the absence of light. Stimulation by light of any color will affect dark-adaptation to some extent. Men who have adapted to some level of red light will still require some time to become completely dark-adapted when the red light is turned off. The effect of a given level of red light can be equated to some level of white light. For example, Rowland and Sloan (9) have shown that exposure to 3 mL of either red or white light requires a certain amount of time for subsequent dark-adaptation, and that 12 mL of red light produces approximately the same degree of adaptation of the rods (the nighttime receptors) as 3 mL

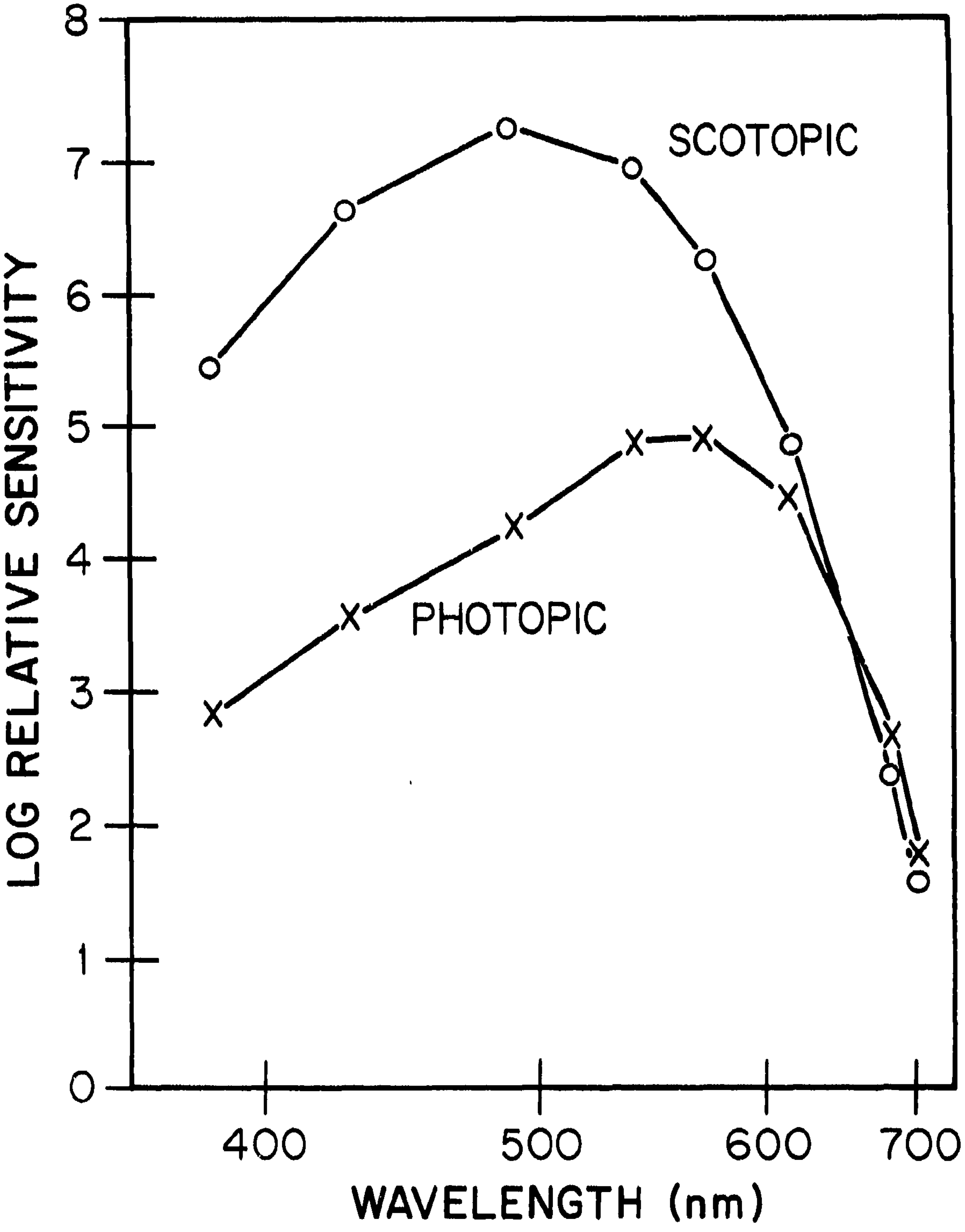

Fig. 5. Luminosity curves of the human eye plotted in correct relation to each other. (Taken from Wald, 33).

