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THE EFFECTIVENESS OF A COLOR/SATURATION BEACON AS A NAVIGATIONAL RANGE INDICATOR

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SUMMARY PAGE

THE PROBLEM

To determine the navigational performance of observers using a simulated aid to navigation proposed by the U.S. Coast Guard. The aid is a single-station range beacon that would indicate lateral position in a channel by displaying a change in color as the vessel operator moved across the channel. The beacon would show a strong green at one side, gradually changing to white in the center, and increasing to a strong red at the other side.

FINDINGS

The ability of observers to detect deviation from range axis and motion across range axis was determined for the simulated color beacon both with and without a white reference light. The sensitivity afforded by this type of indicator to judge on-axis position was found to be questionable, but sensitivity to motion across range axis was found to be superior to that of alternative beacons studied previously.

APPLICATION

The findings describe the navigational sensitivity afforded by a color-encoded single-station range indicator. They will allow comparison with other proposed single-station range indicators and with current two-station parallax range indicators.

ADMINISTRATIVE INFORMATION

This study was conducted at the Naval Submarine Medical Research Laboratory under a modification to Contract No. MIPR-Z51100-9-0002 with the U.S. Coast Guard Research and Development Center, Groton, CT. The manuscript was submitted for review on 19 October 1990, approved for publication on 13 December 1990, and has been designated as NSMRL Report No. 1163.

ABSTRACT

We evaluated the effectiveness as an aid to navigation of a single-station beacon which was white when viewed from the centerline of a channel and became increasingly red or green when viewed from off center to the right and left. First we measured the observers' ability to determine whether a light was white, reddish, or greenish. A wide range of colors, from 575 nm to 585 nm, were judged to be white, making it difficult to specify a beacon that would adequately signal center of channel. Second, we measured the ability of the observers to detect a change in color for slowly changing stimuli. There were seven just noticeable differences in the range of color investigated. This would provide a sensitivity of 21.8 m (71.4 ft) over a 152 m (500 ft) wide channel. Measurements were taken with and without a "white" reference light. Under no condition did the reference light improve performance. For changing stimuli, however, those that were brighter or larger provided better sensitivity than those that were smaller or dimmer.

The Effectiveness of a Color/Saturation Beacon as a Navigation Range Indicator

The U.S. Coast Guard is evaluating various methods for indicating to a navigator if his/her ship is proceeding properly along a channel or "range." A general question is whether or not the two-station or parallax range indicator can be replaced by a single-station device. Previous publications have assessed navigators' performance using several types of parallax ranges (Laxar and Mandler, 1989), as well as a rotating beam (Luria, 1990) and a flashing light (Laxar and Luria, 1990) type of single-station range indicator.

The present study examines the effectiveness of a single-station beacon that would display a beam of light that varied in color according to lateral position in the channel, as shown in Figure 1. At the left edge of the channel, the observer would see a saturated[1] green light. Approaching the range axis, the green light would gradually desaturate until a white light was seen on the centerline. With further movement toward the right edge of the channel, the light would gradually become pink, then a highly saturated red. Comparison of the variable light with an adjacent standard white light could provide a reference for judging the saturation of the variable light and thus the ship's position relative to the range axis. This range display would be similar to a sector light in providing a chromatic code. A sector light, however provides crude information about lateral position in the channel. The proposed light was studied to determine if a continuously varying

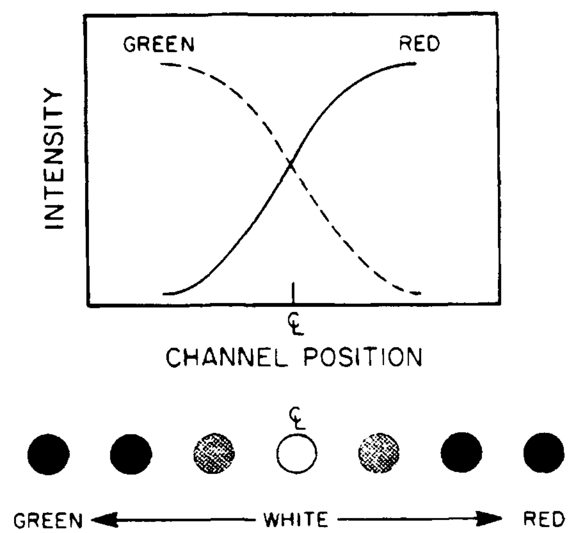

Fig. 1. Chromatic range. When on the centerline a steady white light is seen. As one moves to the right, the light changes gradually to pink and then to deep red. Similarly, movement toward the left of the channel centerline results in a change toward green.

