NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

SUBMARINE BASE, GROTON, CONN.

REPORT NUMBER 1057

AN ANALYSIS OF STIMULUS DETERMINANTS OF TARGET DETECTION IN PBB DISPLAYS

by

Joseph DiVita

Naval Medical Research and Development Command
Research Work Unit M0100.001-1022

Released by:
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1 August 1985

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SUMMARY PAGE

THE PROBLEM

To analyze the critical stimulus attributes underlying target detection in Short Term Averaging (STA) Passive Broadband (PBB) Displays.

FINDINGS

The methods by which targets are simulated in STA PBB have not allowed for a systematic investigation of the underlying stimulus attributes which govern their detection. Three possible stimulus determinants of target detection are discussed: 1) The marking density of the target, 2) The contrast of the target, and 3) Grouping of similar brightnesses.

APPLICATION

This analysis indicates how the presentation of target information on PBB displays can be systematically investigated in order to select the method which most increases detectability of targets.

ADMINISTRATIVE INFORMATION

This research was conducted as part of Naval Medical Research and Development Command Work Unit M0100.001-1022 -- "Enhanced performance with visual sonar displays." It was submitted for review on 1 Jul 1985, approved for publication on 1 Aug 85, and designated as NSMRL Report No. 1057.

PUBLISHED BY THE NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

ABSTRACT

Targets on passive broadband sonar displays may be detected on the basis of three distinct stimulus attributes-- target contrast, target marking density, and by grouping of similar brightnesses. Previous research has failed to isolate and systematically manipulate these variables. Methods of doing so are proposed in order to determine which of these stimulus attributes underlie target detection. Enhancing the proper varables should improve target detection.

TABLE OF CONTENTS

INTRODUCTION

It is generally believed that the use of color in CRT displays will enhance operator performance, and preliminary guidelines for the implementation of color in Submarine Advanced Combat Systems (SUBACS) have been formulated.[1] However the question immediately arises as to why color displays should facilitate operator performance. This question can be answered only by identification and analysis of the critical stimulus features that govern operator performance with each display. Only with a working understanding of these factors may SUBACS displays be effectively modified.

Previous experiments have evaluated the relative effectiveness of various sets of colors in the Passive Broadband (PBB) display. However, the sets were chosen in an entirely arbitrary fashion. Since the number and combination of color sets is infinite, it is obvious that an efficacious use of color must evolve from an understanding of those stimulus attributes in the current monochromatic displays that are essential for target detection. Without this basic understanding, the use and implementation of color in PBB diplays (as well as SUBACS displays in general) is likely to give way to an empirical "free-for-all".

This report analyzes three critical stimulus attributes of targets in the visual array of the monochromatic PBB diplay: Marking density, brightness contrast, and grouping of similar brightnesses. We will discuss each of these in detail. This short list of features is certainly not intended to be exhaustive. However, if the effectiveness of these cues in target detection is evaluated, then colors can be logically introduced into PBB displays. Likewise, the effectiveness of these cues may point to difficulties in implementing color in PBB displays. Indeed, the effectiveness of these cues for target detection may be inherently limited by monochromatic displays. The introduction of color may supersede some of these limitations.

TARGET AND NOISE IN THE PBB DISPLAY

The background noise of the PBB display is composed of eight brightness intensities, or gray levels.[2] The lowest intensity level has the same brightness as the nondisplay edges of the screen and is defined as "black". By definition this luminance varies with the ambient illumination falling on the screen: the greater the ambient illumination, the brighter the non-display edges of the screen. We will arbitrarily assign a value of .5 foot candles (fc) to the ambient illumination. (The ambient illumination in sonar shacks has been measured to fall within the range of less than .01 fc to .62 fc, though the range of illumination falling on major sonar CRT systems ranges from less than .01 to .28 fc.[3]) The other seven levels of brightness each increase in luminance by a factor of the square root of two over the preceding intensity level. (We should note that black is usually referred to as level zero and the PBB display is usually thought of as having seven brightness levels.)

In order to specify the distribution of intensities that compose the noise in the PBB display, it is necessary to examine the underlying model from which noise is generated and the signal levels are quantized-- that is, the method by which signal level is mapped to gray level on the CRT screen.

Sea noise may be idealized as a Gaussian distribution. (Other models of sea noise have been proposed; however, it is not the particular model that is important for this report, but rather the method of analysis that will be proposed: The same analysis may be applied to any model.) For the sake of convenience we chose a Gaussian with a mean of zero and a standard deviation of one; this distribution is often referred to as the normal distribution. Thus, sea noise may be simulated by randomly generating numbers between plus and minus infinity. The probablity that a number will fall within any given interval is represented by the area under the Gaussian within that interval. For example the probability of observing a number less than zero is fifty percent. The mapping of noise to gray levels entails an arbitrary assignment of intervals of numbers to luminance levels. Any number less than zero is given a gray level value of black. Thus on average, fifty percent of a PBB display composed entirely of noise will be off and will have a luminance value associated with the level black. Any number greater than zero is assigned to one of the remaining gray levels as follows. Deviations from the mean may be expressed in units of standard deviation (SD).[4]

$$Z = x-M/SD$$

Where x is a randomly generated number between plus and minus infinity, M is the mean of the distribution and SD is the standard deviation of the population.

