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A COMPARISON OF SIMULATED PARALLAX AND SINGLE-STATION RANGE AIDS TO NAVIGATION

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16. Abstract

An appropriately designed parallax (two-station) range allows a mariner to accurately determine a range line--the correct path to steer his vessel--at greater distances. Less expensive alternatives to parallax ranges are desirable, and many ideas, principally single-station ranges, have been proposed. However, the mariners' abilities to establish range lines with them have not been measured. The present work has quantified the navigational sensitivity afforded by parallax ranges and three different types of single-station range display systems. The single-station ranges used (a) temporal characteristics, (b) spatial representation, or (c) color changes of the signal to represent changes in lateral position. Range systems were simulated either opto-mechanically or on a high resolution computer display system.

The mariners' ability to determine both lateral position in a channel and direction of motion across a channel was assessed psychophysically for each range system. Performance with single-station range systems was compared with that obtained with parallax ranges. This allowed us to evaluate the implications of replacing parallax ranges with the single-station ranges.

All three single-station range types showed the potential for providing navigational sensitivity as good as, or better than, the parallax displays under certain range conditions. However, each of the single-station ranges has a set of variables associated with it that could markedly affect the sensitivity. In general, when compared with parallax ranges, single-station ranges were characterized by greater uncertainty on the part of the observer. Under optimal conditions, the frequency encoded range provided the best sensitivity of the three single-station displays, followed by the color-coded beacon, and the sequentially flashing beacon. Under operational conditions, however, the sequentially flashing beacon would likely prove superior.

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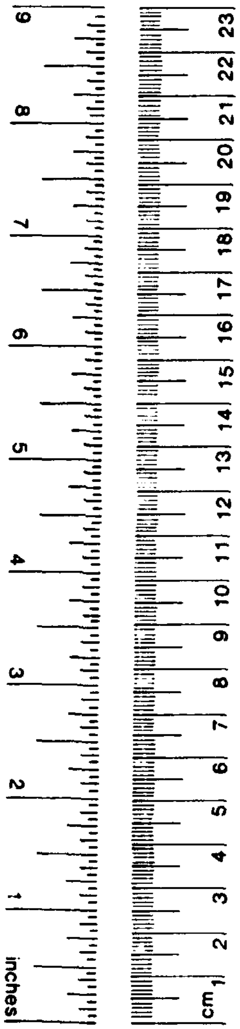
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

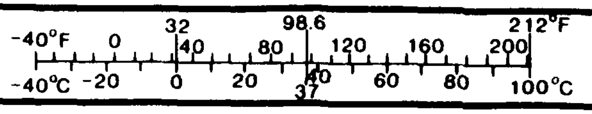
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



SUMMARY PAGE

THE PROBLEM

To compare the navigation performance of observers using parallax (two-station) range lights with three types of single-station range display systems proposed by the U.S. Coast Guard.

FINDINGS

The ability of observers to detect deviation from range axis and motion across range axis was determined for seven types of simulated range display systems. When compared with parallax range systems, the single-station ranges could provide comparable navigational sensitivity under certain conditions, but were characterized by greater uncertainty on the part of the observers.

APPLICATION

These findings describe the navigational sensitivity afforded by current and proposed range display systems, and permit the evaluation of implications of replacing parallax ranges with single-station ranges.

ADMINISTRATIVE INFORMATION

This study was conducted at the Naval Submarine Medical Research Laboratory under 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 12 December 1990, approved for publication on 19 April 1991, and designated as NSMRL Report No. 1168.

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A COMPARISON OF SIMULATED PARALLAX AND SINGLE-STATION RANGE AIDS TO NAVIGATION: FINAL REPORT

The U.S. Coast Guard presently employs a visual method, the parallax, or two-station, range beacon, to indicate to a vessel's operator the correct path or "range" to follow along such navigation channels as approaches to harbors and within rivers. For nighttime use, this consists of a pair of lights positioned on the range axis with the farther light higher than the nearer one (Figure 1). Vertical alignment of the lights indicates that the vessel is positioned on the range's longitudinal centerline, or range axis, and any deviation from this course is readily apparent. The range lights therefore provide a means of accurately judging position in the channel as well as speed and direction of motion perpendicular to the channel. Mariners have great confidence steering their vessels when using a range display because of the constant feedback given about position in the channel.

Although effective and easy to use, such two-station aids are expensive, since the more remote range light is typically located on shore, requiring the purchase, construction, and maintenance of this site. A single-station range indicator--that is, a device located at one site--has therefore long been desired. Several such devices have been tested and have had limited success (Ciccolella, 1958). The present report examines the navigational effectiveness of several alternative range indicators.

In this study we compared visual performance with four types of parallax ranges and three types of single-station ranges under similar conditions. The single-station ranges evaluated had either been proposed, built, or tested by others, or are a variation of current hardware. We determined how well each type of range display provided the necessary information for navigating a channel; specifically, we examined how well observers could judge (a) when they were on and off the range axis, and (b) when they were moving toward and away from the range axis. Measurements were made at different lateral positions in the channel to map the sensitivity of the range system across the width of the channel. The objectives were to determine which range systems provide information adequate for navigation and to provide guidance to the engineer designing range systems.

This, the final report in a series, summarizes the research we conducted on each of the different types of range displays, and compares their effectiveness. Further details about the experiments can be found in the reports referenced in the beginning of each of the following sections on the various simulated display types studied.

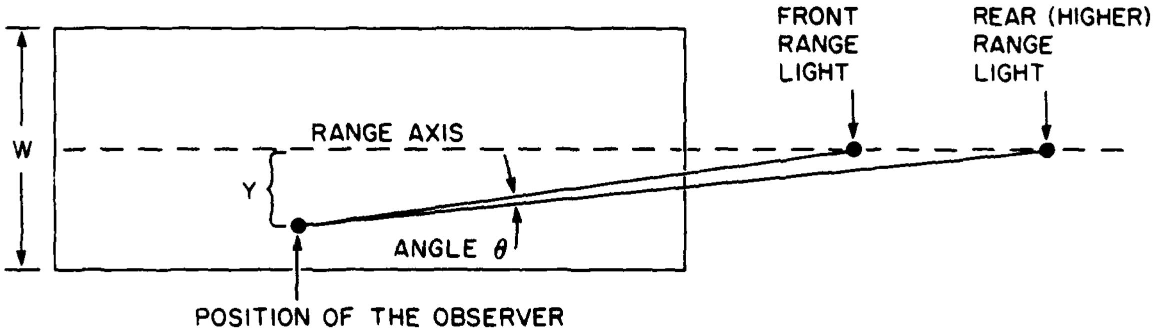

Figure 1. Top view of a parallax range. W: channel width; Y: distance of observer from range axis; θ: horizontal component of the angle between the lights.

Parallax Ranges

Our baseline performance was the observers' ability using parallax ranges to judge their motion toward or away from the range axis (dynamic simulations), and whether they were on or off the range axis (static simulations). A comprehensive report on these experiments can be found in Laxar & Mandler, 1989.

Method

Observers

In all experiments, volunteers ranging in age from 23 to 59 years participated. All had 20/25 or better visual acuity, with spectacle correction if required. In addition, observers participating in experiments requiring color perception were screened for normal color vision. Most were experienced psychophysical observers. In these parallax experiments, 13 observers participated in the dynamic simulations, and four of them also participated in the static simulations.

Apparatus

The range configurations were simulated on a Ramtek 9400 high resolution color display system driven by a DEC VAX minicomputer. Observers responded using an auxiliary key pad.

Displays

Four types of parallax range indicator lights, listed below, were simulated dynamically. The first two types are in use. The latter two have been proposed as alternatives.

Two-point fixed. This range display consisted of two lights that are always on and are vertically aligned when viewed from the center of the channel. The lights were 0.6 arc min in diameter and separated by 4.0 arc min when aligned (Figure 2A). When viewed from off center, they were not vertically aligned, and the misalignment increased with increasing distance from the center of the channel.

Two-point flashing. A second display was similar to the above except that the two lights flashed continuously. The upper light was on for 3.0 sec and off for 3.0 sec, while the lower light was on for 0.3 sec and off for 0.7 sec (Figure 2B).

Extended source. This range display consisted of two bars of light, 0.3 arc min x 6.0 arc min, oriented vertically with no separation between them and always on (Figure 2C). As with the spots of light, they are in vertical alignment only when seen from the center of the channel.

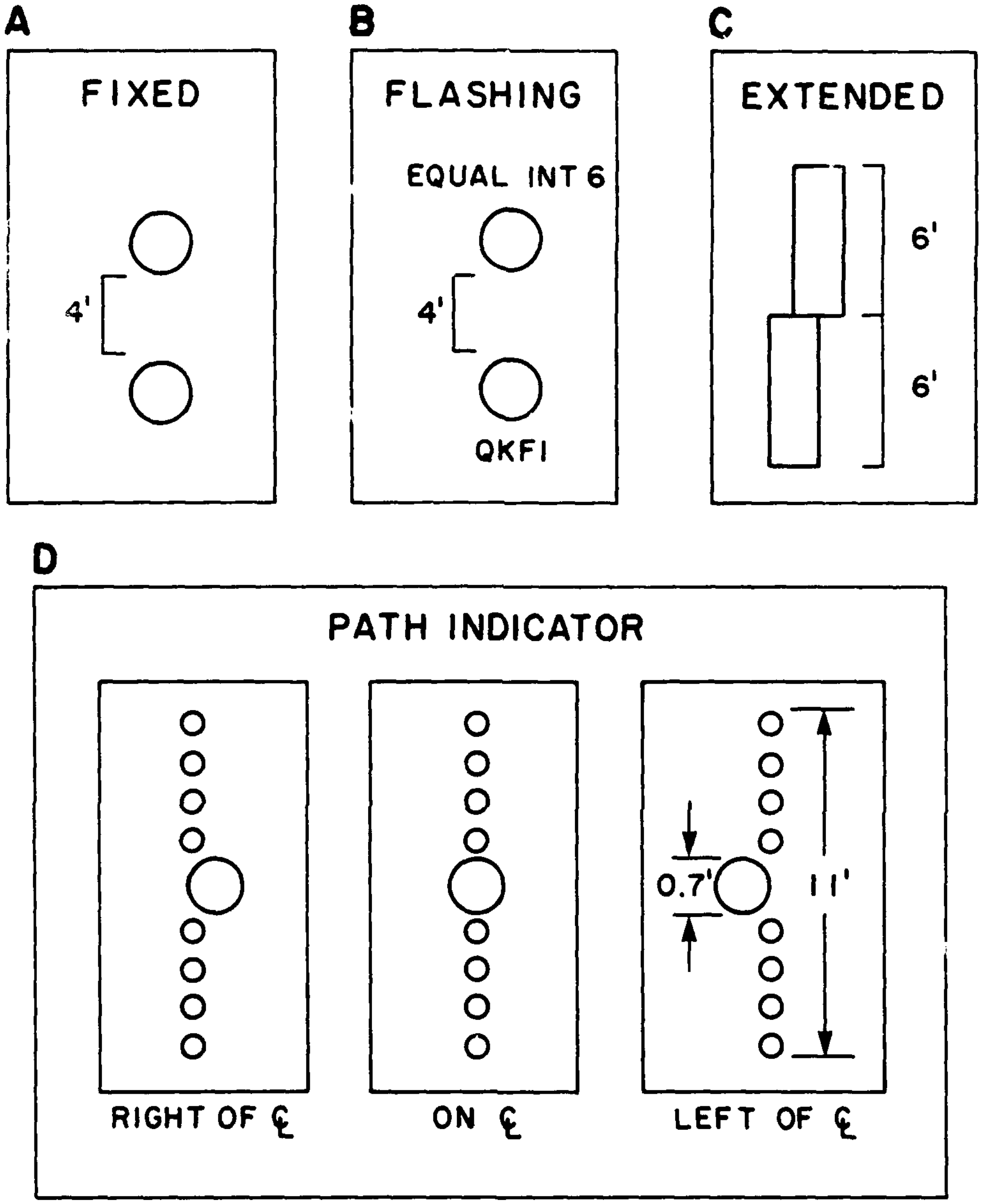

Figure 2. Four parallax range light configurations.

Path indicator. The fourth type of display consisted of a column of lights (Figure 2D). The center light, larger than others, was in alignment with the column only when viewed from the center of the channel. This type of display, oriented horizontally, is typically used as a glide slope indicator on aircraft carriers. We oriented it vertically so that lateral position rather than elevation was indicated. Unlike the device used on aircraft carriers which shows five discrete elevations, our display provided a continuous change in lateral position to determine if this enhanced display improved performance. If implemented, it might be constructed as a single-station range device using Fresnel lenses as on aircraft carriers.

For the static experiments, only the two-point and extended source ranges were simulated.

Procedure

Observers were seated 6 meters from the computer monitor and dark adapted for 5 min. The monitor screen subtended visual angles of 2.4° high x 3.3° wide and was uniformly illuminated to 0.003 cd/m^2, equivalent to the night sky with a partial moon. The white stimuli, at a luminance of 100 cd/m^2, were centered on the screen. The luminance level was imposed by hardware constraints. The testing room was otherwise dark.

Static thresholds. These experiments were similar to the visual acuity experiments of Westheimer and McKee (1977b). The static thresholds, here and throughout this study, were measured with the method of constant stimuli. In separate experiments, either the two-point or the extended source range was presented with the lower light in one of nine positions up to 37.1 arc sec (0.62 arc min) right or left of the upper light. The stimulus positions were chosen to encompass the range whose extreme values could easily be judged by the observers as being off axis. The stimuli were presented in random order once every 4 sec for 0.2 sec. The observer pressed one of two buttons on the keypad to indicate a left or right relative position of the lower light. Each position was presented randomly 30 times in two 270-trial sessions that lasted 18 min each, and the computer recorded each response.