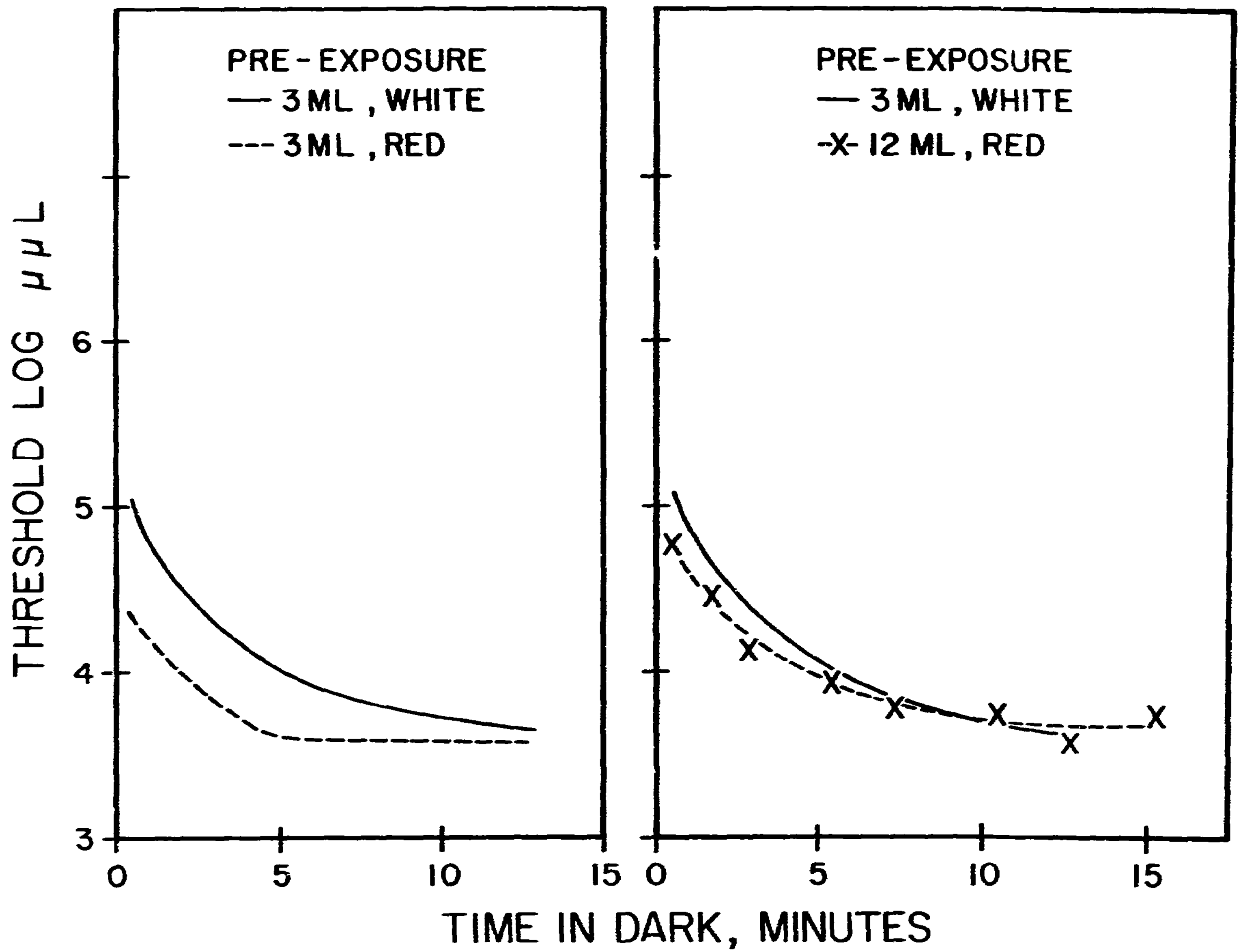

Fig. 6. The time required to dark-adapt after pre-exposure to red or white light. The left-hand panel shows that exposure to either red or white light subsequently requires a certain amount of time to completely dark-adapt, although it is longer for white light. The right-hand panel shows that the effect of the red and white lights can be equated. (Taken from Rowland and Sloan, 9).

of white light (Fig. 6). Although this is an advantage for red, it is far from being equivalent to no light at all.