The seven gray levels correspond to successive deviations from the mean in increments of one third SD, i.e. Z = 0, .33,.67, 1.0, 1.33, 1.67, 2.0. Thus numbers whose probability of occurrence is less than or equal to 2.275% (corresponding to a SD equal or greater than 2.0) will be assigned to the brightest luminance level seven; or in other terms, the percentage of noise in a PBB display which takes on the brightest intensity level represents the area under the curve of all values whose deviation from the mean, as expressed in units of SD (i.e. Z scores), is greater than or equal to 2.0. In this manner the distribution of gray levels in a PBB diplay composed entirely of sea noise may be computed. For example, the area under the curve between Z scores of zero and .33 represents the percentage of noise in the PBB diplay which will map to the first gray level value. Figure 1 shows the mapping of the eight luminance levels of the PBB to the normal distribution of sea noise. Figure 2 is a probability mass function of the distribution of intensities within the PBB display. The distribution of gray levels in the PBB display is represented by a discrete random variable, whereas the sea noise may be thought of as being modeled by a continuous random variable.

The distribution of gray levels in a target is derived by a similar analysis. The signal level of a target may be modeled as follows.

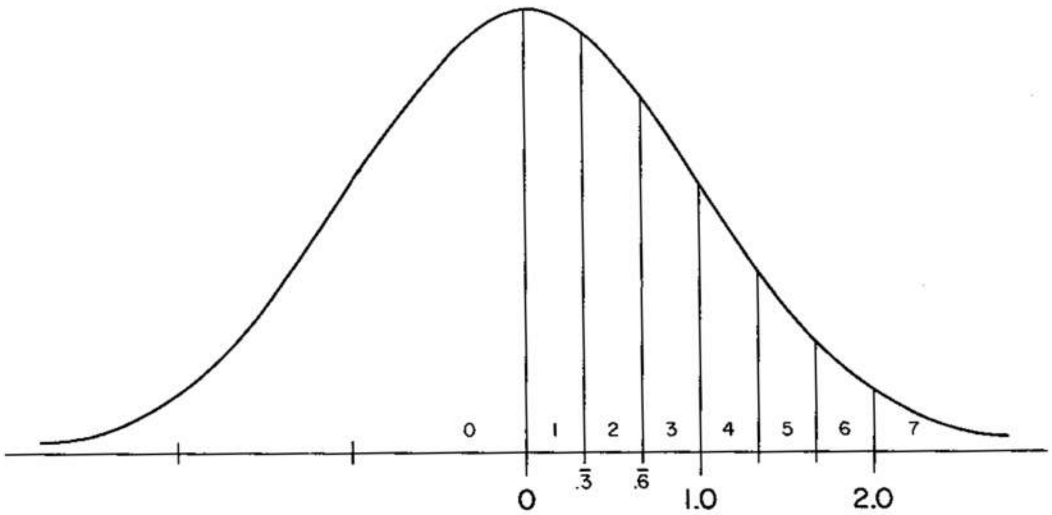

Fig. 1: Sea noise is represented as being distributed along a normal curve. The areas between the 1/3 SD intervals correspond to the percentages of the various luminance levels in a PBB display composed entirely of noise and categorized into 8 luminance (or energy) levels.

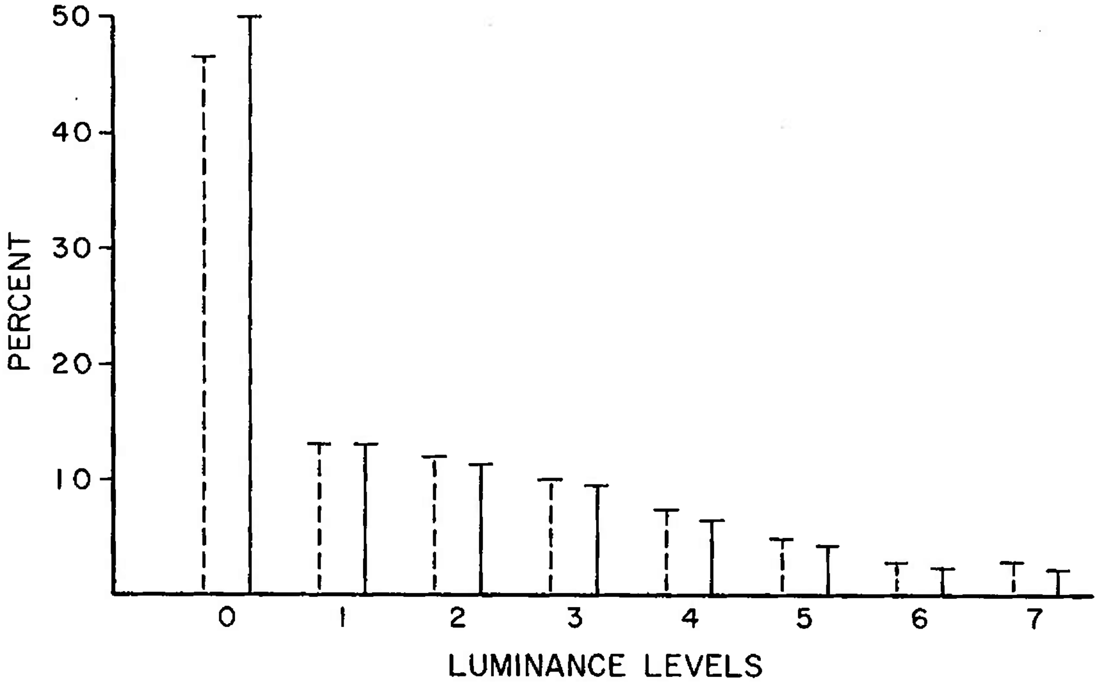

Fig. 2: Probability mass function of the percentage of each luminance level associated with sea noise (solid line), and target (dashed line). Target strength equals -10 dB.

$$\text{Signal Level} = \text{Noise} + 10^{(SNR/10.0)}$$

In this equation signal level is yoked to noise. As signal-to-noise ratio (SNR) approaches minus infinity, the signal level approaches noise. Consider a target coming in at a constant SNR of -10 db. The mean of the distribution of the target signal will be the mean of the noise, zero, plus $10^{-10/10}$, or .1. We assume that the standard deviation of the target's distribution is also equal to one. Thus the distribution of the signal is a normal distribution "shifted" away from the mean of the noise in the positive direction by the constant amount of $10^{(\text{Target SNR}/10)}$. This is pictured in Figure 3 where the distribution of the signal has been superimposed upon that of the noise.