1 Saturation refers to the purity of a color stimulus, that is, its richness or the degree to which it differs from white. Two other aspects of a color stimulus are hue and brightness.

chromatic signal would improve lateral sensitivity. The results may also apply to the design of a graded sector beacon, as well as to a continuously varying beacon, by specifying the optimal number of step gradations displayed across the channel.

Studies of saturation discrimination have found that there are about 20 discriminable steps in color purity between white and red, and between white and green (Jones & Lowry, 1926; Martin, Warburton, & Morgan, 1933), considerably more than, for example, between white and yellow. Other studies, such as those of Priest and Brickwedde (1938) and Jameson and Hurvich (1955), measured the minimal amount of spectral light added to white that is just detectable. These studies all concluded that saturation discrimination is relatively good in the red and green areas of the spectrum and poor in the yellow. All of the studies of saturation discrimination, however, have tested the ability to perceive differences between two static, unchanging colors. None has investigated observers' sensitivity to a gradual change in a light's saturation. In previous reports, however, we have shown that it can be far more difficult to detect a gradual change in a moving stimulus (Laxar & Mandler, 1989) or a flickering stimulus (Laxar & Luria, 1990) than to perceive that two unchanging stimuli are different. We therefore conducted two experiments. In the first, we measured observers' ability to discriminate small differences in color from a white stimulus, in order to assess sensitivity to position on or off the range centerline (static thresholds). In the second, we measured observers' ability to judge gradual changes in color, in order to assess sensitivity to motion across the range (dynamic thresholds).

METHOD

Observers

Eight volunteers, ranging in age from 20 to 50 years, participated in both the static and dynamic experiments. All had normal color vision and 20/25 or better visual acuity, with their spectacle correction if required. Four of them were experienced psychophysical observers.

Apparatus

The stimuli were produced by a two-channel optical system, one channel providing the variable red-to-white-to-green stimulus, the other providing the fixed white reference light (Figure 2). In the variable channel, light from a tungsten source was passed through a blocking filter, a polarizing filter, and a polarizing dichroic filter. As the dichroic filter was rotated 90° in its plane, the colors it transmitted gradually changed from red to white and then to green, as given in Table 1 and shown in Figure 3. The white reference light was produced by setting a dichroic filter to the mean not-red, not-green point of 12 observers. This value was determined psychophysically prior to the start of the experiment. The reference light's color temperature was 3338°K. The stimuli were calibrated with a PR-703A/PC Spot SpectraScan fast spectral scanner (Photo Research Div., Kollmorgen Corp.).

Light from the two channels passed through a vertical pair of apertures separated by a visual angle of 8.2 arc min on center at the 6 m viewing distance. The reference light, when used,

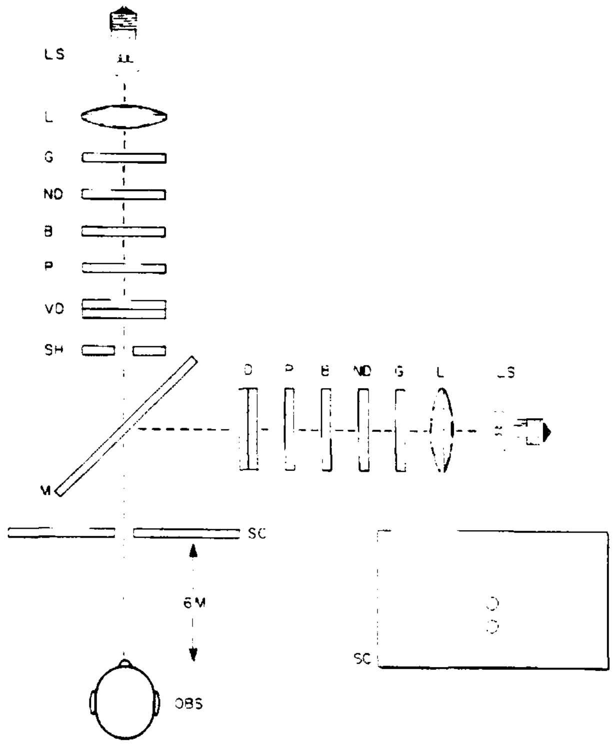

Fig. 2. Diagram of the chromatic range apparatus. The light from each tungsten bulb (LS) goes through a collimating lens (L), ground glass (G), a neutral density filter (ND) when required, a blocking filter (B), a polarizing filter (P), and a dichroic polarizer (D or VD). The variable stimulus goes through and shutter (SH). The fixed reference stimulus is reflected by a mirror (M). Both light beams pass through their respective apertures in a screen (SC) 6 m from the observer. The apertures are vertically aligned, with the variable stimulus under the reference stimulus.