Dynamic thresholds. These thresholds were measured with the method of limits throughout this study. For each trial, a pair of range lights was displayed in a configuration corresponding to a view from some distance off the range axis. After a variable foreperiod (1 to 5 sec), the bottom light began to move slowly to the right or left, simulating a vessel's motion across the channel. As soon as the observer could correctly judge the right-left direction of motion, he/she pressed a button corresponding to that direction. When the correct button was pressed, the angular distance which had been traversed by the lower light was recorded by the computer. The direction of motion toward and away from the centerline was randomized; half of the trials were toward the centerline and half were away. Trials were separated by a 2-sec interval; errors were recorded and those trials rerun later in the session. Figure 3 shows an example of this procedure for a two-point range.

Eleven starting positions were chosen randomly, up to 6.2 arc min right and left of center. This simulated situations in which the mariner was off the centerline by different amounts when first viewing the display, and it allowed us to calculate how much of a change in distance from centerline is required before a change in the display can be detected. The lower light moved at 9.3 arc sec/sec. For typical channel configurations, this corresponded to a speed of 2.6 to 11.5 knots across the channel. This was so imperceptibly slow that judgments were based on the position of the lights at some time after the start of the motion.

Performance was measured in a single experimental session. This consisted first of 42 practice trials. Next, one trial at each starting position was presented in random order in both left and right directions of motion. This was repeated over three blocks. The session thus comprised 66 trials, and lasted about 50 min.

Results

Static Thresholds

Data from the four observers were combined, and probit analyses were conducted on the 2160 trials from both the two-point and extended source range configurations. With chance performance represented by the 50% probability level and certainty represented by 100%, a probability level of 95% correct responses was chosen for the practical purposes of this study. With the two-point range, observers could judge when they were off the range axis by 30.7 arc sec (0.51 arc min). With the extended source configuration, the mean accuracy was 33.2 arc sec (0.55 arc min). The difference between the two range configurations was not significant, $t(3) = 0.80$, $p > .10$. Additional practice and a less conservative criterion probability level would likely have made the performance of these observers approach the 5 to 10 arc sec acuity found by Westheimer and McKee (1977b).

Dynamic Thresholds

Figure 4 shows the average thresholds for detecting motion both to the left and right of start position for the four range displays. Threshold is the average deviation from start position required by the observers to correctly judge the direction of motion for that range.

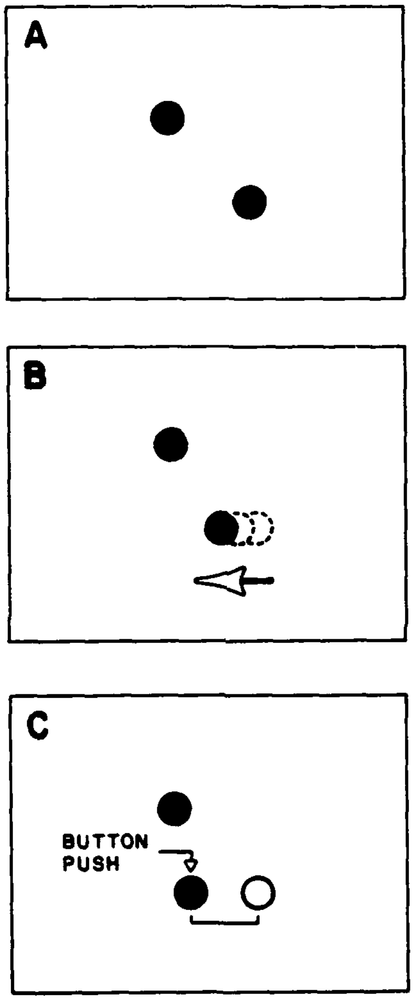

Figure 3. An example of the experimental procedure for motion threshold (dynamic) experiments. A: Start position; B: lower light in motion; C: position when observer detects that lower light has moved. The angular distance moved is recorded by computer.

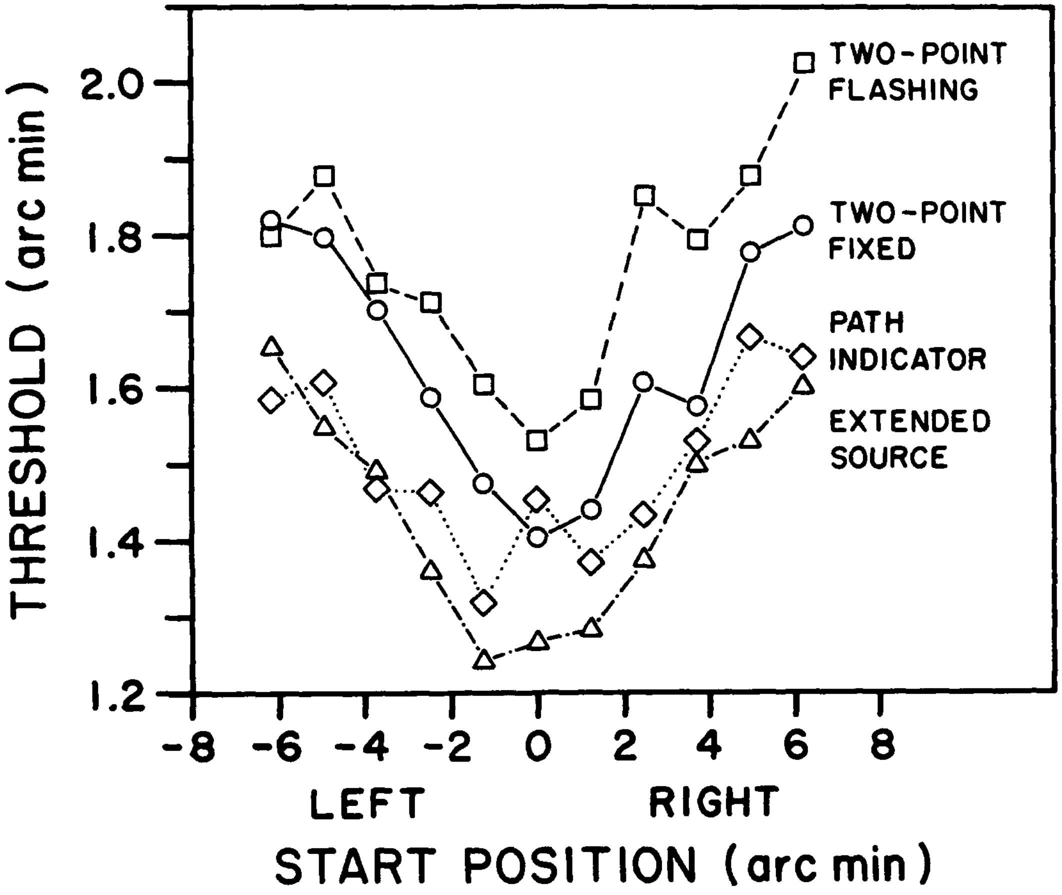

Figure 4. Motion thresholds for four parallax range light configurations. Note: In all references to thresholds, lower thresholds indicate greater sensitivity, or better performance.

A repeated measures analysis of variance (ANOVA) was computed on the deviations for the following factors: 4 Range Indicator Configurations x 2 Directions of Motion (to the right or left) x 11 Start Positions x 13 Subjects. Thresholds vary significantly with range configuration, $F\ (3,36) = 3.46$, $p < .05$. A Newman-Keuls test showed a significant difference between only the extended source and the two-point flashing range configurations ($p < .05$), however.

The effect of start position was also significant. Thresholds are smallest for start positions at or near the range axis (start position of 0.0) and increase as the start position distance increases left or right from center. This means that observers can easily determine whether they are moving toward or away from the range axis when near the axis, but they require a greater change in lateral position to correctly judge their direction of motion when farther from the range axis.

The right-left direction of motion effect was not significant. However, a significant interaction was found between direction of motion and start position, $F\ (10,120) = 15.36$, $p < .001$. This interaction defines the direction of relative motion effect (DRM, toward or away from range axis), which was significant in separate ANOVAs for all four range configurations. This DRM effect indicates that thresholds for judging motion toward the range axis are different from thresholds for motion away from the range axis. Figure 5 shows an example of these results for the two-point fixed range. Observers were better at judging changes when the direction of relative motion was toward the range axis than when it was away, by an average of 0.31 arc min. Results for the other types of parallax displays were comparable.

Four of the 13 observers had extensive experience in making fine perceptual judgments. To determine if such experience had any effect on motion thresholds, we compared their performance with that of the inexperienced group. The experienced observers had thresholds averaging 0.9 arc min more sensitive than the inexperienced group, a significant difference, $t(3) = 6.63$, $p < .01$.

Errors--that is, when the observer responded with the wrong direction of motion--were analyzed in a corresponding manner to that for motion thresholds. Table 1, mean error rates for the four range configurations, shows that the two-point flashing range produced almost twice as many errors as the other configurations. A four-way ANOVA showed a significant effect on errors for range configuration, $F\ (3,36) = 3.44$, $p < .05$. A Newman-Keuls test showed that the two-point flashing range was significantly different from the other three configurations, $p < .05$, which were not significantly different from each other.

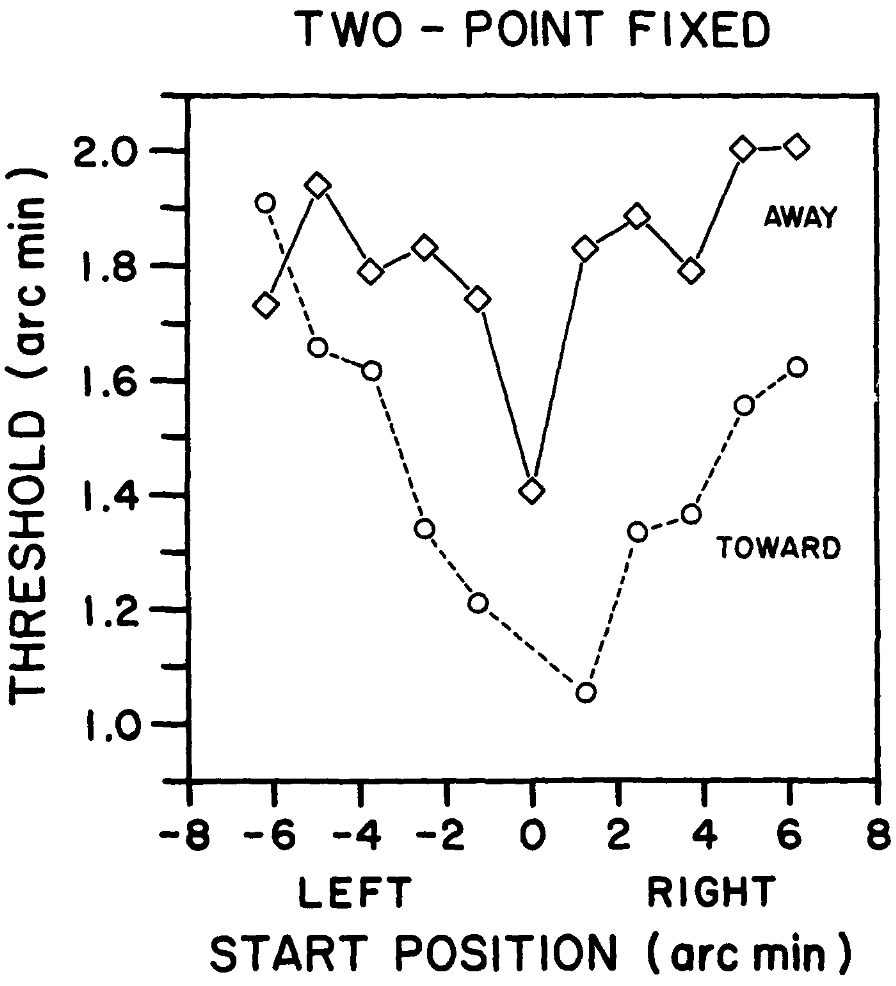

Figure 5. Thresholds for relative motion toward and away from the range axis for the two-point fixed range.

Table 1

Mean Error Percentages by Parallax Range Configuration

	Direction of Relative Motion		
Range Configuration	Toward	Away	Mean
Two-point fixed	9.5	12.4	11.1
Two-point flashing	17.1	18.0	17.5*
Extended source	6.7	10.3	8.6
Path indicator	4.4	13.3	9.2
All			11.6

*Significantly different from all others, which were not significantly different from each other.

The effect of start position was also significant, F (10,120) = 3.68, $p < .001$. The error data for all range configurations combined are shown in Figure 6. As with judgment of motion, best performance was near the on-axis position and became increasingly poorer with distance off axis. Interestingly, direction of relative motion toward or away from the range axis had no effect on error rate, in contrast to the significant effect it had on judgment of motion.

Rotating Beams Single-Station Range

This proposed range indicator displays a horizontal triplet of lights which appear to flash simultaneously when viewed from the channel centerline; when the vessel is to the right of centerline the right light would appear to flash first, and when to the left of centerline, the left light would appear to flash first (Brown, 1982). This asynchrony would alert the mariner that the vessel was off course and in which direction. The course could then be altered until the lights were again flashing simultaneously.

To design such a beacon, the smallest interval at which most viewers can perceive temporal order with reasonable reliability must be determined. Earlier studies found intervals ranging from as little as 3 msec (Westheimer & McKee, 1977a) to 30 msec (Lichtenstein, 1961) for binocular viewing, depending on the stimuli used. To approximate point source lights under night viewing conditions, the following experiment was conducted (Luria, 1990a) to simulate this single-station range indicator.