The distribution of gray levels in the target is also depicted in Figure 3, represented by the area under the curve of the target's signal level between each .33 SD interval from the mean of the noise, zero. For example, if a target is coming in at a constant SNR of -10 db, its mean is shifted from zero by .1 SD. Consequently only 46% of the signal will map onto gray level zero, or black. Thus 54% of the target signal will map onto one of the seven brightness levels. This represents an increase of 4% over the proportion of noise (50%) which maps onto the seven brightness levels. The area between 0 and .33 under the signal's curve is approximately 13% (in practice the area between -.1 SD and .23 SD on the normal curve is computed.) In a similar fashion, the percentage of each of the brightness levels in the target may be computed. Figure 2 also shows the probability mass function for the distribution of gray levels in a target with an SNR of -10 db. As the SNR of the signal increases, the percentage of the signal that maps onto one of the seven brightness levels increases. Likewise, the percentage of the signal that maps onto the brightest gray level increases. The distribution of gray levels for signals of increasing strength is given in Table I.

DEFINITIONS

1) MARKING DENSITY

Marking density may be defined as the percentage of the signal that maps onto the seven brightness levels above level zero (screen black). As noted above, as signal strength increases, the marking density of the signal increases whereas the marking density of the noise remains constant at 50%.

The effect of marking density on target detection may be illustrated by the following example. For simplicity, assume one target, whose bearing is constant, and a PBB display composed of two luminance levels, black (screen off) and one brightness level (screen on). The visual array may be conceptualized as a two-dimensional matrix. Each cell of the matrix is randomly assigned a luminance level such that half the cells are on and half are off. Thus, we would expect a 50% marking density in any column of the matrix. One column in the matrix represents the target. As the target's signal strength increases, the number of cells in the target column which are on increases. At some level of signal strength, the fact that the

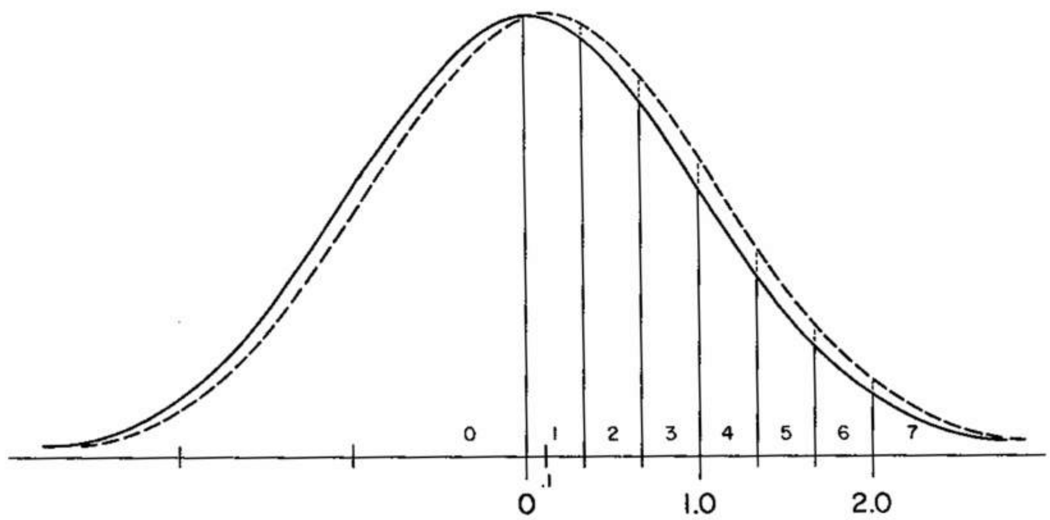

Fig. 3: The distribution of signal levels associated with a target (-10 dB) superimposed upon the distribution of noise. The areas under the target's distribution between the 1/3 SD intervals correspond to the percentage of each luminance in the PBB display that maps to the target.

Table I: The percentage of the target's signal that maps onto each luminance level (columns) as a function of marking density (MD).

MD	EIGHT LUMINANCE LEVELS							
	0	1	2	3	4	5	6	7
50	50	13.0	11.5	9.5	6.5	4.5	2.5	2.5
54	46.5	13.0	12.0	10.0	7.5	5.0	3.0	3.0
56	44	13.0	12.5	10.5	8.0	5.5	3.5	3.0
58	42.5	13.0	12.5	11.0	8.5	5.5	3.5	3.5
60	40.5	13.0	13.0	11.0	8.5	6.0	4.0	4.0
62	38.5	13.0	13.0	11.5	9.0	6.5	4.0	4.5
64	36.0	13.0	13.0	12.0	9.5	7.0	4.5	5.0
66	34.0	13.0	13.0	12.0	10.0	7.5	5.0	5.5
68	32.5	12.5	13.0	12.5	10.5	8.0	5.0	6.0
70	30.5	12.5	13.0	12.5	11.0	8.0	5.5	7.0
72	28.5	12.0	13.0	13.0	11.0	8.5	6.0	8.0
74	26.5	12.0	13.0	13.0	11.5	9.0	6.5	8.5
76	24.5	11.5	13.0	13.0	12.0	9.5	7.0	9.5
78	22.5	11.0	13.0	13.0	12.0	10.0	7.5	11.0
80	20.5	10.5	12.5	13.0	12.5	10.5	8.0	12.5