illuminated the upper aperture. Two aperture sizes, subtending 1.0 and 3.5 arc min., were tested. Two luminance levels, given in Table 1, were tested as well. The lower luminance was achieved by placing a 1.0 neutral density filter in each channel.

PROCEDURE

The observer sat with his/her chin in a chinrest, in a room with barely enough light to see the large objects in the room. After a brief practice session, the static thresholds were always measured first, with the dynamic thresholds measured in subsequent sessions. Data were collected and analyzed in terms of the angular setting in degrees of the polarizing dichroic filter, and later converted to dominant wavelength for reporting purposes.

Conditions. Eight conditions were measured, combinations of the following factors: presence and absence of reference light, large and small apertures, and high and low luminance level. The order in which the conditions were presented was counterbalanced across the eight observers.

Static thresholds. Static thresholds were measured using the method of constant stimuli. The observer was presented with a stimulus for 1 sec, and then he/she responded "red," "green," or

Table 1
Stimuli for Chromatic Range Experiment

Color	Dominant Wavelength	Excitation Purity	CIE Chromaticity Coordinates x	CIE Chromaticity Coordinates y	Luminance (cd\m^2) Low	Luminance (cd\m^2) High
Red	603 nm	98%	.630	.367	218	2184
White	578 nm	68%	.439	.454	288	2878
Green	518 nm	48%	.195	.565	542	5424

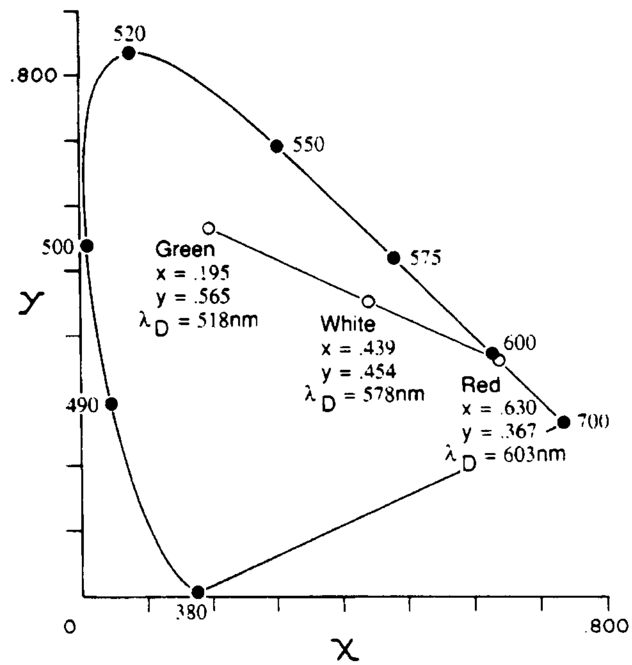

Fig. 3. The CIE Chromaticity Diagram showing the locus of stimuli displayed by the variable light beam. The fixed beam showed only the white reference stimulus.

"neither." For each of the eight conditions, there were usually eight stimuli, covering the range from one that appeared consistently red to one that appeared consistently green for that observer. Each stimulus was presented five times. The experiment was run in a single session lasting about an hour.

Dynamic thresholds. The method of limits was used to measure the dynamic thresholds. Five starting points were used: 518 nm -- the extreme green end of the range, 537 nm -- moderately greenish, 578 nm -- the white stimulus the same as the reference light, 597 nm -- moderately reddish, and 603 nm -- the extreme red end of the range. The stimulus was exposed, and after a random foreperiod of 0 to 5 sec, the experimenter rotated the variable dichroic filter at one-half degree per second (0.5 nm/sec average). The observer was required to judge when the color of the light appeared to change, and in which direction, and then respond "more green," "less green," "more red," or "less red," at which point the variable stimulus was extinguished. At the two extreme starting points, of course, the direction of change could only be in the "less" direction, resulting in a total of eight combinations of starting point and direction of color change. These eight thresholds, measured in random order for each condition, were as follows: 518 nm to Less Green, 537 nm to More Green, 537 nm to Less Green, 578 nm toward Green, 578 nm toward Red, 597 nm to Less Red, 597 nm to More Red, and 603 nm to Less Red. Typically three to five measures were taken to determine each threshold, depending on the variability of the observer.