Method

Apparatus

The three flashing lights were produced by three cylinders with apertures, rotating about separate light sources. Figure 7

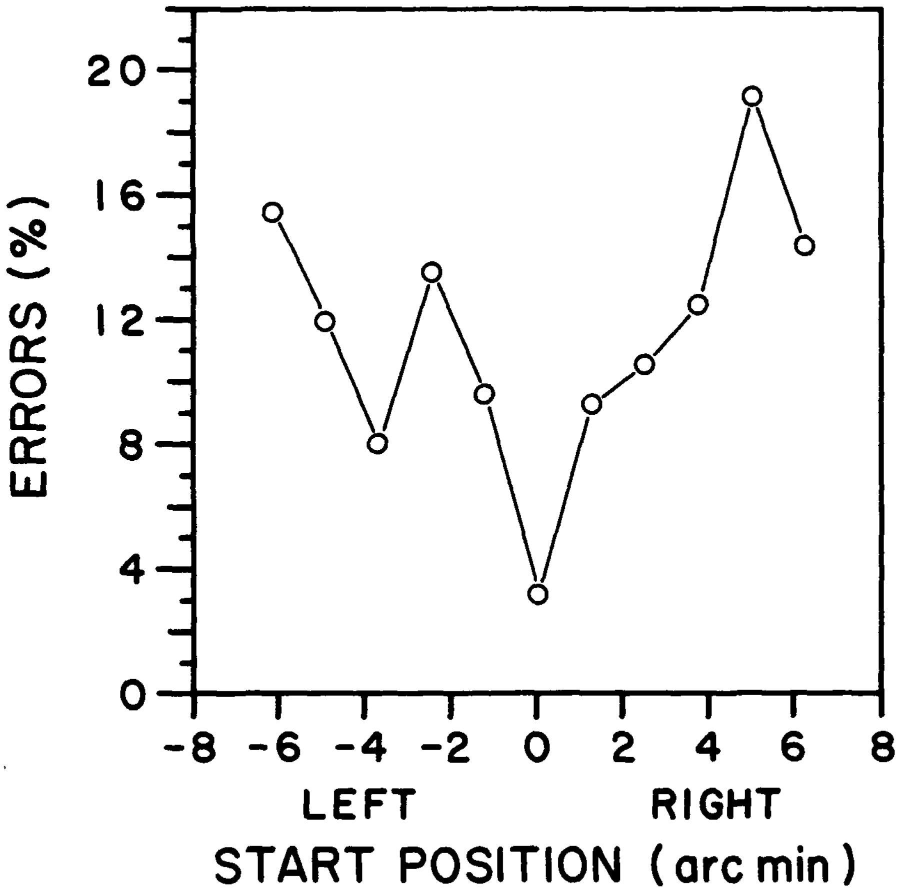

__Figure 6__. Mean percent errors for four parallax range light configurations combined.

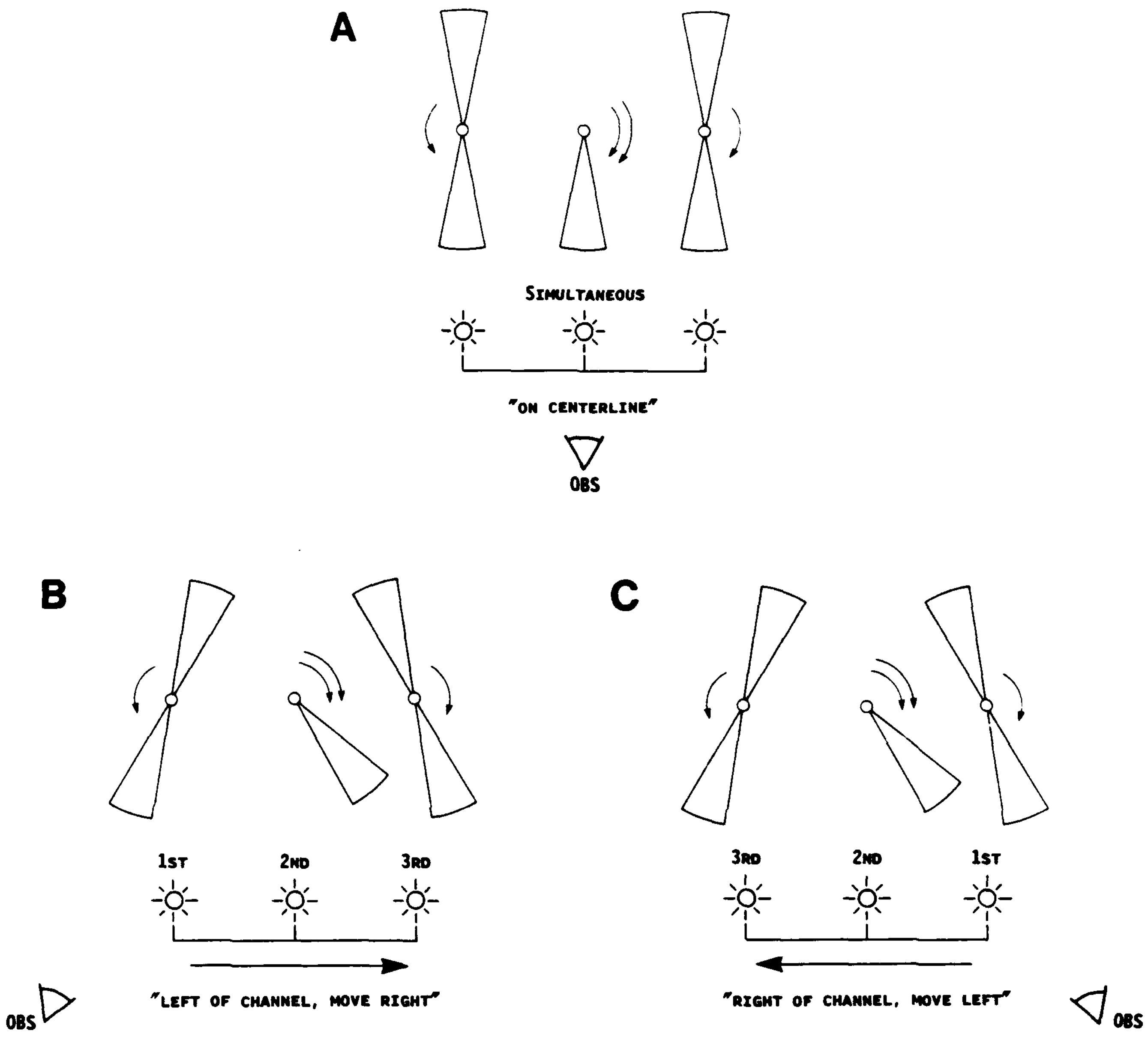

Figure 7. Operation of the sequential beacons. The left beacon, with two beams, rotates counterclockwise at a given speed. The center beacon, with one beam, rotates clockwise at twice that speed. The right beacon, with two beams, rotates clockwise at the same speed as the left beacon. All three beacons therefore flash at the same rate. A: When viewed from the range axis, the three beacons flash simultaneously. B: When viewed from left of range axis, the left beacon is seen first; the center is seen later, but before the right beacon, since the center beacon is rotating more rapidly. The interval between sequential flashes increases with distance from range axis. C: When viewed from right of range axis, the right beacon is seen first, followed by the center and then the left. Obs: Observer position.

illustrates the operation of the apparatus. To simulate angles off the centerline, movable apertures were placed in front of the beams, rather than rotating the apparatus or moving the observer. At the viewing distance of 6.1 m, the lights were 0.78 deg (47 arc min) apart and subtended 0.01 deg (0.6 arc min) visual angle. The lights were flashed at a rate of once every two seconds (0.5 Hz). Their luminance was 230 cd/m^2, and the flash duration was about 50 msec. This experiment and those following were conducted in a room with barely enough illumination to see the large objects in the room.

Procedure

Ten observers were given several practice sessions prior to the start of the study, and two minutes of adaptation to the ambient illumination before each session.

Static thresholds. The observer viewed the set of lights at either 0 deg (centerline) or at various viewing angles. The magnitude of the angle needed for a correct judgment of the temporal order (left light first versus right light first) was measured. A given angle of view was set and the flashing lights exposed until the observer made a judgment. The lights were occluded while a new angle of view was set, and so on.

Dynamic thresholds. The minimal amount of change in the viewing angle of the flashing lights that the observers could perceive was measured. Starting with randomly varied viewing angles of 0 (simultaneity), 1, 2, 4, or 6 deg to the right or left of centerline, the difference threshold was measured for both increasing and decreasing viewing angles. For each trial, the display was exposed and the viewing angle remained constant for a random foreperiod of 5 to 10 sec, after which the angle was changed at the rate of 5 deg/min. The observer reported when a change in the flash pattern was detected and whether the change was toward more or less simultaneity. Incorrect responses were not recorded, but the trial was repeated at some random time later in the session.

Results

Static Thresholds

Mean thresholds were calculated to determine the viewing angle at which the observers correctly identified the left-right direction of temporal order. A probit analysis was used to compute the 95% correct threshold. This resulted in a mean temporal interval of 8.4 msec between the flashes of the left and middle beacons, or 42.7 arc min (SD = 21.4 arc min) of angle from the centerline position.

To further study this type of range display, several parameters were varied. Thresholds were measured using only two flashing lights rather than three. Thresholds were not significantly different, although the variability with the two lights was greater. Again using just two lights, no significant differences in thresholds were found when the lights were separated by only 16 arc min of visual angle rather than the original 47 arc min. Thresholds were significantly worse, however, when the luminance of the lights was decreased in three steps from the original level of 230 cd/m^2 to 0.65 cd/m^2 (Luria, 1990b).

Using the three-light display, performance was measured when the display was flashed at twice the flash rate (once per second) and at half the flash rate (once every four seconds) with that presented in the previous experiments (once every two seconds). The temporal interval threshold to identify temporal order remained constant at about 5.6 msec for all flash rates, but the angular deviation from centerline at which the observers could perceive non-simultaneity decreased proportionally as flash rate decreased. When flashed at the slowest rate, sensitivity was doubled in comparison with the figures given above, a substantial improvement in performance.

An additional experiment showed that temporal interval threshold, and therefore viewing angle, decreased when the lights were defocused by putting lenses up to +2 diopters in front of the observers' eyes (Luria & Newacheck, 1991). Performance improved nearly twofold with the blurred image.

Dynamic Thresholds

Figure 8 shows the mean difference thresholds both in terms of the change in the viewing angle and in the temporal interval for each of the five starting positions. The standard deviations of these values were on the order of 35 arc min. The data show means for only nine observers, as one observer found it too difficult to do the task at the 4 and 6 deg conditions.

As the angle of the starting position from the centerline increased (and, therefore, the magnitude of the temporal interval between flashes increased), it generally became more difficult for the observers to detect a change in the flash pattern. The effect of start position was highly significant according to the Friedman Analysis of Variance by Ranks, ($r_2 = 11.93$, $p < .01$). The difference between toward and away from simultaneity was not significant.

The curves are, of course, not monotonic. There is a drop in the thresholds around 1 and 2 deg after which the thresholds rise continuously. One explanation seems evident. There is a range of perceptual simultaneity, temporal intervals around simultaneity which the observer cannot discriminate. When this

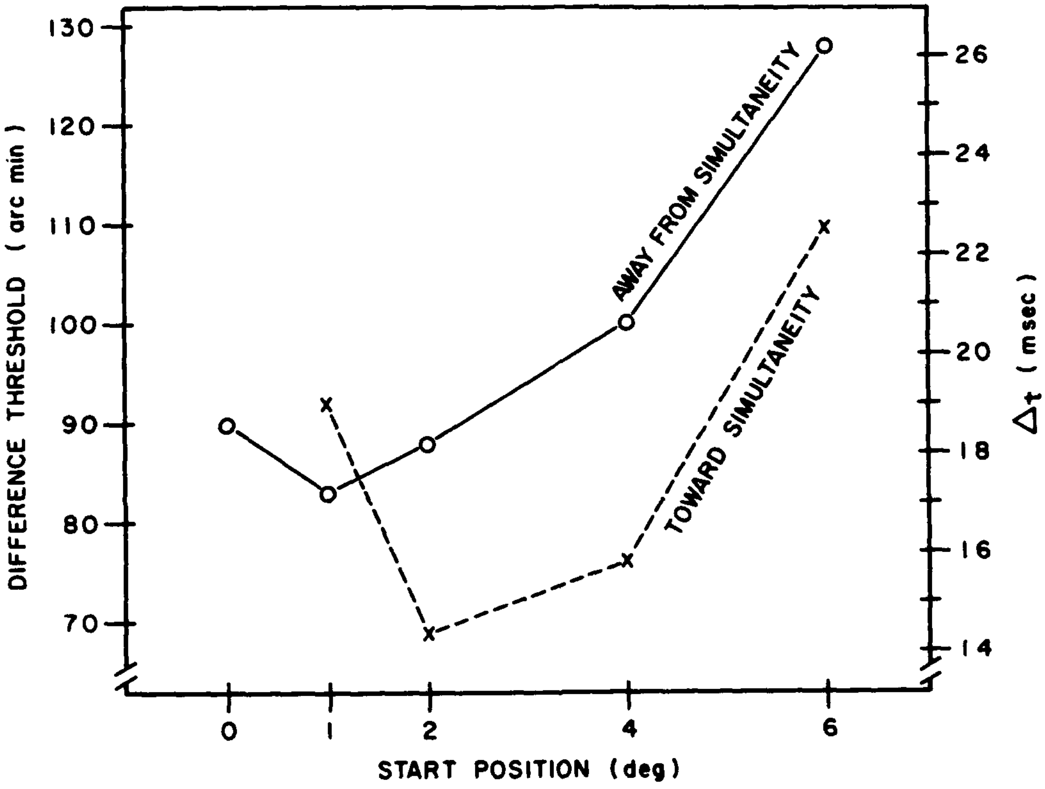

Figure 8. Rotating beams difference thresholds in minutes of arc of viewing angle and temporal interval, as a function of start position in degrees of off-center viewing. Thresholds are shown for changes toward and away from simultaneity.

range is exceeded the observer can detect non-simultaneity, which for most observers occurs at a viewing angle of between 1 and 2 deg. If the starting position is 1 deg off center, the resulting temporal interval is typically too small for the observer to detect. However, only a small increase in temporal interval is required to detect that the lights are no longer simultaneous. If the starting position is simultaneity, then a larger change is required to exceed the range of perceptual simultaneity. If the starting position is 2 deg off center, this is typically just outside the range of perceptual simultaneity. Thus only a small decrease in temporal interval results in the observer readily reporting simultaneity. A much larger change is required if the temporal interval is increasing.