MD	FIVE LUMINANCE LEVELS				
	0	1	2	3	4
50	50.0	22.0	16.0	8.0	4.0
54	46.0	22.5	17.5	9.5	5.0
56	44.0	22.5	18.0	10.0	5.5
58	42.0	23.0	18.5	10.5	6.0
60	40.0	23.0	19.0	11.5	6.5
62	38.0	23.0	19.5	12.0	7.5
64	36.5	23.0	20.0	12.5	8.0
66	34.0	23.0	20.5	13.5	9.0
68	32.5	22.5	21.0	14.0	10.0
70	30.0	22.5	21.5	15.0	11.0
72	28.0	22.0	22.0	16.0	12.0
74	26.0	21.5	22.5	16.5	13.5
76	24.0	21.0	22.5	17.5	15.0
78	22.0	20.5	23.0	18.0	16.5
80	20.0	20.0	23.0	19.0	18.0

number of "on" cells in the target column exceeds the number of "on" cells in any of the other columns is visually detectable.

2) CONTRAST RATIO

In the above example, as signal strength increased, the number of "on" cells in the target column increased. Consequently, the average luminance of the target column increased. For example, suppose the luminances of level zero and level 1 are .125 and .177 foot-Lamberts (fL), respectively. The average luminance of the noise is .15100 fL. A signal with an SNR of -10 db will have a marking density of approximately 54%. The average luminance of the target column is .15133 fL, an increase of .00033 fL. The difference between the luminance of the target and background may be expressed in the form of a contrast ratio.[5] There are several contrast ratio formulas. We shall use:

$$C = Lt/Lb$$

where Lt is the average luminance of the target, and Lb is the average luminance of the background (see Appendix I). Thus in the above example, the target will have a contrast ratio of 1.002. As the target's SNR increases, its contrast ratio will increase.

In a similar fashion the average luminance of target and noise may be computed for a PBB display composed of 8 luminance levels. One simply takes into account the percentage of each of the luminance levels to obtain a weighted average of signal or noise luminance. The contrast ratios of signal to noise for PBB displays composed of two through eight luminance levels are plotted in Figure 4 as a function of increasing signal strength. The eight luminance levels are .125, .177, .25, .35, .5, .71, 1.0, and 1.4 fL.

3) GROUPING SIMILAR BRIGHTNESSES

Grouping by similarity of brightness is a difficult stimulus variable to quantify, although the idea is easily demonstrated.[6] In Figure 5 the visual system groups together patches of gray that are equal in lightness and perceives the letter G. In a similar fashion, since a target is composed of more bright dots than the background, the visual system may detect a target by grouping these dots together on the basis of similar brightness. We may begin to quantify this stimulus variable by simply specifying the actual distribution of luminance levels in the target.

Grouping similar brightnesses need not be limited to the more intense luminance levels; grouping may occur if there is a significant increase at any level or group of levels in the target column compared to that of the background. However, for our model, the difference between the target and noise along any one luminance level is insignificant for moderate differences in marking density. This may be seen from Table II where the distributions of luminance levels for noise are subtracted from the distributions of luminance levels for targets of increasing signal strength in a PBB display composed of eight luminance levels. The critical

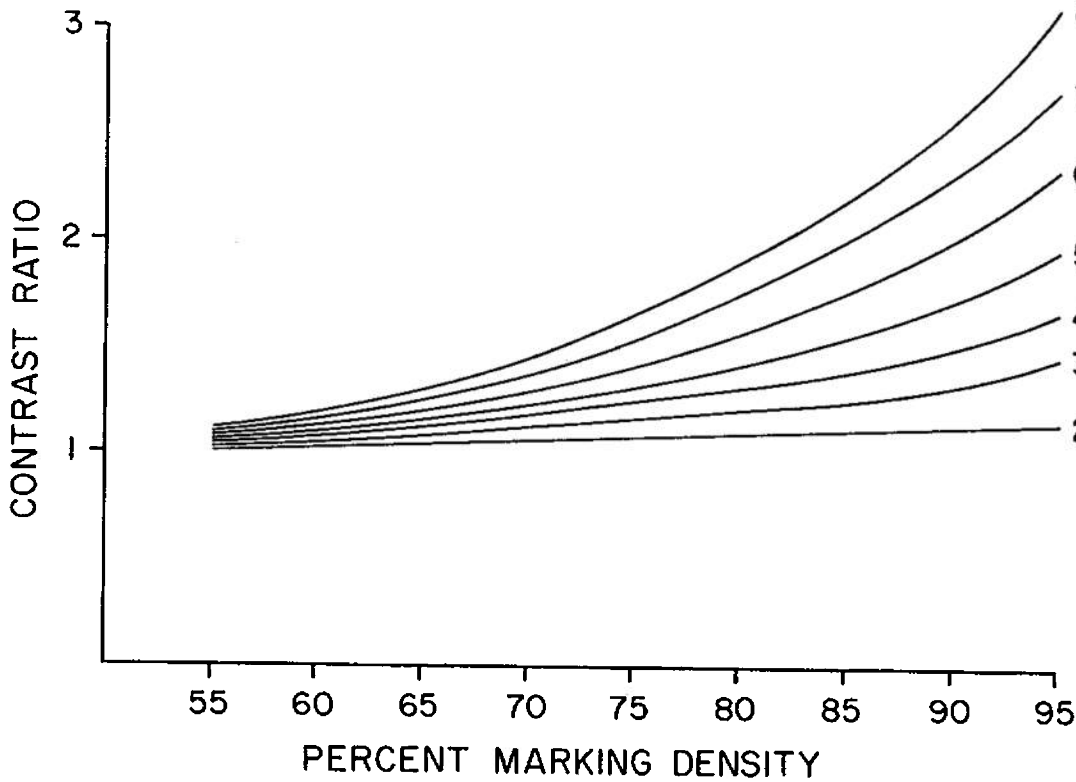

Fig. 4: Contrast ratio as a function of marking density for PBB displays composed of two to eight luminance levels.