The observers were told when their judgment was in error. The errors were recorded, but those data were not averaged in the results for that threshold; those trials were rerun later in the session. No adjustment to the data was made for observers' guesses that happened to be correct, so the results may be biased slightly towards overestimating sensitivity. Each condition was run in a separate session, lasting about one-half hour.

RESULTS

Static Thresholds

Probit analysis was used to determine the 95% response point for the red and green thresholds for each observer under each condition. These thresholds were the points at which the observer changed his/her response 95% of the time from neither red nor green to either just noticeably red or just noticeably green. Thresholds varied widely, both across observers as well as within observers, over the eight conditions. Some lights that were called "red" by some observers were consistently called "green" by others. For the eight observers, the mean threshold across all conditions for a green response was a light with a dominant wavelength of 575 nm (SD = 6). For a red response, the wavelength was 585 nm (SD = 5).

Mean red and green thresholds for the three main pairs of experimental conditions are shown in Figure 4. Absence of reference light, and lights of higher luminance level and larger size, all tended to shift both red and green thresholds in the long-wavelength direction. It was hypothesized that the presence of a white reference light would make observers more sensitive to small changes toward reddish or greenish. To test this, as well as the effects of luminance level and aperture size, repeated measures analyses of variance (ANOVAs) were computed on the threshold data for the following factors: 2 Conditions of Reference Light (with and without) x 2 Luminance Levels x 2 Aperture Sizes x 8 Subjects. A separate ANOVA was computed for the red and the green thresholds; the results are shown in Table 2. In both cases, the effect of Reference Light was not significant, and Luminance Level was significant. Aperture Size was significant for the green thresholds only.

A similar ANOVA was computed for the differences between the red and

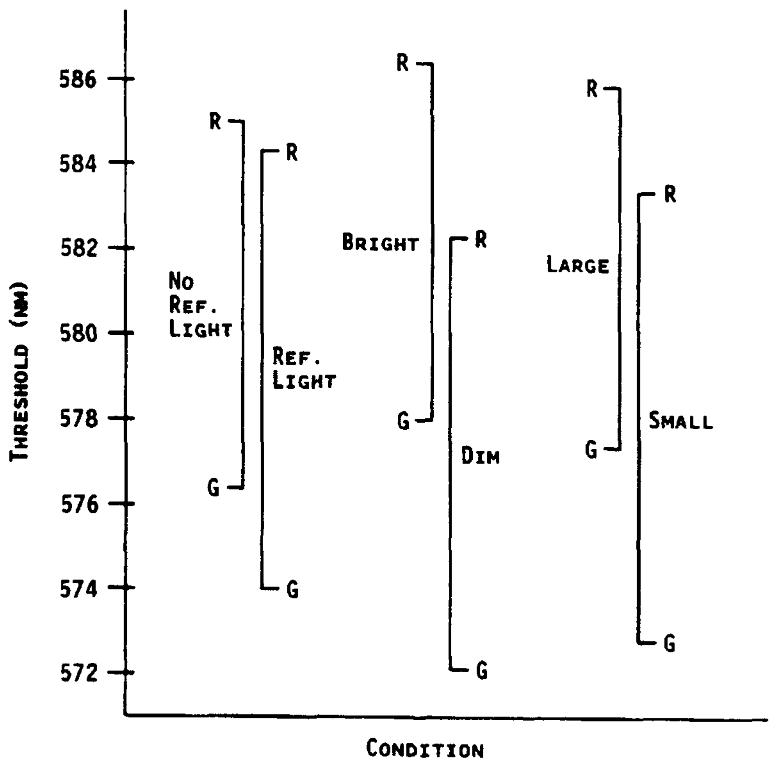

Fig. 4. Red and green static thresholds for the three experimental parameters (left to right): absence or presence of reference light, luminance level, and aperture size. Mean data for eight observers.