Frequency Encoded Single-Station Range

This proposed flickering or flashing light range display would indicate lateral position in the channel by varying the flash frequency, combined with chromatic information to indicate left or right side (Figure 9). When on the centerline, the navigator would see a steady light. As the vessel moved off the centerline, the navigator would see the light start to flash on and off, increasing in frequency with distance from the centerline. Moving to the right could be signalled by a flashing red light, and moving to the left by a flashing green light. The range centerline position could be indicated by a steady white light. The color aspect, however, was not simulated in these experiments.

The basic question is, how well can observers discriminate the frequency of a flashing light? Earlier studies (Brown, 1959; Gebhard, Mowbray, & Byham, 1955; Mandler, 1984; Mobray & Gebhard, 1955) found that over the range of 1 to 20 Hz, the difference threshold, Δf, was a monotonically increasing function of frequency, but results varied widely in the range of 0.01 to 2.4 Hz, depending on stimulus size and experimental procedure. None used a point source of light on a dark background nor measured difference thresholds of a constantly flashing light as it slowly changed frequency, as would be the case with a flashing range indicator when a vessel traveled across the width of the range. The following experiment was therefore conducted (Laxar & Luria, 1990).

Method

Apparatus

The light source was a diffused white beam that subtended a visual angle of 1.9 arc min at the 6 m viewing distance. Its steady-state luminance was 41 cd/m^2. The 50% duty cycle of the

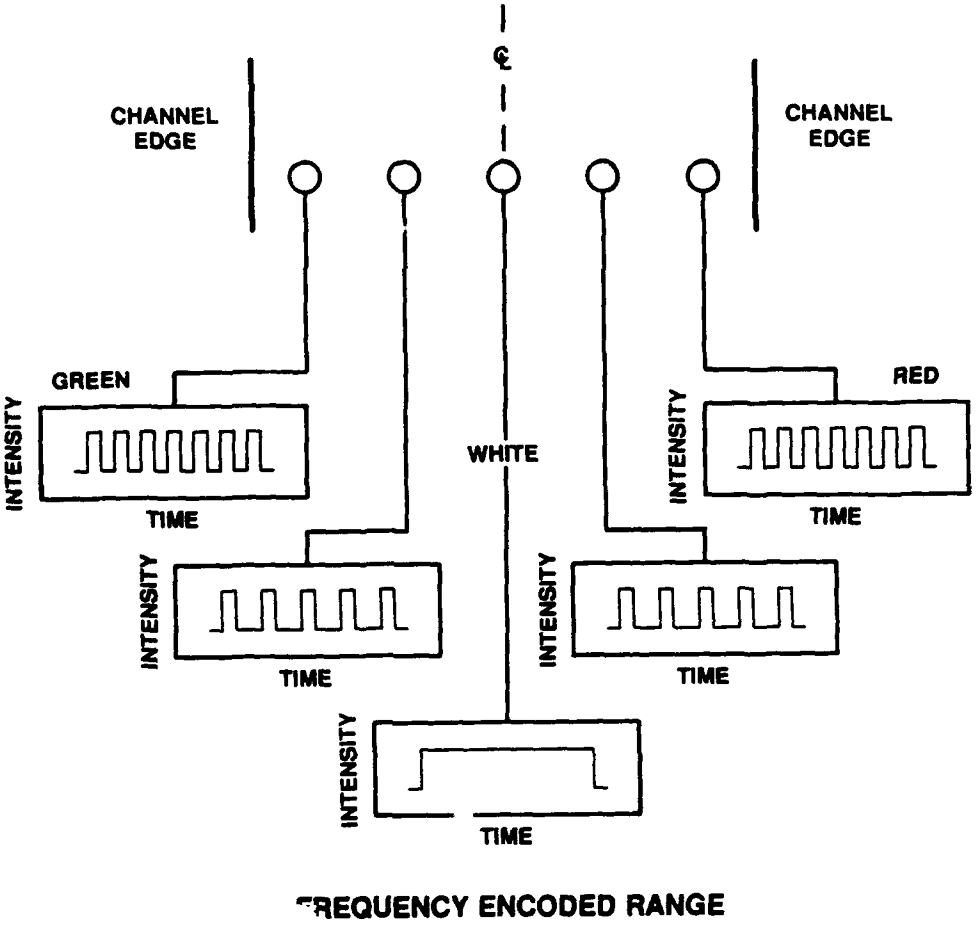

Figure 9. Frequency encoded range. When on the centerline, the observer sees a steady light. As the observer moves away from the centerline, the light is seen as flashing, with the frequency of flash increasing with distance from the centerline. A color code, such as shown, would be additionally required to indicate center, right, or left side of channel. The color aspect was not simulated in these experiments.

light was modulated by a rotating half-sector disk mounted on a rheostat-controlled electric motor. By adjusting the speed of the motor, the light could be made to flicker at the desired frequency, which was calibrated by a Strobotac (General Radio Corp.). Five base frequencies were used: 0.5, 1.0, 2.0, 4.0, and 6.7 Hz.

Procedure

The observer sat in a dimly illuminated room and binocularly viewed the apparatus, which was set to one of the five base frequencies. The frequency was then slowly increased or decreased, at the rate of approximately 1 Hz in 30 sec, until the observer correctly reported "faster" or "slower," and the change in frequency was recorded. A minimum of three such thresholds was determined for both faster and slower flicker rates at each base frequency. Four observers participated. Only thresholds for changes in frequency, simulating a vessel's motion across a channel, were measured as it was assumed that position on centerline would be displayed as a light constantly on. The distance from the centerline at which the light appeared to flash would be determined by the angle through which the steady light was displayed and the distance the observer was from it.

Results

The mean faster and slower frequency difference thresholds for all observers at each base frequency were calculated. Since the two thresholds were similar, their mean was calculated, and these difference thresholds (Δf) and their standard deviations are shown as a function of base frequency in Figure 10. Difference thresholds increase nearly linearly as base frequency increased. The standard deviations also increase at the higher base frequencies. The results show that the observer's sensitivity to changes in frequency decreases as the frequency of the flashing light increases. This would mean that the mariner's sensitivity to lateral motion decreases, and performance becomes poorer, as the vessel approaches the edge of the channel.

The mean difference threshold can be termed a just noticeable difference (jnd) in frequency. The number of jnds were summed up within the range of 0 to 6.7 Hz, resulting in 24 discriminable steps. The cumulative jnds are given by base frequency in Figure 10.

Chromatic Single-Station Range

The final type of proposed range aid investigated would display a beam of light that varied in color according to lateral position in the channel, as shown in Figure 11. At the left

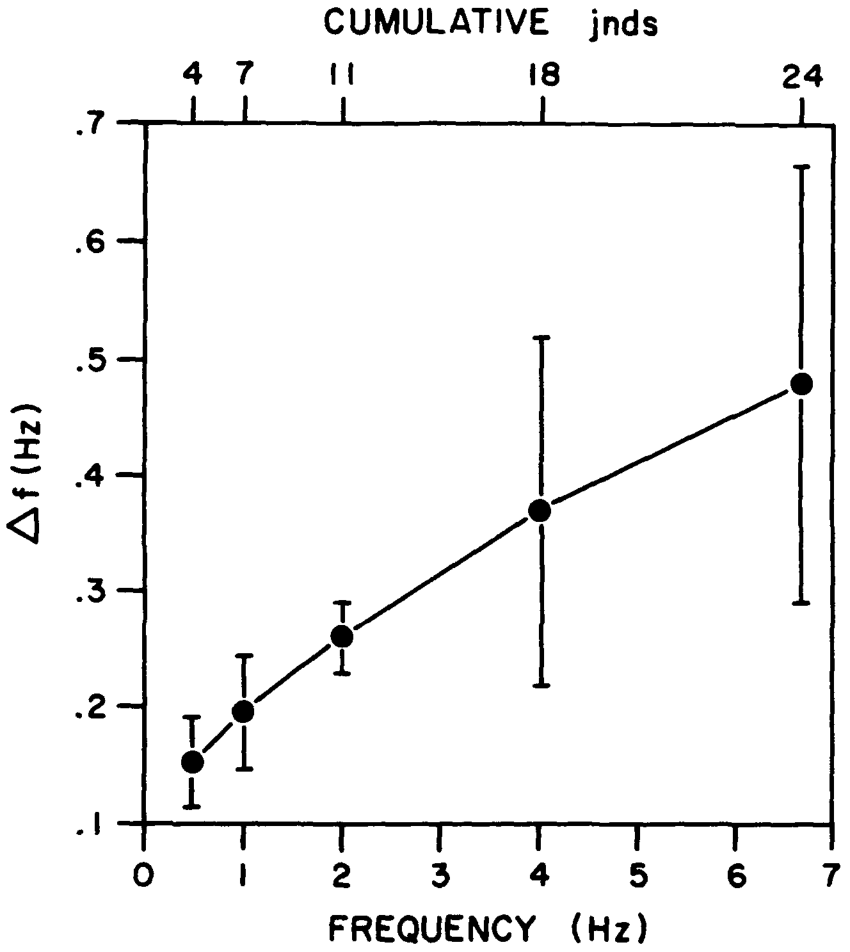

Figure 10. Frequency difference thresholds (Δf) by base frequency for four observers. Error bars show standard deviations. Cumulative jnds are given for 0 Hz to 6.7 Hz.

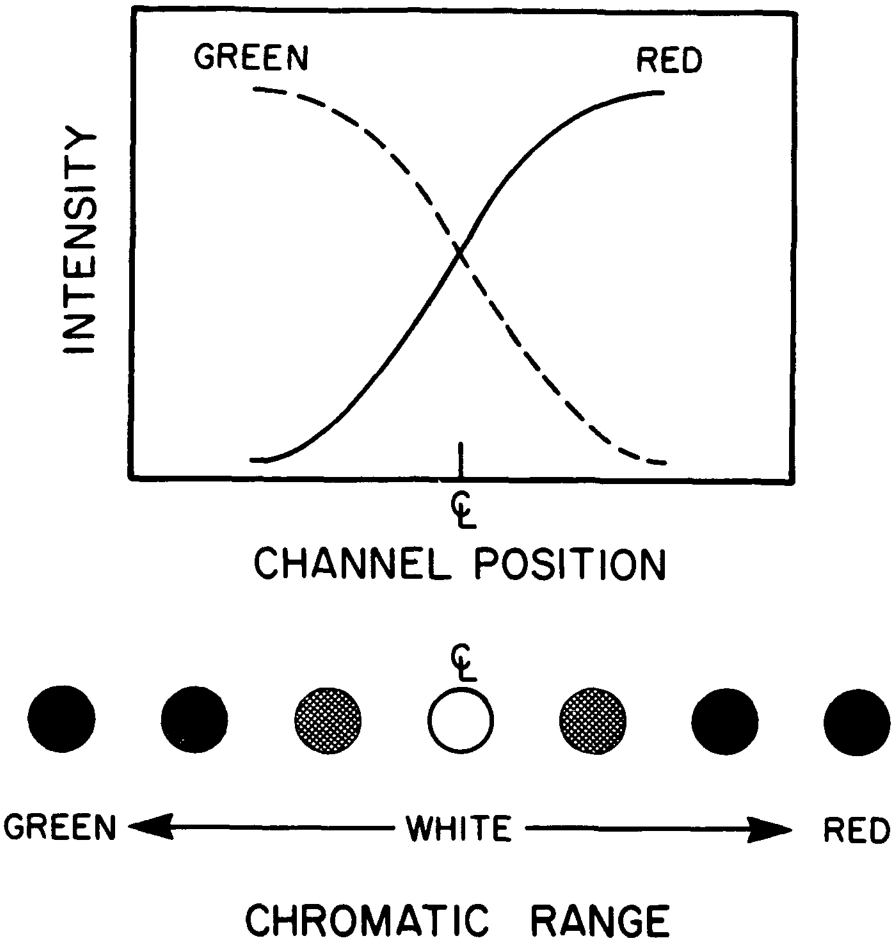

Figure 11. Chromatic range. When on the centerline a steady white light is seen. As one moves to the right the light changes gradually to pink and then to deep red. Similarly, movement toward the left of the channel centerline results in a change toward green.

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 chromatic signal would improve lateral sensitivity. The results might 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, 1990a) than to perceive that two unchanging stimuli are different. We therefore conducted two experiments (Laxar & Luria, 1990b). 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).

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[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.

Method

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 12). 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 2 and shown in Figure 13. The white reference light was produced by setting a dichroic filter to the mean neutral (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, illuminated the upper aperture. Two aperture sizes, subtending 1.0 and 3.5 arc min., were tested. Two luminance levels, given in Table 2, were tested as well. The lower luminance was achieved by placing a 1.0 neutral density filter in each channel.