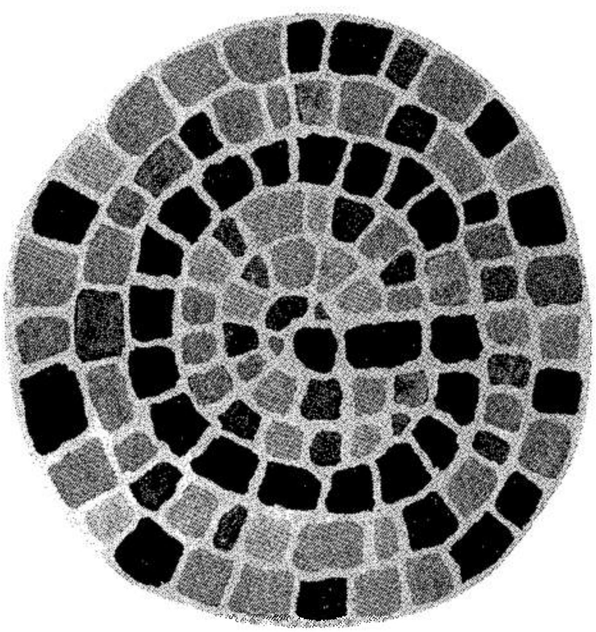

Fig. 5: Example of grouping of similar brightnesses.

TABLE II: The difference between the percentage of the signal and the percentage of the noise that maps onto each luminance level as a function of marking density (MD).

SEVEN LUMINANCE LEVELS ABOVE SCREEN BLACK

MD	1	2	3	4	5	6	7
54	0	.5	.5	1.0	.5	.5	.5
56	0	1.0	1.0	1.5	1.0	1.0	.5
58	0	1.0	1.5	2.0	1.0	1.0	1.0
60	0	1.5	1.5	2.0	1.5	1.5	1.5
62	0	1.5	2.0	2.5	2.0	1.5	2.0
64	0	1.5	2.5	3.0	2.5	2.0	2.5
66	0	1.5	2.5	3.5	3.0	2.5	3.0
68	.5	1.5	3.0	4.0	3.5	2.5	3.5
70	.5	1.5	3.0	4.5	3.5	3.0	4.5
72	1.0	1.5	3.5	4.5	4.0	3.5	5.5
74	1.0	1.5	3.5	5.0	4.5	4.0	6.0
76	1.5	1.5	3.5	5.5	5.0	4.5	7.0
78	2.0	1.5	3.5	5.5	5.5	5.0	8.5
80	2.5	1.0	3.5	6.0	6.0	5.5	10.0

FOUR LUMINANCE LEVELS ABOVE SCREEN BLACK

MD	1	2	3	4
54	.5	1.0	1.5	1.0
56	.5	2.0	2.0	1.5
58	1.0	2.5	2.5	2.0
60	1.0	3.0	3.5	2.5
62	1.0	3.5	4.0	3.5
64	1.0	4.0	4.5	4.0
66	1.0	4.5	5.5	5.0
68	.5	5.0	6.0	6.0
70	.5	5.5	7.0	7.0
72	0	6.0	8.0	8.0
74	.5	6.5	8.5	9.5
76	-1.0	6.5	9.5	11.0
78	-1.5	7.0	10.0	12.5
80	-2.0	7.0	11.0	14.0

differences between the target and noise distributions occur as luminance increases across the four brightest levels at the higher marking densities. Thus, for this model, grouping may apply to only the higher luminance levels.

METHODOLOGICAL CONSIDERATIONS FOR PSYCHOPHYSICAL RESEARCH ON PBB DISPLAYS

The experimental paradigm employed in previous research investigating target detection in STA PBB displays entailed systematically increasing the SNR of the target until detection occurred. The drawback to this approach is that systematically varying SNR only has a probabilistic effect on the stimulus. In actuality, the critical stimulus features which underlie target detection may erratically vary. Thus from a psychophysical view point, SNR imprecisely specifies the target stimulus. Because of this imprecision, the relative strengths of marking density, contrast, and grouping by similarity of brightness, have not been ascertained.

1) MEASUREMENTS OF STIMULUS CHARACTERISTICS OF THE PBB DISPLAY

An AED 512 color graphics terminal and PDP 1104 were used to simulate waterfall displays. The addressibility of the monitor was 512 x 483 lines (48 pixels per inch horizontally and 62 pixels per inch vertically). Only the green phosphors were utilized in the display, the C.I.E. chromaticity coordinates (x,y) were .296 and .580. The sonar display simulated one depression-elevation (1 D/E) sector of a spherical array passive broadband (SAPBB) short term averaging (STA) display with bearing represented along the horizontal axis, time along the vertical axis, and amplitude of signal encoded by the intensity of the pixel. The display was 150 pixels in the horizontal dimension by 200 pixels in the vertical dimension, 2.2 x 2.75 in. A target was modeled as being fixed in bearing and one pixel in width. As targets of increasing signal strength were generated, stimulus attributes of the target were measured. These are reported below.