Table 2
Summary of ANOVAs for Red and Green Static Thresholds

Threshold	Source	df	F	Probability
Red	Reference Light	1,7	0.23	---
	Luminance Level	1,7	50.46	$p < .001$
	Aperture Size	1,7	4.97	---
Green	Reference Light	1,7	2.07	---
	Luminance Level	1,7	77.52	$p < .001$
	Aperture Size	1,7	37.45	$p < .001$

green thresholds. The only significance found was for the effect of Reference Light, $F(1, 7) = 8.45$, $p < .05$. Examination of Figure 4 shows, however, that, contrary to expectations, the presence of the reference light increased the difference between the red and green thresholds. The variables that were manipulated in this experiment therefore had no apparent effect on reducing the red-green threshold differences that would indicate improved sensitivity.

To get an approximation of the neutral (not-red, not-green) point, we calculated the midpoint of the red and green thresholds for each observer by condition. Averaged over all conditions, mean neutral points for the observers spanned a wide range, from 574 nm ($SD = 3.5$) to 588 nm ($SD = 3$). The overall mean midpoint was 580 nm ($SD = 6$), slightly redder than the 578 nm wavelength of the reference light determined prior to the experiments. A corresponding ANOVA on these midpoint data yielded results comparable to those of the red and green thresholds.

Dynamic Thresholds

A three-way repeated-measures ANOVA, corresponding to those for the static data, was computed for each of the eight dynamic thresholds measured. The presence of the reference light, as with the static thresholds, never produced a significant effect. In general, the brighter stimuli and the larger stimuli produced smaller thresholds and improved performance, although the effects were only significant at the longer-wavelength thresholds. The ANOVA results for these factors are summarized in Table 3. The dynamic thresholds for the large bright stimuli are plotted on the CIE Chromaticity Diagram in Figure 5 in terms of starting wavelength from which the just noticeable difference was measured. The arrows on the diagram show the overall means across all eight experimental conditions. Except for the 537 nm to Less Green threshold, the thresholds are larger for the small dim stimuli than for the larger brighter stimuli. In addition, thresholds are generally larger for thresholds in the green region than in the red. The effects of stimulus size, luminance, and chromaticity found here are in keeping

Table 3
Summary of ANOVAs and Mean Errors for Dynamic Thresholds

	Factor				
	Luminance Level		Aperture Size		
Threshold	F	p	F	p	Mean Errors (%)
518 nm to Less Green	---		---		22.4
537 nm to More Green	---		---		9.3
537 nm to Less Green	---		---		1.6
578 nm toward Green	---		6.9	.05	1.2
578 nm toward Red	---		---		0.0
597 nm to Less Red	---		13.7	.01	0.6
597 nm to More Red	10.3	.05	11.8	.05	1.6
603 nm to Less Red	157.3	.001	26.6	.005	9.3

Note. In all cases, df = 1,7

with results found earlier by other methodologies (Brown, 1957; MacAdam, 1942; Wyszecki & Fielder, 1971).

Error percentages by condition were calculated for each observer. The mean errors for each threshold are presented in Table 3. Observers made the largest number of errors (22.4%) on the 518 nm to Less Green threshold. Though they could perceive a change, they could not tell whether it was toward more green or less green, since it was not apparent to the observers that this was the extreme green stimulus. Not quite as difficult, but still producing substantial errors, was the similar threshold at the extreme red stimulus (603 nm to Less Red), and the 537 nm to More Green threshold. Some of these errors may be attributable to the slower change in wavelength at the extreme ends of the scale as the polarized dichroic filter was rotated, relative to the change at the middle of its range. The slower change at the red and green ends may have placed an additional memory or perceptual burden on the observer, making the error rate higher. ANOVAs corresponding to the previous ones were computed on the error percentage data for these three thresholds. The only factor found significant was Luminance Level for the 537 nm to More Green threshold, $F(1, 7) = 9.9$, p .05. Surprisingly, the brighter stimulus produced 11.7% errors, whereas the dimmer stimulus produced only 6.9%. Perhaps the observers made fewer errors with the dim stimuli because they were acting more conservatively in making more difficult judgments.