Table 2

Stimuli for Chromatic Range Experiment

			CIE Chromaticity Coordinates		Luminance (cd/m^2)	
Color	Dominant Wavelength	Excitation Purity	x	y	Low	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

Procedure

The observer sat with his/her chin in a chinrest, and adapted for several minutes to the dim ambient illumination. 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

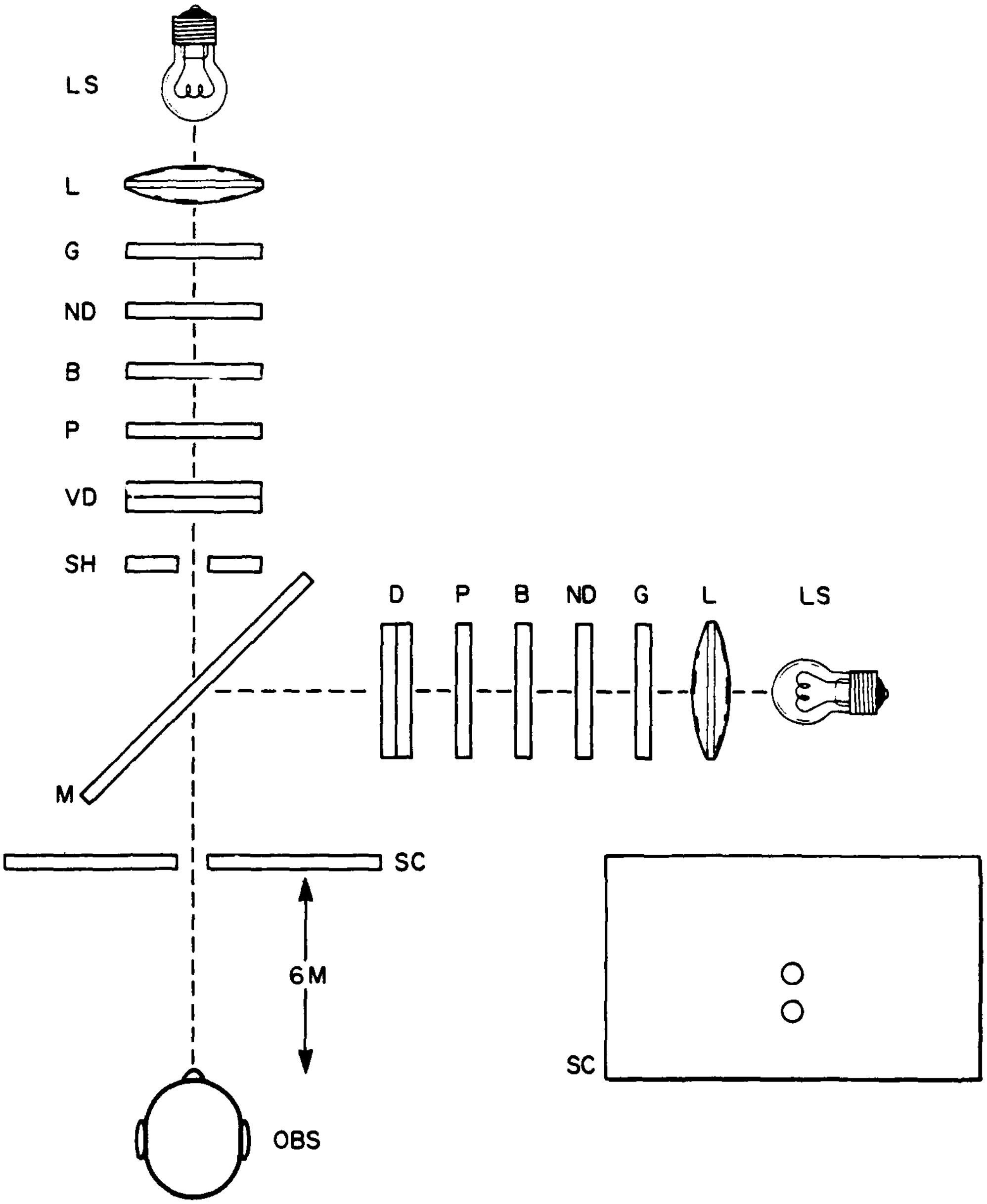

Figure 12. Diagram of the chromatic range apparatus. The light from each tungsten bulb (LS) goes through a collimating lens (L), ground glass (G), a neutral density filter (ND) when required, a blocking filter (B), a polarizing filter (P), and a dichroic polarizer (D or VD). The variable stimulus goes through a 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.

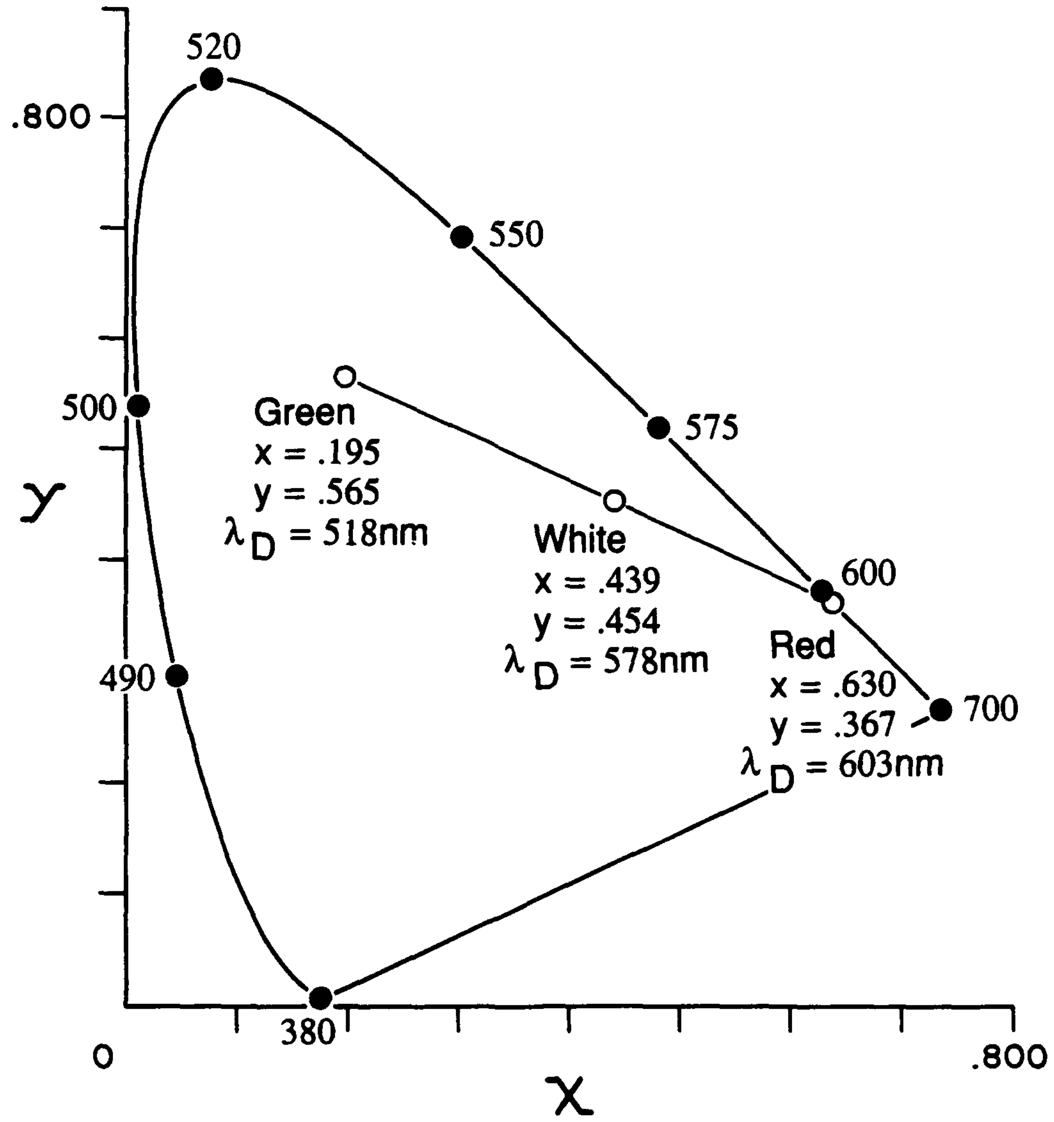

Figure 13. The CIE Chromaticity Diagram showing the locus of stimuli displayed by the variable light beam. The fixed beam displayed only the white reference stimulus.

angular setting in degrees of the polarizing dichroic filter, and later converted to dominant wavelength in nanometers (nm) for reporting purposes. Most observers had served in some of the previous experiments.

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 "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 each.

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 14. 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 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 3. 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

Table 3

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	$p < .001$

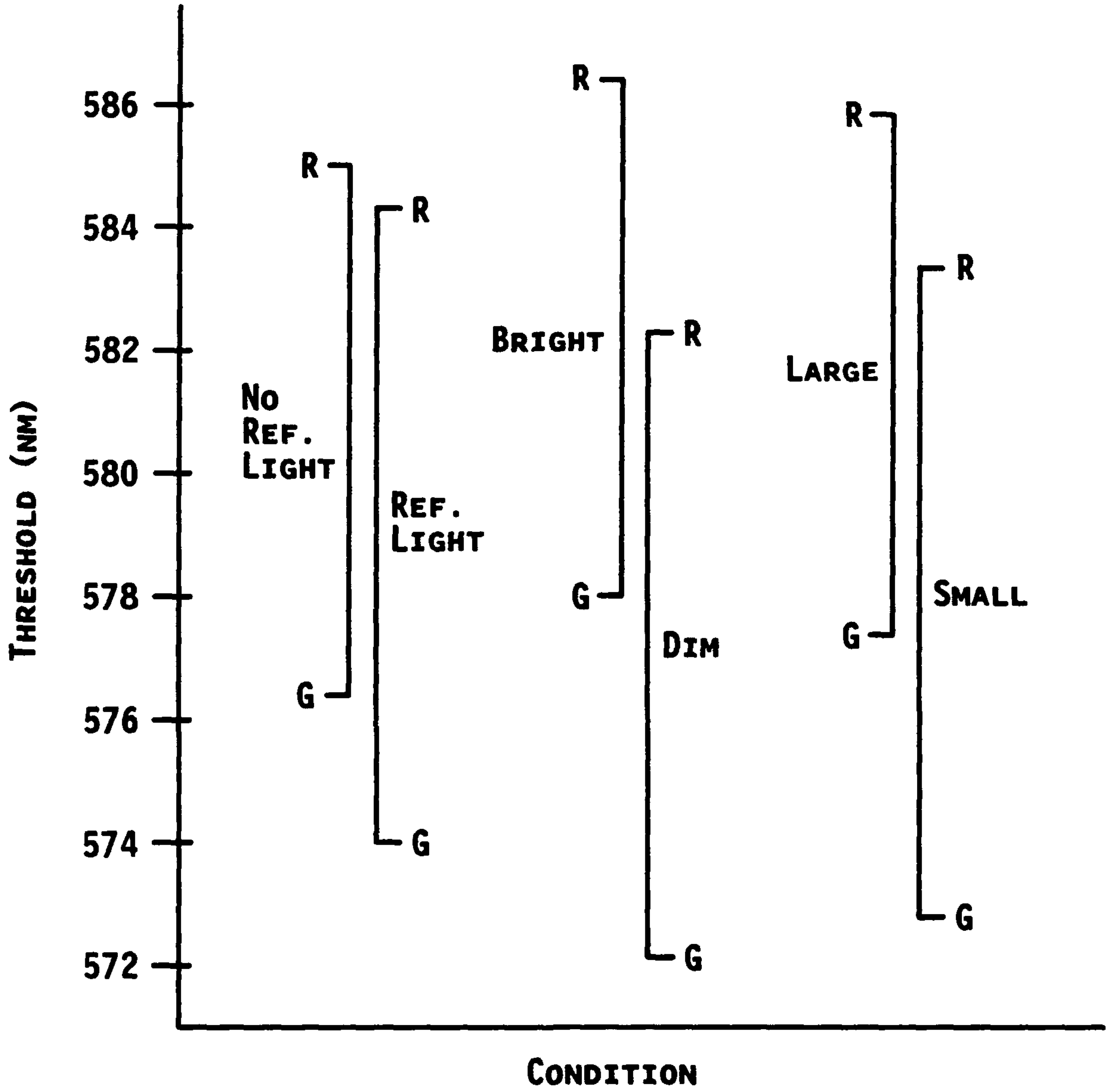

Figure 14. Red and green static thresholds for the three experimental parameters (left to right): absence or presence of reference light, luminance level, and aperture size. Mean data for eight observers.

and green thresholds. The only significance found was for the effect of Reference Light, $\underline{F}$ (1, 7) = 8.45, $\underline{p} < .05$. Examination of Figure 14 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 ($\underline{SD}$ = 3.5) to 588 nm ($\underline{SD}$ = 3). The overall mean midpoint was 580 nm ($\underline{SD}$ = 6), slightly redder than the 578 nm wavelength of the reference light determined prior to the experiments. A corresponding ANOVA on these 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 4. The dynamic thresholds for the large bright stimuli are plotted on the CIE Chromaticity Diagram in Figure 15 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 in the green region than in the red. The effects of stimulus size, luminance, and chromaticity found here are in keeping 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 4. Observers made the largest number of errors (22.4%) on the 518 nm (extreme green) 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