The time required to completely dark-adapt has been measured after adaptation to various intensities of red light. Hecht and Hsia (11) found that after adaptation to 3 mL of red light, dark-adaptation required a little less than two minutes. Luria and Schwartz (27) found that it took a little over three minutes to be able to resolve an acuity target near threshold after adaptation to 3.4 ft-L of red light. Rowland and Sloan (9) and Hulburt (14) found that adaptation to 3 mL of red light subsequently required about four minutes to dark-adapt. Mitchell (13) reported that after adapting to 6 mL of red, it required 6 minutes to become fully dark-adapted.

As discussed above, red-adaptation is not dark-adaptation, but there is an alternative. The two eyes can be adapted independently; one eye can be light-adapted while the other is dark-adapted (35). This is easily accomplished by covering one eye with an opaque eye-patch. Although having one eye light-adapted and one eye dark-adapted produces the impression of looking through a veiling light, measurements of target thresholds showed that the illusory light did not interfere with the absolute threshold (27). It is for this reason that NSMRL recommended the use of an opaque eye-patch over one eye in place of red goggles (27).

The Practical Advantage of Red Light

Despite the fact that red-adaptation is not equivalent to dark-adaptation, it is still better for subsequent dark-adaptation than exposure to an equivalent brightness of white light. The next question then is, to what extent will dark-adaptation actually be retarded on submarines when the crew are exposed to white light rather than red? The foregoing discussion has made it clear that the magnitude of the degradation will depend on the intensity of the illumination. NAVSEA specifies that normal white light levels shall be about 15 ft-C (26). When red goggles are worn in such an environment, the effective illumination at the eye is then about 1.5 to 2.0 ft-C. When the ship is rigged for red, NAVSEA specifies that the illumination shall not exceed 2.0 ft-C (26). In fact, our surveys of sonar compartments showed that the luminance of the various lighted indicators under rig-for-red ranged from .01 to .28 ft-C, and the illumination reflected from the surfaces of the equipment ranged from .01 to .6 ft-L (36). Light levels in other compartments are probably quite similar.

If white light were substituted for red light, and these brightness levels were kept the same, then the studies cited above indicate that the additional time required to become fully dark-adapted under these conditions would be about 1.5 minutes. Is this added time of practical significance?

In those instances when the crew knows in advance that it will surface, the difference of a minute or two is clearly of no importance. In order to dark-adapt, the red light would have to be turned off in advance; if they are operating under dim white light, then the light would have to be turned off a minute or two sooner, a constraint which cannot be of any practical significance.

On those occasions when there is an unscheduled, emergency need to surface or to come to periscope depth, two questions must be answered: What is the total time required to dark-adapt, and how long would it take to bring the submarine to periscope depth? Not many studies have measured dark-adaptation time from an intensity level of less than 1 ft-c, but Hulburt (14) stated that it is about 4 minutes (Fig. 7). Hecht and Hsia's (11) data suggest that it would be even less. Luria and Schwartz (27) found that it took 2 minutes to reach threshold scotopic acuity after adaptation to 0.2 ft-L. It seems safe to assume that it takes 2-4 minutes to dark-adapt from exposure to a low level white. If the submarine must be brought to periscope depth in an emergency, this must also take a certain amount of time. The actual amount of time would depend, of course, on the depth at which the ascent begins. It seems reasonable to assume that on the average it would take one or two minutes. If this is the case, and if the dim white lights were extinguished as soon as the need to ascend was realized, then by the time the submarine came to periscope depth, the crew would be close to complete dark-adaptation.

Is Complete Dark-Adaptation Necessary?