DISCUSSION

Static Thresholds

Based on the results of this study, it would appear very difficult to choose a

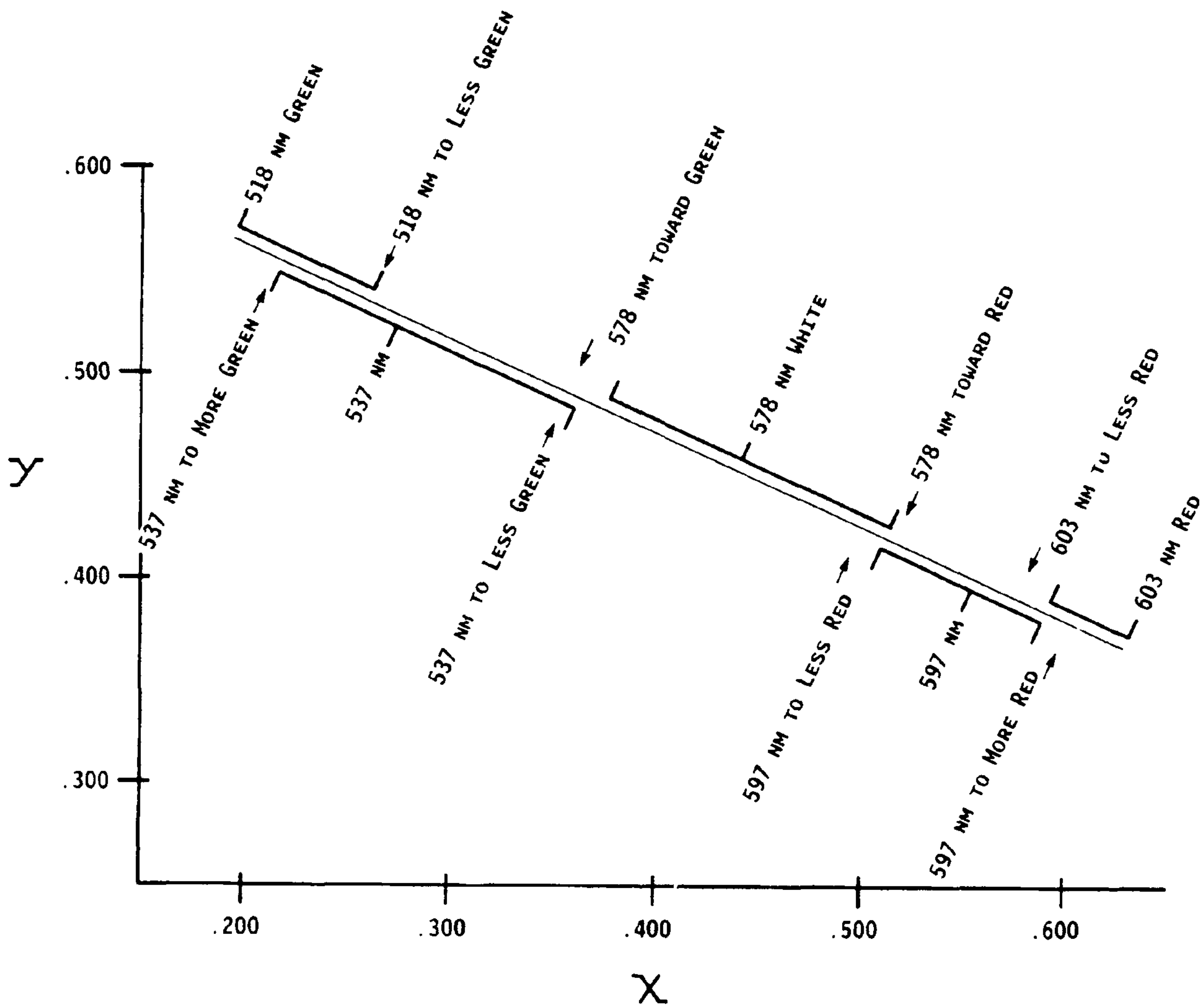

Fig. 5. Dynamic thresholds for the larger brighter stimuli plotted on the 1931 CIE Chromaticity Diagram, labeled in terms of dominant wavelength of starting point. Arrows indicate mean thresholds for all eight stimulus conditions. Mean data for eight observers.

"white" light to indicate center of the channel that would be immediately recognized as white under a variety of conditions by a large proportion of observers with normal color vision. When looking at either individual or grouped data, discrimination between white and reddish or greenish colors appears quite good. When comparisons are made among different observers, however, it is clear that wide and consistent differences exist in the judgment of hues. Recently, Neitz and Jacobs (1986, 1990) have documented the wide range of performance on a color matching task by a large number of color normal observers. In addition, studies have shown that significant shifts occur in the judgment of hues with age (Schefrin & Werner, 1990) and even over relatively short time periods within the same observer (Laxar, Miller, & Wooten, 1988).