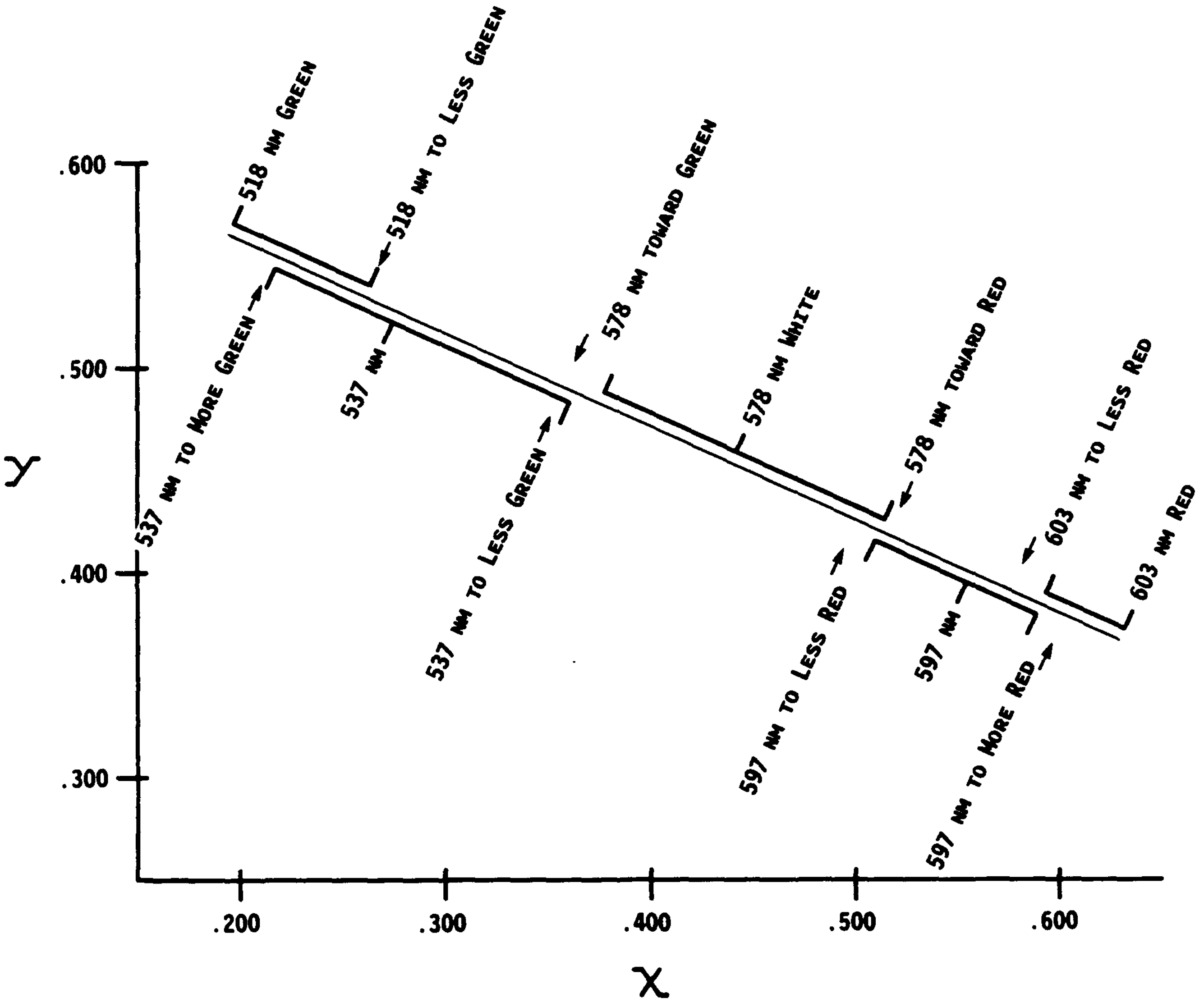

Figure 15. Dynamic thresholds for the larger brighter stimuli plotted on the 1931 CIE Chromaticity Diagram, labeled in terms of dominant wavelength of starting point. Arrows indicate mean thresholds for all eight stimulus conditions. Mean data for eight observers.

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.

Table 4

Summary of ANOVAs and Mean Errors for Chromatic Dynamic Thresholds

	Factor				
	Luminance Level		Aperture Size		Mean
Threshold	F	p	F	p	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, $df = 1, 7$.

Discussion

Observer sensitivity for judging position in the channel depends on the type of range display, the starting point in the channel, the direction of motion, and the experience of the observer. The results thus far have been presented in terms of angular measures of sensitivity or just noticeable differences. To relate the obtained thresholds to accuracy of navigation it is necessary to convert these measures to distances in a given channel. The Commandant, U.S. Coast Guard (1980), has specified optimal limits for parallax range configurations, represented by a lateral sensitivity factor, K. This is a proportion of the channel width that the observer must laterally depart from the range axis to make it apparent that the two range lights are no longer on the same bearing line, that is, are no longer in vertical alignment. Lateral sensitivity is based on the length and width of the range and the placement of the range lights, and is defined by the following equation:

$$K = (\theta/\Delta)/(Y/W)$$

where θ is the horizontal angular separation between the two range lights, Δ is the vertical angular separation, Y is the lateral distance of the observer from the range axis, and W is the width of the range or navigation channel (Commandant, U.S. Coast Guard, 1980) (see Figure 1). Design guidelines require that ranges have K factors between 1.5 and 4.5. A range with a K factor less than 1.5 will not change its alignment perceptibly with significant changes in lateral position. A range with a K factor greater than 4.5 will change alignment too rapidly with changes in lateral position. In the following discussion, we will assume a range 152 m (500 ft) wide by 1219 m (4000 ft) long, with the near end of the range 610 m (2000 ft) from the range beacon. This gives us a K factor of 4.5 at the near end of the range and 1.5 at the far end, and provides a basis for direct comparison of the various range displays. For a given K factor, thresholds are directly proportional to channel width, so the results are applicable to any range configuration.

Static Thresholds

Figure 16 compares performance of four types of range displays, at both the near and far ends of the channel. Relative performance is similar for both ends of the channel, with thresholds at the far end three times greater than those at the near end, since the distance from the beacon(s) is three times greater. The two-point fixed and the extended source parallax displays are nearly identical, with thresholds of approximately 4.5 m around the range axis at the near end and 13.5 m at the far end of the channel.

The rotating beam display appears to afford much poorer sensitivity than the parallax displays, with thresholds that are nearly twice the size. The threshold was 7.6 m at the near end of the channel and 22.7 m at the far end, with standard deviations equal to half the measured threshold. Results showed, however, that the thresholds would be halved when the lights were flashed at half the rate illustrated by these data, bringing the levels similar to those of the parallax displays.

The frequency encoded display, on the other hand, shows much better sensitivity than any of the other range types. This result, however, depends on the design of the beacon. In this type of display the centerline would be indicated by a fixed-on beam, and with a departure from centerline, the beam would start to blink. Centerline sensitivity would therefore depend on the angle covered by the steady on-center beam. The data shown here, 1.1 m at the near end and 3.2 m at the far end, are based on the 24 jnds within the range of flash frequencies tested, as discussed in the section on dynamic thresholds, which follows.

Figure 16 does not show data for the chromatic range display. The study of that display shows wide and consistent differences within and among observers, confirming previous studies on the variability in judgment of hues (Laxar, Miller, & Wooten, 1988; Neitz & Jacobs, 1986, 1990; Schefrin & Werner, 1990) and in judgment of white points (Jameson & Hurvich, 1951; Richards, 1967; Wright, 1969). These results make it difficult to choose a "white" light to indicate center of the channel that would be immediately recognized as white by a large proportion of observers with normal color vision. This suggests that a chromatic range beacon may not be an appropriate device for displaying center of channel position.

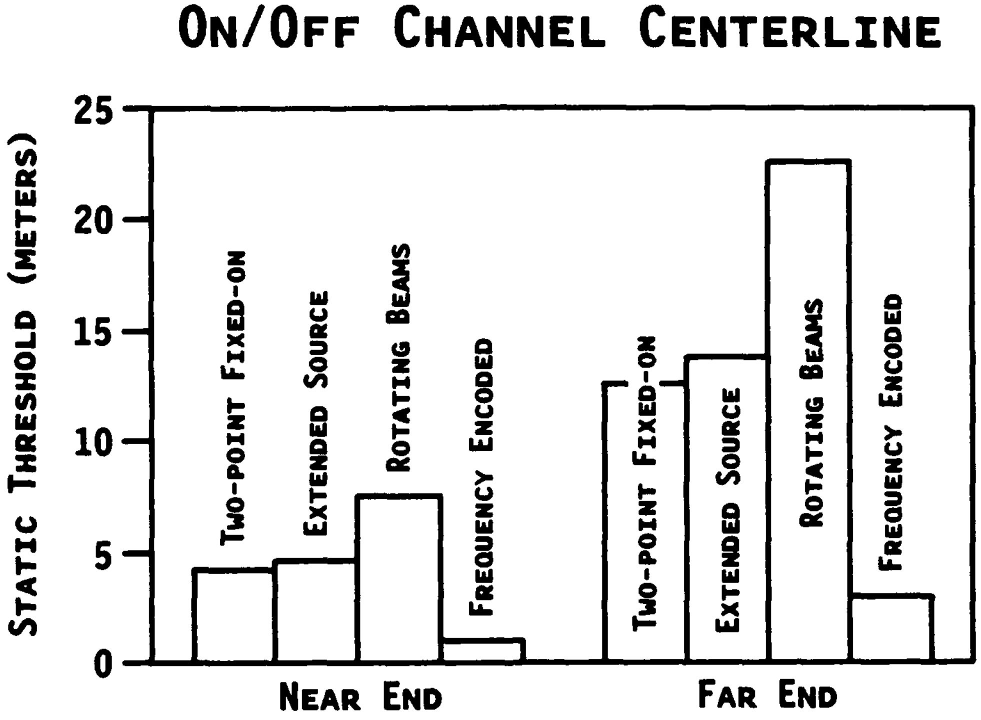

Figure 16. Thresholds for perceiving position on or off range centerline, for two parallax and two single-station range displays, at the near and far ends of the channel.

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. Performance could be estimated, however, from the dynamic threshold data, as discussed in the Application section, following. A slightly different procedure may have yielded more useful results, that is, asking the observer to judge whether on or off centerline rather than make a color judgment.

Dynamic Thresholds

Figure 17 shows motion thresholds for the four types of parallax and two types of single-station range displays, on-axis and at the edge of the channel. The results are given for the far end of the channel (K = 1.5). Thresholds for the near end of the channel (K = 4.5) are one-third the size shown in Figure 17. Over all, the extended source is the best of the parallax range displays, followed by the path indicator. At the far end of the channel, the extended source, at 30.9 m sensitivity on axis, was 4.5 m better than the currently used two-point fixed-on display. At the channel edge, the extended source was 4.9 m better. As noted earlier, however, the extended source was significantly different only from the two-point flashing display.

Performance was significantly better with motion toward the range centerline than away for parallax range displays. The mean difference of 0.31 arc min shown for the two-point fixed range display in Figure 5 is equivalent to having sensitivity 2.6 m better at the near end of the channel and 7.9 m better at the far end. Results for the other types of parallax range displays are comparable. This means that with such displays, mariners are less sensitive to motion when approaching the edge of the channel than when moving toward the centerline, perhaps contrary to what a range indicator should be capable of displaying.

The greater accuracy found with the group of highly experienced observers, 0.5 arc min, is equivalent to 4.3 m at the near end of the channel and 12.7 m at the far end. This suggests that with training or experience, performance can be improved for a variety of range light configurations.

The single-station rotating beam display shows higher thresholds than the others, at 47.9 m on-axis and 42.1 m at the channel edge, at the far end of the channel. When the lights were flashed at half the rate, sensitivity was improved twofold for static thresholds. Although we did not measure motion thresholds, it is reasonable to assume that sensitivity to motion also would be greatly improved at slower flash rates. This could make the rotating beam display as good as, or better than, the parallax displays for static thresholds. The dynamic conditions would probably still remain difficult for the observers.

The frequency encoded display appears to afford superior sensitivity. Based on the 24 jnds found between 0 Hz and 6.7 Hz, if this range of flash frequency were displayed across each side of the 152 m (500 ft) channel width (one side red, one side green)

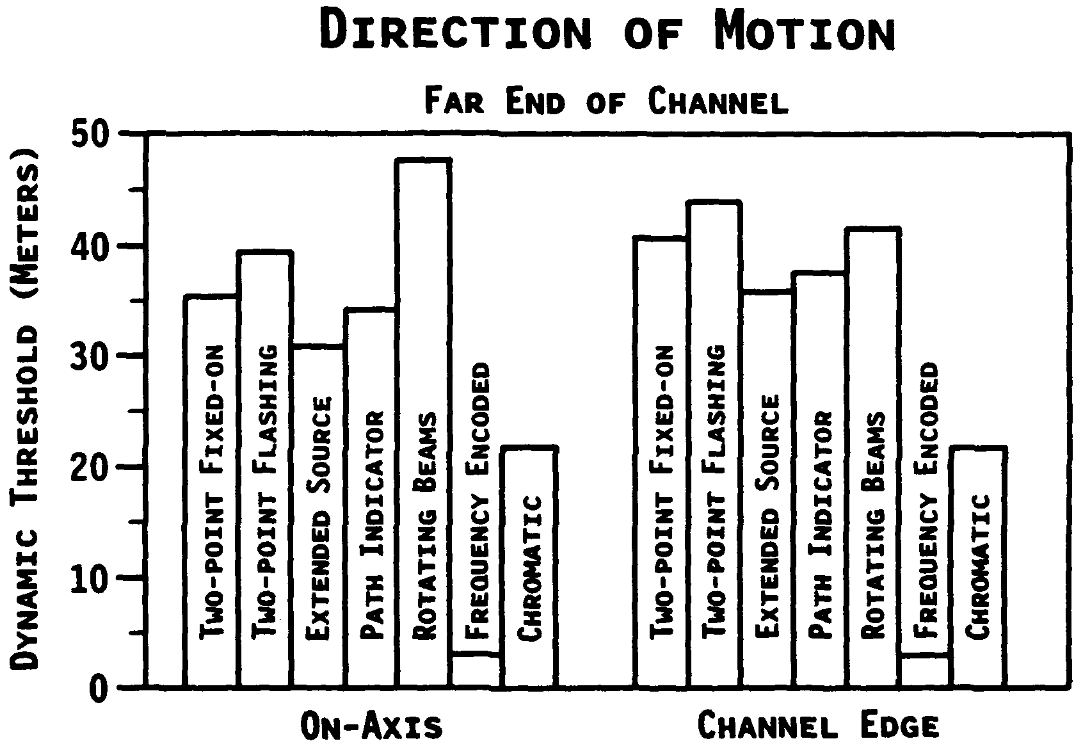

Figure 17. Thresholds for perceiving motion across the channel width for four parallax and three single-station range displays, on the range axis and at the edge of the channel. Data describe performance at the far end of the channel. Thresholds for the near end of the channel are one-third those shown.

at the far end of the range (Figure 18), each half would contain a 0 Hz segment around the range axis plus 23 jnds, 1 + 2*(23) = 47 jnds across the channel width. If equally spaced, these would provide a sensitivity of 3.2 m (10.6 ft) perpendicular to the range axis. At the near end of the range, the same angular display would subtend 50.8 m (167 ft), with a sensitivity of 1.1 m (3.6 ft). Extrapolating to a flash rate of 20 Hz would provide an additional 16 jnds on each side if the display were to cover the full channel width at its near end, as shown in Figure 18. This would afford a sensitivity of 3.2 m (10 ft) at the outside segments of the channel.