Another question now arises. Is complete dark-adaptation always necessary? Probably not. Absolute threshold is around .00001 to .000001 mL for the average young man (37), although this will vary somewhat with age (38), the size of the target (39), and other variables (40, 41). However, the presence of starlight raises the brightness of the sky to .0001 mL, and a quarter moon raises it to .001 mL. This is two orders of magnitude greater than absolute threshold. Furthermore, a full moon raises the brightness of the sky an additional order of magnitude (.01 mL). A certain proportion of the time, therefore, the sensitivity of complete dark-adaptation is not necessary. Thus the increment of time required to attain complete dark-adaptation resulting from the use of white rather than red light may in many situations be irrelevant.

The Disadvantages of Red Light

One further aspect of red light should be considered. Red light has never been very popular. There have always been complaints that it is fatiguing and that it makes it difficult to keep logs and impossible to read color-coded material.

There is little question that the long wavelengths produce some physiological discomfort and degradation. They require more accommodation to focus them on the retina, which could be uncomfortable

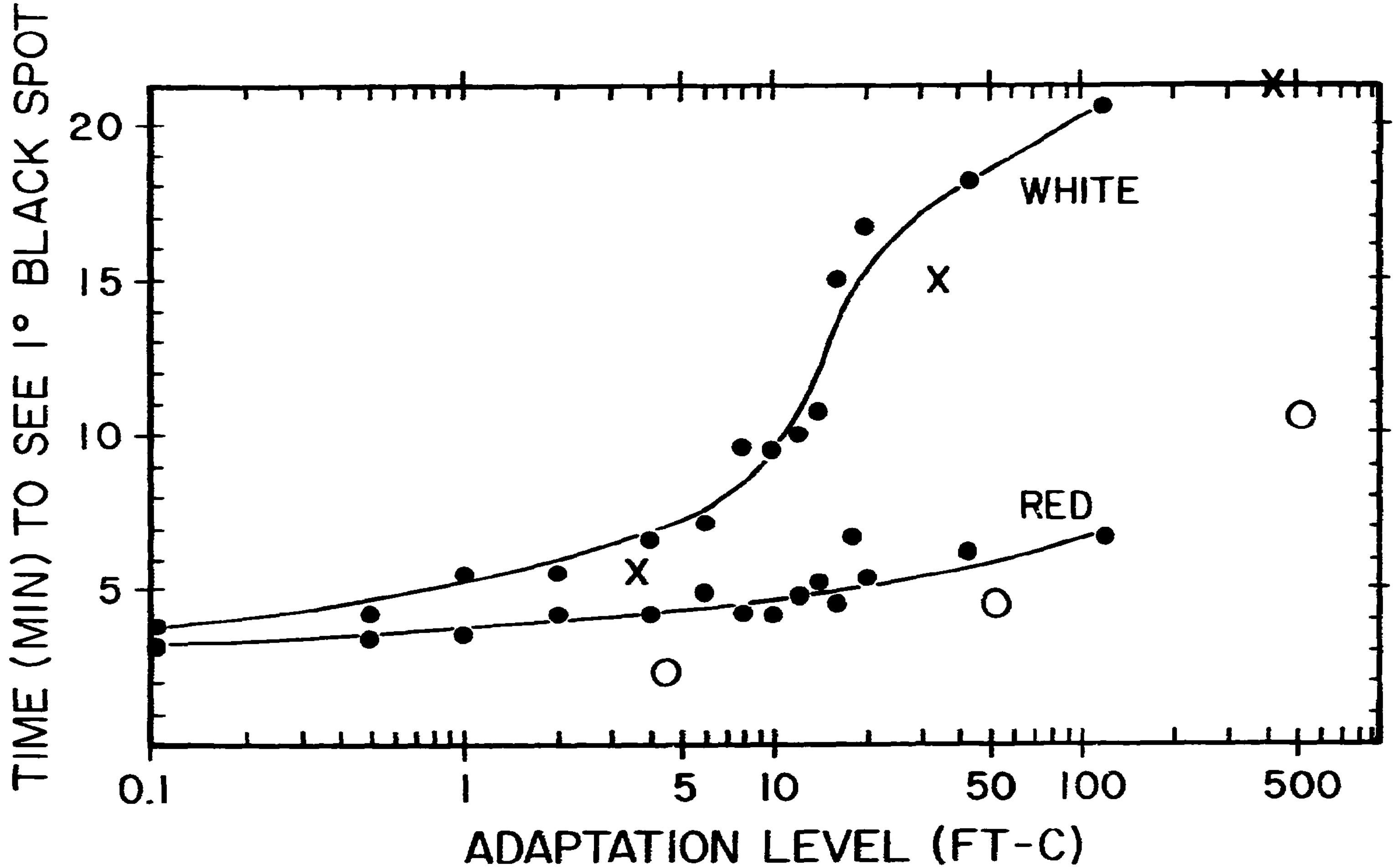

Fig. 7. The time required to become dark-adapted after adaptation to red or white light of different intensities. The dots in this figure are from Hulburt's measurements; the circles and crosses were taken by Hulburt from the data of Hecht and Hsia (11). (Taken from Hulburt, 14).

for older or far-sighted crewmen. Indeed, a recent study of the eye-movements of men monitoring a sonar display for two hours under different colors of ambient light gave some evidence of greater physiological fatigue under red light than under blue or white (42). Other studies have reported that red light has a deleterious effect on such measures as hand tremor and galvanic skin reflex (43-46). Kuller showed that color had appreciable effects on EEG, pulse rate, and emotions (47). He commented that despite some inconsistent results, "there remains an impressive amount of significant evidence showing that the illumination and colour of architectural space have a profound influence on the physiology and behavior of man." Whether or not the ambient light affects such objective variables, there is widespread agreement that it does affect subjective reports of perceived comfort, and that red light is less "restful" than other colors (48-55). Several sonar crews have reported that red light is particularly worse under stressful conditions at sea (55).

The widespread unpopularity of red light (55, 56) should not be dismissed out of hand, because it has been shown (57, 58) that there is a relationship between reports of how people feel and their physiological measures. Liebhart has reviewed the evidence that the emotions are aroused when one believes that one has been exposed to an unpleasant stimulus (59). It is not unlikely that the arousal of such negative emotions degrades performance (55).

Conclusions: Red Light or White?