Choice of a more neutral (less yellowish) white may improve inter-observer agreement. Equipment limitations precluded this. In any case, however, individual differences would still exist. The literature contains many examples of the variability of white points, including differences due to exposure duration and stimulus size (Jameson & Hurvich, 1951), as well as physiological variables (Richards, 1967; Wright, 1969). In this study, the large, bright stimuli produced the smallest difference between the mean red and green thresholds; that is, sensitivity to centerline position would be optimal. However, the neutral points (roughly, the midpoints between the red and green thresholds) for only three out of the eight observers fell between the red and green thresholds. These data show that individuals have widely varying values for what they call white. This suggests to us that no observer looking at the reference light actually thinks of it as white; it always looks either reddish or greenish, and consequently does not do much to help his/her performance. A slightly different experimental task, in which the observer was asked to directly indicate "left," "center," or "right" channel position, rather than color, may have shown the reference light to be more useful in identifying center of channel.

These results suggest that a chromatic range beacon may not be an appropriate device for displaying center of channel position. Given the data from the present simulations, we consider it not meaningful to try to specify the sensitivity afforded by this type of beacon for identifying center of channel position. It cannot be predicted whether, from a brief glance, a vessel operator could tell if he/she were on or slightly off the channel centerline.

Dynamic Thresholds

As expected, discrimination of slowly changing color stimuli proved much poorer than measures of static discrimination found in the literature. As shown in Figure 5, under the optimal conditions of higher luminance level and larger aperture size, there exist seven just noticeable differences in the range of colors tested. Let us assume a nominal range 1219 m (4000 ft) long with a channel width of 152 m (500 ft) and the navigational beacon 610 m (2000 ft) from the near end of the range (see Laxar & Luria, 1990). If a single-station range beacon were to display these colors over the channel width at the far end of the range, the observer's sensitivity would be one-seventh of the width, or 21.8 m (71.4 ft). This would mean that the vessel would have to move that distance across the channel before the operator could determine that the ship had moved, and in which direction (right or left). In a recent study of two-station parallax ranges, Laxar and Mandler (1989) found that observers could perceive a change in horizontal offset of the near and far range lights of approximately 1.5 minutes of arc. This is equivalent to a sensitivity of 39 m (128 ft) within a channel 152 m (500 ft) in width. Under optimal conditions, therefore, the color/saturation single-station beacon may provide better sensitivity to motion across a channel than present parallax displays. At the end of the range near the beacon, however, the colors, being displayed at the same angles, would span only the central 51 m (167 ft) of channel width. In some instances, this may be impracticably narrow, and careful consideration would have to be given to the dimensions of the range for which an angular display beacon could be used.

Aperture size may be more important in determining performance than the luminance levels tested here. It has long been known that color discrimination becomes poorer with lights of smaller subtense (Bedford & Wyszecki, 1958). With extremely small lights, discrimination becomes especially poor in the blue-green region of the spectrum (Willmer and Wright, 1945). The smaller aperture, 1 arc min, would be 0.54 m (1.77 ft) in diameter and the larger aperture, 3.5 arc min, would be 1.89 m (6.19 ft) in diameter at 1 nautical mile distance. At greater distances, the lights would have to be proportionately larger, and may prove impractical for a single-station beacon.

With the exception of the extreme green end of the scale, errors on the color/saturation dynamic thresholds averaged lower than those found with current two-station range indicators, which were on the order of 11% (Laxar & Mandler, 1989). The 22.4% error rate found at the green extreme may be related to the relative lack of saturation of that stimulus light, excitation purity of 48%, making it difficult to tell when it was changing toward the yellowish white. In the middle of the color range, errors were virtually nil.

CONCLUSIONS

The color/saturation concept shows promise for a single-station range beacon for indicating lateral motion in a navigational channel. For observers with normal color vision, sensitivity was better than with current two-station and some alternative single-station range indicators, although errors were very high at the extreme green end of the color range. With the colors of lights tested, however, it was unclear that such a beacon would perform adequately for signaling when the vessel was on or near the centerline of the channel. Further study with a more saturated green, a more neutral white, and a longer wavelength red would provide further information on the adequacy of a color/saturation single-station range indicator. The colors would also have to be carefully chosen and tested to ensure minimal confusion by color defective observers, estimated to comprise over 8% of the male population (Wyszecki & Stiles, 1982).

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