Care must be taken in interpreting the results of the frequency encoded display, however. There are many factors that affect the perception of flicker, which could influence the frequency difference thresholds and alter our conclusions. These include the luminance, size, and color of the light, the duty cycle, waveform, and amplitude of flicker, and the background luminance. Operationally, factors such as atmospheric conditions and sea state could decrease an observer's sensitivity, thereby degrading performance.

Not evident here is the uncertainty the observers expressed in judging changes in flash rate. Figure 10 showed large standard deviations in frequency difference thresholds. This would further tend to worsen sensitivity and increase uncertainty as the observer approached the edge of the channel. The sensitivity afforded by an operational frequency encoded range indicator may be considerably poorer than that shown here.

With the chromatic range display, as expected, discrimination of slowly changing color stimuli proved much poorer than measures of static discrimination found in the literature. As shown in Figure 15, 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 the nominal range discussed above and shown in Figure 18. If a single-station range beacon were to display the extent of its 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 means that the vessel would have to move that distance across the channel before the operator could determine that the ship had moved and correctly identify lateral direction of motion. Under optimal conditions, therefore, the chromatic beacon may provide better sensitivity to motion across a channel than the parallax or the rotating beams 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 might 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 of the chromatic range display 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,

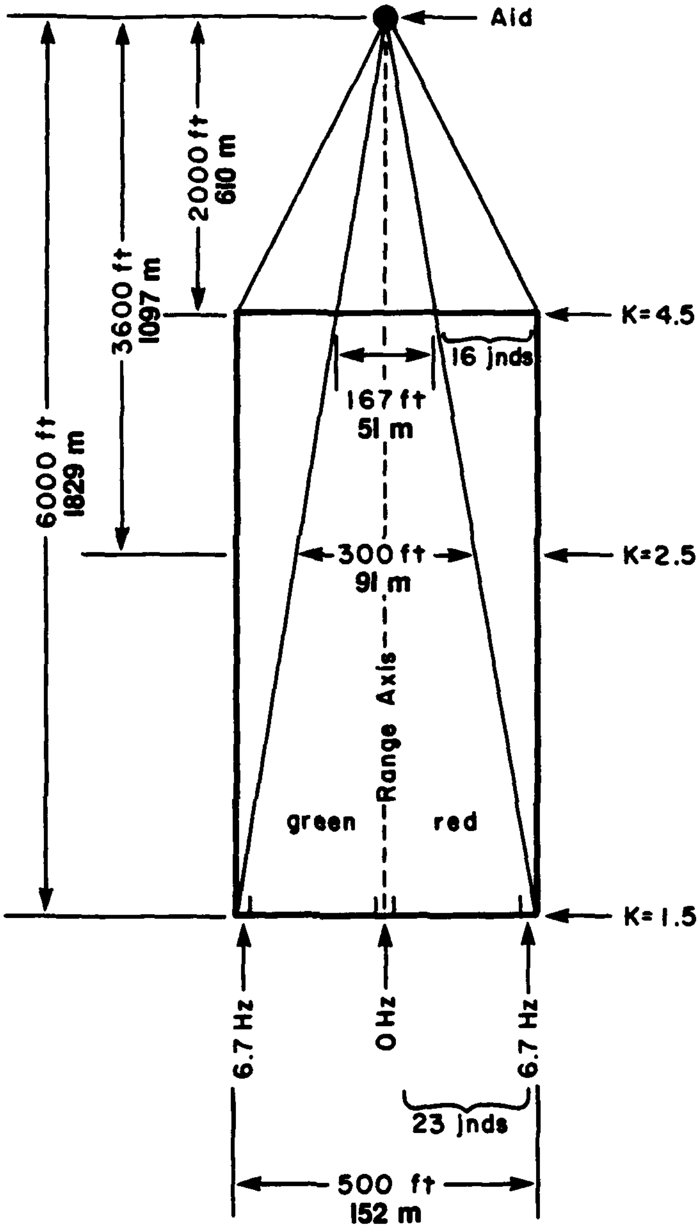

Figure 18. Single-station frequency encoded range display on an assumed range, showing flash frequencies and jnds. K is the range sensitivity factor for a parallax range.

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 might 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% (see Table 1). 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.

Application

The previous section discussed the relative performance afforded by the various types of simulated range displays within an assumed channel configuration. In this section we will present threshold data for each range display, computed from the experimental results, as they relate to a range of channel widths and distances from the beacons. Since the types of display used different methods of presenting the lateral information, a comment will be made on the computation of thresholds for each type of range display.

Static Thresholds

Table 5 and Figure 19 show at what distances from the channel centerline, in meters, an observer can just discern that he/she is off the centerline and to which side. Smaller values indicate better sensitivity to lateral position. Thresholds are given for one parallax display and the three single-station displays, for five channel widths from 100 m to 500 m. In the case of the parallax range, values were calculated for three different range sensitivities (K factors). For the rotating beams display, thresholds were calculated for distances of 0.5 or 5.0 nautical miles (NM) from the beacons. Thresholds for the frequency encoded and the chromatic beacons were calculated as being independent of these factors.

For parallax displays, data for the two-point fixed range are presented; the results for the extended source display were virtually identical. For a given range sensitivity (K factor) and a given channel width, a deviation from channel centerline can be computed in terms of the horizontal separation of the two range lights. This value is independent of the distance of the observer from the nearer range beacon and directly proportional to channel width. Using the threshold for horizontal separation of the two lights determined in the experiment, 0.51 arc min, the deviation from channel centerline was computed for values of K = 1.5, 3.0, and 4.5 at the five channel widths.

The rotating beams display provides a simple angular static threshold of 42.7 arc min from the centerline. This angle subtends 11.5 m at a distance of 0.5 NM, and 115 m at 5.0 nm.

Table 5

Static Threshold Summary Data (meters)

Range Display	Channel Width (m) 100	200	300	400	500
Two-point fixed, K=1.5	8.5	17.1	25.6	34.2	42.7
Two-point fixed, K=3.0	4.3	8.5	12.8	17.1	21.3
Two-point fixed, K=4.5	2.9	5.7	8.6	11.4	14.3
Rotating Beams at 0.5 nm	11.5	11.5	11.5	11.5	11.5
Rotating Beams at 5.0 nm	115.0	115.0	115.0	115.0	115.0
Frequency Encoded	2.1	4.3	6.4	8.5	10.6
Chromatic	14.3	28.6	42.9	57.1	71.4

These values are independent of channel width, since the angle subtended is a constant. As pointed out in the Results section, the standard deviation of this measure was one-half the threshold, or ± 5.8 m at 0.5 NM, and ± 57.6 m at 5.0 NM.

For the frequency encoded display, we assumed 47 jnds, based on the dynamic thresholds, equally spaced across the channel width. For a 100-m channel width, for example, the threshold would be 100/47 or 2.1 m. These values, then, depend only on channel width and are independent of distance from the beacon.

Similarly, we based the static thresholds for the chromatic display on the number of jnds obtained from dynamic thresholds, simply dividing channel width by 7 jnds. This may be a conservative estimate of performance, since static thresholds are typically smaller than dynamic. Here, too, the values are independent of distance from the beacon.

Dynamic Thresholds

Table 6 and Figure 20 give the dynamic thresholds about the channel centerline. These figures represent the lateral distance the observer has to move before he/she discerns motion and direction away from the centerline. Table 7 and Figure 21 show motion thresholds at the channel's edge for each given width.

For parallax displays, data are presented for the two-point fixed and two-point flashing ranges; thresholds for the extended source and path indicator were marginally better than these. A linear regression function was fitted to the ranges' threshold versus start position data shown in Figure 4, giving an on-axis dynamic threshold of 1.39 arc min horizontal separation for the two-point fixed range and 1.55 arc min for the two-point flashing, with larger values as start position increased toward channel edge. On-axis thresholds were calculated in the same manner as the static thresholds for the three K factors and five channel widths. Edge-of-channel thresholds were similarly calculated, except that thresholds increased slightly with the value of K due to the inherent configuration of a two-station range display. For the sake of clarity, the data for the two-point flashing range are not illustrated in Figures 20 and 21.

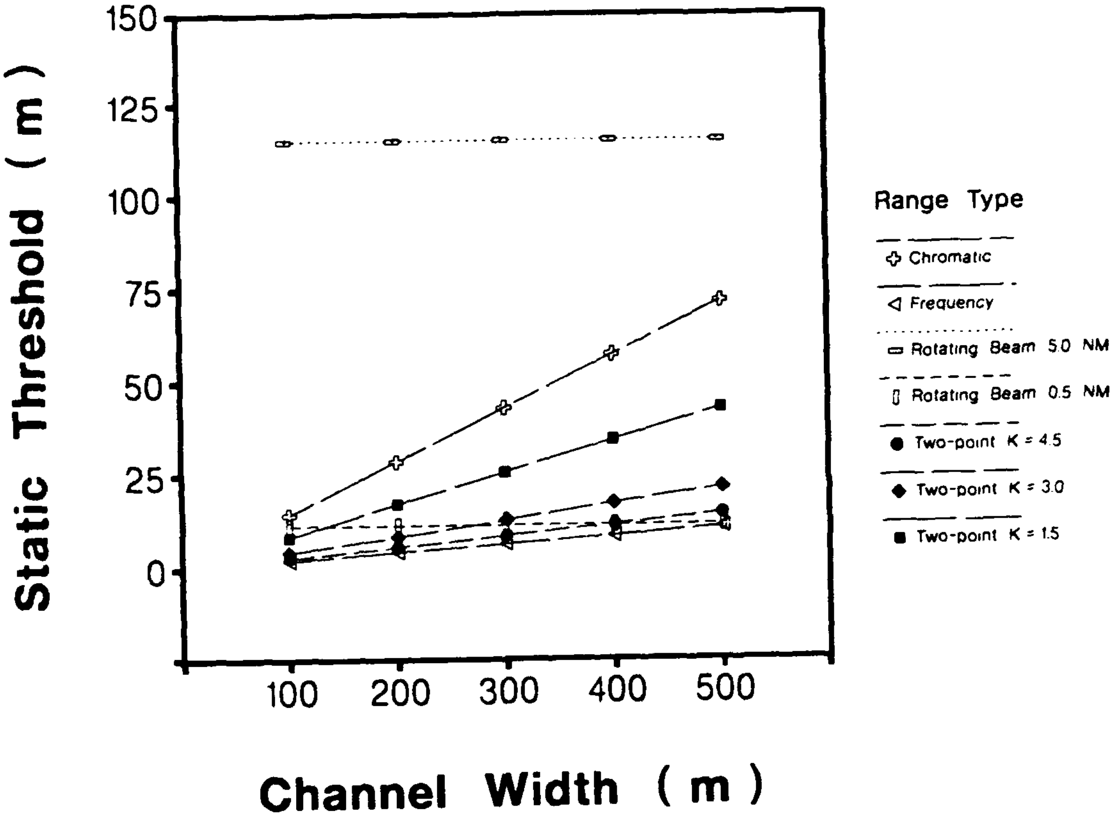

Figure 19. Static thresholds for the simulated range displays by channel width.

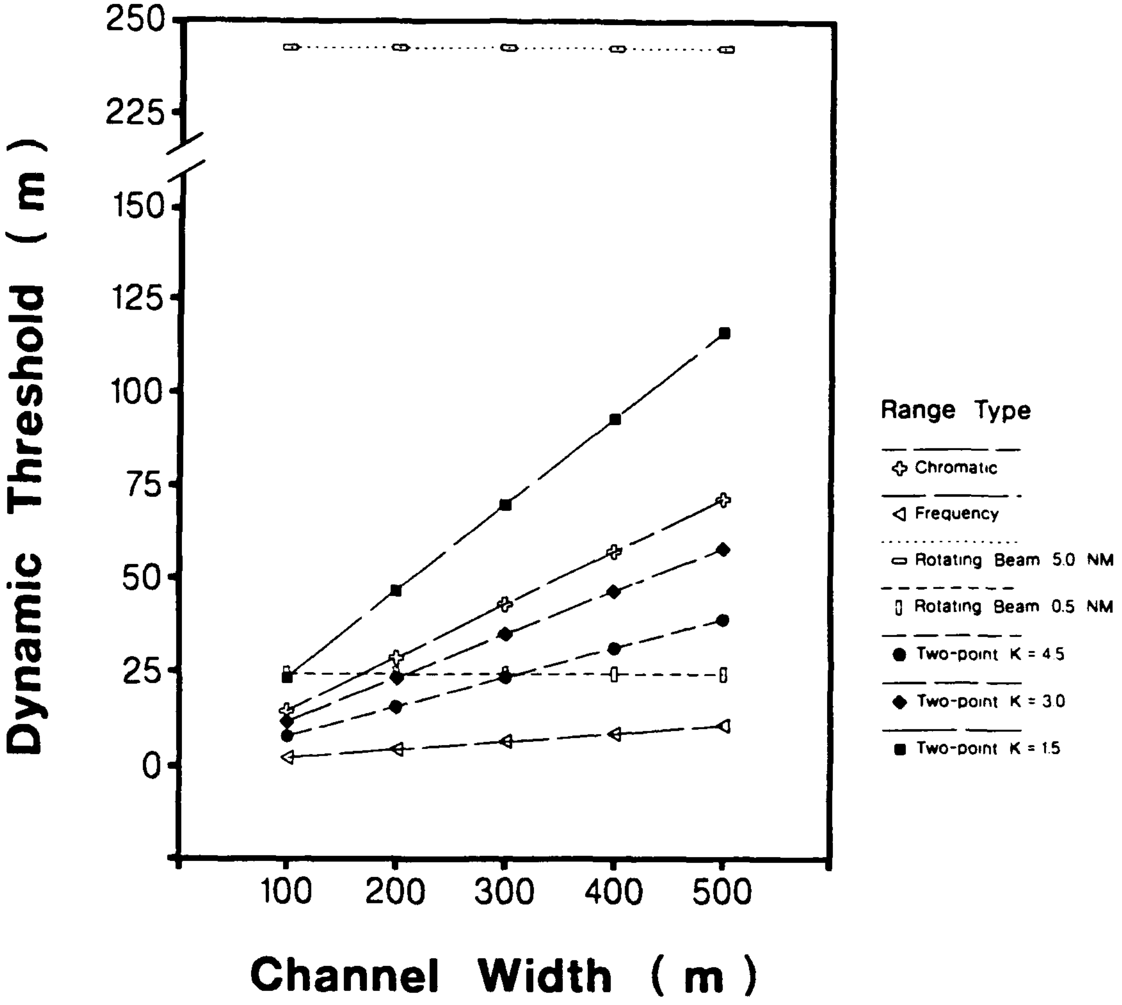

Figure 20. Dynamic thresholds at channel centerline for the simulated range displays by channel width.