Distribution of Luminance Levels

The variability in the stimulus stems from the manner in which targets are simulated on the display units. As noted above, a target with an SNR of -10 db will generate a distribtion with a mean of .1 which when quantized into gray levels will lead to a marking density of 54%. However, in an experiment, a target is generated at an SNR of -10 db for a specified number of display lines. In essence, this is equivalent to sampling from a normally distributed population with a mean of .1 and an SD of 1. The sample size, N, is equal to the number of displays lines. The actual distribution of luminance levels sampled will be different than the predicted distribution. In Table III the actual distributions of luminance values for targets of increasing strength generated over 200 display lines may be compared to the theoretical distributions listed in Table I. As can be seen from Table III, in the actual display the distributions of luminance levels are erratically varying as signal strength is increasing. The erratic variation in the distribution of luminance levels precludes a systematic investigation and evaluation of the role of grouping by similarity of brightness in target detection.

TABLE III: The percentage of the target's signal that actually mapped onto each luminance level as a function of theoretical marking density (MD).

MD	LUMINANCE LEVEL							
	0	1	2	3	4	5	6	7
50	48.5	15.5	11.5	11.0	8.0	1.0	1.5	1.5
54	48.0	13.5	8.5	10.0	7.5	6.5	3.5	2.5
56	52.0	14.5	10.0	6.5	7.5	4.0	1.5	4.0
58	33.0	19.0	13.0	9.0	9.5	10.0	4.5	2.0
60	45.5	8.5	11.0	12.5	6.5	4.0	8.0	4.0
62	37.5	10.5	12.5	12.0	10.0	9.5	4.0	4.0
64	39.0	13.0	12.5	9.0	8.5	7.0	6.0	5.0
66	35.5	12.0	11.5	11.0	9.0	7.0	7.0	7.0
68	32.5	10.0	15.0	16.5	11.5	6.5	4.0	4.0
70	31.5	9.5	12.5	14.5	15.0	6.5	5.0	5.5
72	35.5	12.5	13.0	8.0	15.5	6.0	4.0	5.5
74	29.5	13.0	11.5	12.5	14.0	5.0	6.0	8.5
76	28.0	12.5	10.5	19.0	9.5	9.5	2.0	9.0
78	21.5	10.0	13.5	20.0	9.5	9.0	6.5	10.0
80	19.0	10.0	11.5	13.0	12.0	10.0	8.5	16.0

TABLE IV: Actual marking density at various theoretical marking densities (Columns) for seven targets (Rows). Targets were generated for 200 lines of STA PBB.

	THEORETICAL MARKING DENSITY													
TARGET	54	56	58	60	62	64	66	68	70	72	74	76	78	80
1	50.0	55.5	60.5	58.5	68.5	68.0	57.0	65.5	65.5	72.5	73.0	80.5	76.0	82.5
2	49.0	59.5	64.0	57.5	58.0	64.0	65.5	64.5	66.5	72.0	78.0	79.0	73.0	80.5
3	52.0	48.0	67.0	54.5	62.5	61.0	64.5	67.5	68.5	64.5	70.5	72.0	78.5	81.0
4	47.5	61.5	59.5	57.5	58.0	64.5	70.0	64.0	69.0	72.5	75.0	74.0	81.0	73.5
5	54.5	59.5	55.0	60.5	57.0	63.5	65.5	69.5	70.0	72.0	76.5	77.0	74.0	78.0
6	57.5	60.5	61.5	60.5	62.0	66.0	62.5	65.0	66.5	70.0	69.0	82.0	77.0	81.5
7	50.0	63.0	54.0	58.0	58.5	67.0	67.5	64.5	71.0	71.5	71.5	77.0	81.0	83.5
MEAN	51.5	58.2	60.2	58.1	60.6	64.9	64.6	65.6	68.1	70.1	73.0	77.5	77.4	80.4
SD	3.46	5.07	4.63	2.06	4.06	2.36	4.11	2.00	2.04	2.75	3.21	3.38	4.09	1.62

Marking Density

For a target with an SNR of -10 db, the probability that the mean of our sample distribution will be greater or less than .1 is 50%. That is, half the time we would expect the sample mean to be below .1 and half the time above .1. Consider the consequence of this outcome on the marking density of the target: Half the time the target's marking density will be greater than 54%, and half the time less than 54%. If the experimenter systematically increases the SNR of the target, the target's marking density should theoretically increase; in reality the target's marking density will erratically vary across trials. This is illustrated in Table IV for a PBB display of 200 lines. The target was presented at a constant bearing, and a record was kept of the target's luminance values after the quantization of signal level. In Table IV, the theoretical marking density, as determined by the target's SNR, may be compared to the actual marking density of the target over 200 lines.

Average Luminance of the Target

The actual average luminance of the target will also erratically depart from the predicted value. In a PBB display composed of eight luminance levels, the predicted average luminance is derived by a weighted average of the theoretical distribution of luminance levels in the target. The variability in the signal level will affect the actual distribution of luminance levels in the target. As was the case for marking density, if the experimenter systematically increases the target's SNR, in theory the target's average luminance should systematically increase; however, in practice the average luminance of the target is erratically changing.

This has been shown by actually measuring the average luminance of targets of different signal strengths. A Spectra Pritchard Photometer was used to measure luminance. In the display eight luminance levels were employed, .125,.177, .25, .35, .5, .71, 1.0, and 1.4 Fl. These readings were obtained for a single pixel on an AED 512 color monitor (see Appendix II).