The evidence indicates, first of all, that red-adaptation is not a substitute for dark-adaptation. Exposure to red light will always result in some degradation of dark-adaptation, although when the red light is dim, the loss of sensitivity is small.

Second, although exposure to white light produces a greater degradation of dark-adaptation than does exposure to red light, the increment of degradation decreases as the intensity of the lights decreases. In other words, the additional time required for subsequent dark-adaptation after exposure to white light rather than red becomes shorter as the intensity of the light decreases. When the light level is as low as that found on submarines which are rigged for red, the time required for complete dark-adaptation after the light is extinguished is on the order of two minutes when the light is red and no more than another minute or two if the light is white.

Third, it seems likely that in most cases the submarine will come to periscope depth at a predetermined time, allowing the crew to take into account the small additional time required to dark-adapt. Even when the submarine must come to periscope depth unexpectedly, it seems likely that an appreciable portion of the time required to dark-adapt after the lights are extinguished will be taken up by the time required to ascend to periscope depth. Moreover, in many instances, complete dark-adaptation may not be required of the periscope operator because of the level of natural light.

Finally, consideration must be given to the disadvantages of red light: it is highly unpopular, it increases fatigue, it has undesirable physiological side-effects, and it makes it difficult to write and to read color-coded material. These disadvantages would be reduced or eliminated if subdued white light were used.

Operational Recommendations

In view of these considerations, we conclude that the substitution of dim white light, equated in brightness to the red, is desirable. The question is, how much time is required for complete dark-adaptation when the dim white light is turned off? If the white light is set so that the crew is adapted to an intensity level of about 0.5 ft-L, then five minutes is sufficient time for dark-adaptation (11, 14). Thus, if after operating under bright white light, dim white light is desired for some portion of the dark-adaptation process, then it should be on for about 10 minutes, after which the compartment should be rigged for black for 5 minutes. If the crew finds it acceptable to run under the dim white light all night, then, of course, they would never be more than about 4 minutes from complete dark-adaptation.

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The literature concerning the effectiveness of red and white light for permitting subsequent dark-adaptation is reviewed. Although red light is clearly superior to white, its advantage decreases as intensity decreases, and at levels of ambient light found in submarine compartments, its superiority over white is probably not of practical significance in most situations. Considering the disadvantages of red light, it is concluded that low level white light is preferable to red light as general night-time ambient illumination.

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