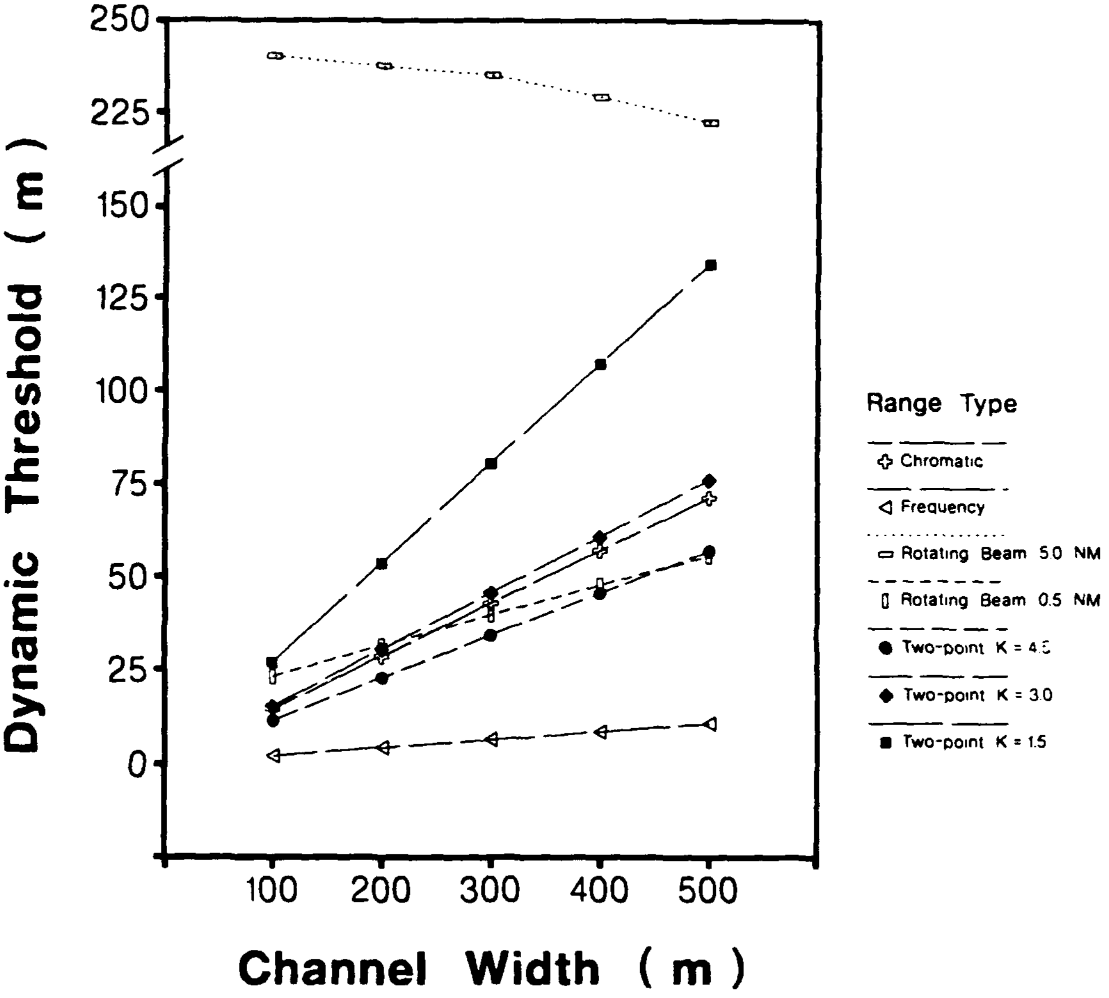

Figure 21. Dynamic thresholds at channel edge for the simulated range displays by channel width.

Table 6

Dynamic Threshold Summary Data -- Channel Centerline (meters)

	Channel Width (m)				
Range Display	100	200	300	400	500
Two-point fixed, K=1.5	23.2	46.5	69.7	92.9	116.1
Two-point fixed, K=3.0	11.6	23.2	34.8	46.4	58.0
Two-point fixed, K=4.5	7.8	15.5	23.3	31.1	38.9
Two-point flashing, K=1.5	25.9	51.8	77.7	103.6	129.5
Two-point flashing, K=3.0	12.9	25.9	38.9	51.8	64.8
Two-point flashing, K=4.5	8.7	17.3	25.9	34.7	43.4
Rotating Beams at 0.5 nm	24.2	24.2	24.2	24.2	24.2
Rotating Beams at 5.0 nm	242.4	242.4	242.4	242.4	242.4
Frequency Encoded	2.1	4.3	6.4	8.5	10.6
Chromatic	14.3	28.6	42.9	57.1	71.4

Table 7

Dynamic Threshold Summary Data -- Channel Edge (meters)

	Channel Width (m)				
Range Display	100	200	300	400	500
Two-point fixed, K=1.5	26.8	53.7	80.5	107.3	134.2
Two-point fixed, K=3.0	15.2	30.4	45.7	60.8	76.1
Two-point fixed, K=4.5	11.4	22.8	34.2	45.6	57.0
Two-point flashing, K=1.5	29.0	58.0	87.0	116.0	145.0
Two-point flashing, K=3.0	16.0	32.1	48.2	64.2	80.3
Two-point flashing, K=4.5	11.8	23.6	35.2	47.1	58.9
Rotating Beams at 0.5 nm	23.2	31.5	39.7	47.8	55.7
Rotating Beams at 5.0 nm	240.0	237.5	235.0	229.2	222.5
Frequency Encoded	2.1	4.3	6.4	8.5	10.6
Chromatic	14.3	28.6	42.9	57.1	71.4

Dynamic thresholds for the rotating beams display were calculated in the same manner as the static thresholds. The on-axis values were based on the 90 arc min found in the experiment; the edge-of-channel values were obtained by means of linear regression on means of the experimental data shown in Figure 8.

For the frequency encoded and chromatic range displays, the values given are the same dynamic thresholds as shown under static thresholds.

The following conclusions can be drawn from the summary data presented here:

> Static thresholds are generally better than dynamic thresholds.
>
> For the two-point fixed range display, thresholds become poorer as channel width or K factor increases.
>
> Thresholds for the rotating beams display are basically independent of channel width, except for edge of channel at the 5.0 NM distance. In that case, thresholds improve slightly with channel width, due to the decrease in threshold at starting positions near the channel centerline, as shown in Figure 8. In any case, sensitivity afforded by the rotating beams display decreases rapidly with distance from observer to the range beacon, due to the strictly angular nature of the display.
>
> For the frequency encoded and chromatic displays, thresholds become poorer with channel width, but are independent of distance from the beacon if one assumes that all jnds are displayed across the channel width at that one distance. For a given beacon, however, thresholds will vary with distance along particular range, as pointed out in the Discussion section on dynamic thresholds of the frequency encoded display and shown in Figure 18. Caution is once again advised in reliance on these values, due to their variability.

Whether the sensitivity afforded by the various range displays, as shown by the thresholds given here, is suitable for use on a particular range is a question that involves many parameters. Among them are the size, speed, and maneuverability of the vessels using the range, expected atmospheric visibility, sea state, weather, wind velocity and direction, and vessel traffic patterns, including density and direction relative to the navigational aid.

Conclusions

From this research we conclude that it would be difficult to improve on parallax range displays as effective means for indicating position within a channel or direction of motion across a channel. They afford good sensitivity for proximity to range centerline, and observers are confident in the judgments made using them. They are effective for use over the entire width and length of the navigational range, although thresholds become poorer at lower K factors (Figures 19-21). The two-point flashing display, however, was associated with a higher error rate than the other types of parallax displays. The extended source, a proposed display configuration, provided slightly better sensitivity to motion across the range than the other types of parallax displays. Further research could be conducted to determine if this superiority were greater with different vertical offsets, as the present experiments were conducted with a vertical offset of 4 arc min, the distance specified as optimal for two-point ranges (Commandant, U.S. Coast Guard, 1980).

The rotating beams system, being an angular display, affords relatively poor thresholds at long ranges (Figures 19-21).

However, it shares the advantage of the parallax displays in its effectiveness for use over the entire width and length of the navigational range as long as the distance from observer to beacon is not too great. As the observer moves to a greater angle off the range axis, the interval between the flashing lights simply increases. This advantage does not apply to the other two types of single-station range displays, the frequency encoded and the chromatic displays. With the latter two, the angle of displayed information is limited. If the angle is set for full coverage of the channel width at the far end of the range, any deviation beyond those angular limits would provide no additional information as to distance or direction of motion from the centerline. As the observer approaches the beacon, the channel width covered by the beacon's display angle proportionally decreases, so that the use of such types of displays might best be limited to relatively short or sector shaped ranges.

Figures 16 and 17 indicate somewhat superior sensitivity afforded by the parallax ranges over the rotating beams display within the assumed channel. Additional results showed, however, that the critical variable is the observer's ability to discriminate temporal intervals between flashes. Sensitivity for the rotating beams display, therefore, could be improved by decreasing the average flash rate of the three beams. Additional studies could be conducted to determine the flash rate for maximizing sensitivity while still providing frequent enough information updates for optimal navigation. Sensitivity for the rotating beacons, however, is significantly affected by many variables, including flash rate, luminance, and refractive error, making it difficult to assign a sensitivity value. Moreover, judgments with this display proved very difficult under the dynamic simulation condition.

The large standard deviations of the frequency encoded display shown in Figure 10 are evidence of the observers' variability in judging change in frequency. When only the averages are considered, as in Figures 16, 17, 19-21, sensitivity appears to be superior to other types of beacons tested. The notable uncertainty on the part of the observers, however, makes the concept of frequency encoding extremely dubious for use in a single-station range display. Additional studies with observers who are highly practiced in distinguishing flash rates might show that such a display is acceptable for experienced operators, however.

The color/saturation concept shows promise for a single-station range. 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).

Summary

This study has compared four different current and proposed parallax range indicators and three types of proposed single-station range indicators. Parallax ranges have been used successfully for many decades, but results found here show that equally good performance might be obtained under some conditions with single-station range indicators, which may be associated with reduced costs. All range indicators, however, showed poorer sensitivity and increased uncertainty of judgment as the observer approached the channel edge. These results, then, provide a basis for conducting additional laboratory or field tests for further determination of the adequacy of single-station range indicators.

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Figure Captions

Figure 1. Top view of a parallax range. W: channel width; Y: distance of observer from range axis; : horizontal component of the angle between the lights.

Figure 2. Four parallax range light configurations.

Figure 3. Experimental procedure for motion threshold (dynamic) experiments. A: Start position; B: lower light in motion; C: position when observer detects that lower light has moved. The angular distance moved is recorded by computer.

Figure 4. Motion thresholds for four parallax range light configurations. Note: In all references to thresholds, lower thresholds indicate greater sensitivity.

Figure 5. Thresholds for relative motion toward and away from the range axis for the two-point fixed range.

Figure 6. Mean percent errors for four parallax range light configurations combined.

Figure 7. Operation of the sequential beacons. The left beacon, with two beams, rotates counterclockwise at a given speed. The center beacon, with one beam, rotates clockwise at twice that speed. The right beacon, with two beams, rotates clockwise at the same speed as the left beacon. All three beacons therefore flash at the same rate. A: When viewed from the range axis, the three beacons flash simultaneously. B: When viewed from left of range axis, the left beacon is seen first; the center is seen later, but before the right beacon, since the center beacon is rotating more rapidly. The interval between sequential flashes increases with distance from range axis. C: When viewed from right of range axis, the right beacon is seen first, followed by the center and then the left. Obs: Observer position.

Figure 8. Rotating beams difference thresholds in minutes of arc of viewing angle and temporal interval, as a function of start position in degrees of off-center viewing. Thresholds are shown for changes toward and away from simultaneity.

Figure 9. Frequency encoded range. When on the centerline, the observer sees a steady light. As the observer moves away from the centerline, the light is seen as flashing, with the frequency of flash increasing with distance from the centerline. A color code, such as shown, would be additionally required to indicate center, right, or left side of channel. The color aspect was not simulated in these experiments.

Figure 10. Frequency difference thresholds (f) by base frequency for four observers. Error bars show standard deviations. Cumulative jnds are given for 0 Hz to 6.7 Hz.

Figure 11. 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.

Figure 12. 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 a 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.

Figure 13. The CIE Chromaticity Diagram showing the locus of stimuli displayed by the variable light beam. The fixed beam displayed only the white reference stimulus.

Figure 14. 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.

Figure 15. 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.

Figure 16. Thresholds for perceiving position on or off range centerline, for two parallax and two single-station range displays, at the near and far ends of the channel.

Figure 17. Thresholds for perceiving motion across the channel width for four parallax and three single-station range displays, on the range axis and at the edge of the channel. Data describe performance at the far end of the channel. Thresholds for the near end of the channel are one-third those shown.

Figure 18. Single-station frequency encoded range display on an assumed range, showing flash frequencies and jnds. K is the range sensitivity factor for a parallax range.

Figure 19. Static thresholds for the simulated range displays by channel width.

Figure 20. Dynamic thresholds at channel centerline for the simulated range displays by channel width.

Figure 21. Dynamic thresholds at channel edge for the simulated range displays by channel width.