The target was presented at one bearing. The photometer, with a 2 minute aperture, was placed approximately 2 ft from the display screen. At this distance, the aperture of the photometer covered a circular area composed of a single color dot and the black area of the screen around it (see Appendix II). A one second delay was introduced between successive updates of the display in order to stablize the photometric readings. The analog output from the photometer was sent to an Analog to Digital converter, and the digitalized readings were stored on a PDP 1104. Thus the sequence of events was as follows: the display updated and then paused for one second after which a reading was taken; this reading was digitalized and stored, and the process was repeated. The target's SNR remained constant for 200 lines; thus 200 readings were taken and averaged for each SNR level of the target.

Table V gives the changes in the actual average luminance of the target

TABLE V: Average luminance (fL) of a target presented in displays of two and eight luminance levels as a function of theoretical and actual marking density (MD).

THEORETICAL MD	ACTUAL MD	MEAN LUMINANCE 2 LEVELS	MEAN LUMINANCE 8 LEVELS
54	50.0	.51	2.37
56	55.5	.55	2.53
58	60.5	.57	2.65
60	58.5	.55	2.53
62	68.5	.59	2.95
64	68	.59	3.15
66	57.5	.55	2.71
68	65.5	.60	3.31
70	65.5	.58	3.41
72	72.5	.64	3.79
74	73.0	.66	4.16
76	80.5	.69	4.10
78	76	.64	3.80
80	82.5	.77	4.47

as a function of the target's SNR. The theoretical and the actual marking densities are given for the target. The data was collected for one PBB display of two luminance levels and another of eight luminance levels. In the case of only two luminance levels, on and off, an increase in the actual marking density of the target should correspond to an increase in the average luminance of the target. Thus we would expect average luminance to correlate more strongly with actual marking density than with theoretical marking density. This was indeed the case. A correlation coeffecient of .94 was obtained for actual marking density and average luminance as opposed to a correlation coefficient of .88 for theoretical marking density and average luminance.

In the case of eight luminance levels the situation is more complex. Suppose theoretical marking density increases but due to chance the actual marking density decreases. The average luminance will not necessarily decrease from the previous SNR because the probability of obtaining higher luminance levels has increased. Thus the average luminance may increase even though the actual marking density has decreased because the percentage of brighter luminance levels in the target has increased: Although there are fewer dots turned on in the target column the ones that are on are brighter.

For example, in Table V we see that at the actual marking density of 57.5%, the average luminance was higher (2.71 fL) than at the marking density of 58.5%, (2.53 fL). This may be explained by the fact that the 57.5% marking density was generated from a target with an SNR of -3.87 (theoretical marking density of 66%), whereas the 58.5% marking density was generated by a target with an SNR of only -6.02 db (theoretical MD of 60%).

However, this balancing does not always occur. For example, we see again in Table V that when the theoretical marking density increased from 64% to 66% (and the SNR increased from -4.5 to -3.87 db) there was nevertheless a considerable drop in average luminance from 3.15 to 2.71 fL. This is easily explained by the higher than average actual marking of 68% for the theoretical marking density of 64% and the substantially lower than average actual marking density of 57.5% for the theoretical marking density of 66%. Thus, the erratic changes in average luminance may be attributed to a complex interaction between the actual marking density and the increasing probability of higher luminance levels as target strength increases. A correlation coefficient of .96 was obtained for actual average luminance and actual marking density, whereas a correlation coefficient of .95 was obtained between the actual average luminance and theoretical marking density.

Are Controlled Targets Artificial?

One criticism of experimenting with targets whose distribution of gray levels and marking density has been accurately controlled is that these targets are artificial. For any given SNR, the variability that arises is a consequence of noise being added to the signal. In a realistic situation, two targets with the same SNR will almost certainly not have the exact same distribution of luminance levels.

There are two separate issues that arise when answering this criticism: 1) Controlled targets are needed to determine what stimulus factors are critical to target detection. 2) For a given SNR of the target, the probability that the sampled mean signal level differs from the mean signal level of the population by a specified amount may be computed. Assuming that the sampled distribution is normal (an assumption which readily follows since we have assumed that we are randomly sampling from a normally distributed population of signal levels), the distribution of luminance levels, marking density, and average luminance may all be derived. In essence, computing the probability that the mean sampled signal level deviates from the predicted value is tantamount to computing the probability that the sampled marking density, mean luminance, and distribution of luminance levels will deviate from their predicted values by those amounts derived from the sampled mean signal level. Hence, once we know a threshold value of a stimulus variable necessary for target detection we may compute the probability of sampling that stimulus magnitude over N number of lines for a given SNR of the target.

Conclusions

Actual marking density and average luminance vary erratically on PBB display simulators. As the experimenter systematically increases the SNR, the underlying stimulus attributes which may be essential to target detection vary erratically. The importance of these stimulus parameters cannot be successfully investigated unless they are systematically manipulated in a psychophysical study.

EVALUATING THE RELATIVE IMPORTANCE OF MARKING DENSITY, CONTRAST RATIO, AND GROUPING OF SIMILAR BRIGHTNESSES IN TARGET DETECTION

As the SNR increases, the marking density of the target, its contrast ratio, and the number of bright bins all increase. Marking density, contrast ratio, and grouping of similar brightnesses are therefore confounded. Does the sonar operator detect the target because its average luminance exceeds that of the background by some threshold value or because its marking density does? Or, is a target detected because the number of bright dots which represent the target is great enough to allow them to be grouped by similarity? It is possible that there is an interaction between these three stimulus variables which together underlie target detection. These factors can be isolated experimentally and their relative contributions to target detection determined.

1) MARKING DENSITY VS CONTRAST RATIO

Effect of Range of Luminance Levels

Consider the simple PBB display of two luminance levels. In this example, grouping of similar brightnesses cannot be a factor, since all the pixels which are on are of equal brightness. Thus only marking density and brightness contrast are potential factors underlying target detection. If the difference between the luminance levels is increased, for any given marking density of the target, the contrast ratio of target to background will be increased. Thus, for a target marking density of 60% (-6.02 dB), if the luminance levels are .125 and 1.14 fL (high contrast) as opposed to .125 and .177 fL (low contrast), the contrast ratio is 1.17 for the first set of luminance values and 1.03 for the second set. Thus, if target detection is solely a function of contrast ratio--that is, if sonar operators detect targets when they have reached a given contrast--the marking density (and SNR) necessary for target detection will be lower for the high contrast display than the low contrast display, because a weaker target generates a signal of the same contrast in a high contrast display as a stronger target in a low contrast display. Put in other terms, the same contrast ratio (1.03) is achieved with a marking density of 60% (SNR = -6.02 dB) in the low contrast display and with a marking density of 52% (SNR = -13.01 dB) in the high contrast display. One would thus expect better performance on the high contrast display than on the low contrast display. On the other hand, if target detection is solely a function of marking density, we would expect no difference in performance on the high and low contrast displays.

This analysis may be easily adapted to a PBB display of eight luminance levels, for either a high contrast display in which the stepwise increase in luminance is by a factor of two or a low contrast display where the stepwise increase in luminance is by a factor of the square root of two. The contrast ratios for the high and low contrast displays are plotted over increasing signal strength in Figure 6 and presented in Table VI.

Effect of the Number of Luminance Levels

Another way to increase the contrast ratio is simply by increasing the number of luminance levels used to encode amplitude information. The increase in the target contrast as the number of luminance levels in the display increases from two to eight is plotted in Figure 4. These contrast ratios were computed using the theoretical distribution of luminance levels for given SNR's. In these displays the deviations from the mean were mapped onto luminance levels in the following manner. The total number of luminance levels in the display above "black" was divided into 2.33 to determine the stepwise increments in deviations from the mean that corresponded to an increase in luminance level. For example in a display employing three luminance levels including black, all signals below the mean of the noise, zero, were encoded as black; a positive deviation from the mean of less than or equal to 1.167 (2.33/2) was mapped to luminance level 1, and any positive deviation greater than 1.167 was mapped onto level 2.

If target detection were solely a function of contrast ratio, we would expect performance to improve as the number of luminance levels in a display increased. However, once we introduce more than two luminance levels into the display, then grouping of similar brightnesses may become a factor.

2) GROUPING SIMILAR BRIGHTNESSES

Effect of Range of Luminance Levels

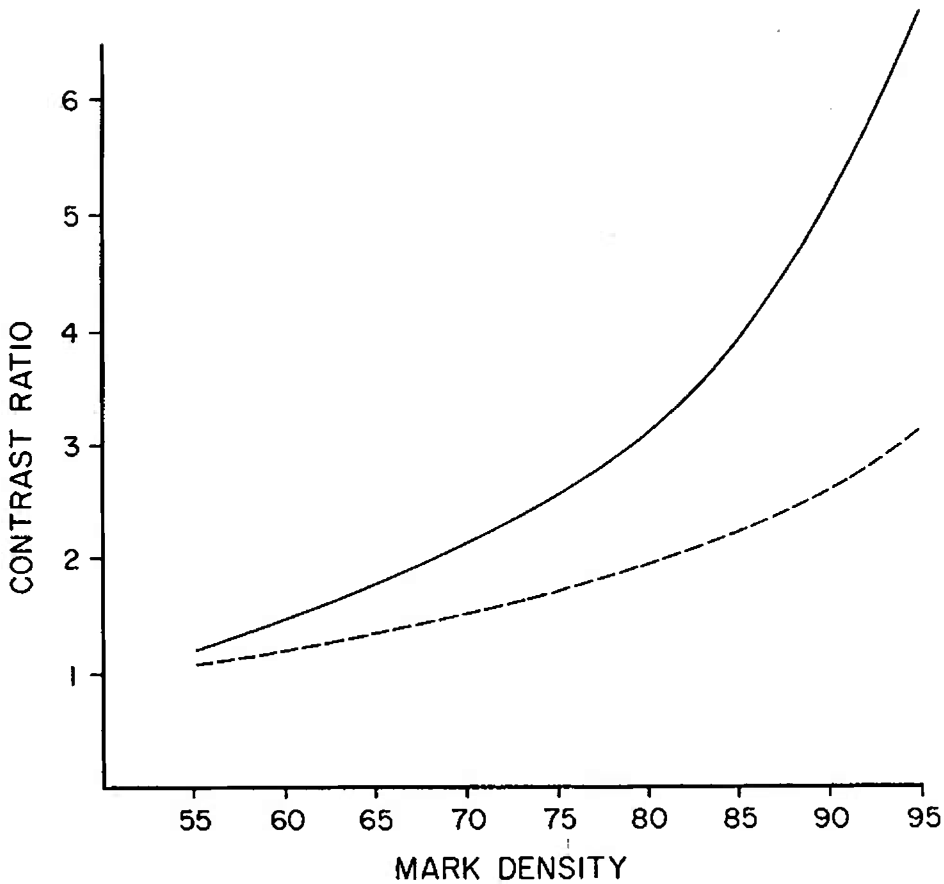

Fig. 6: Contrast ratio as a function of marking density for a high (solid line) and low (dashed line) contrast display composed of eight luminance levels.

TABLE VI: Contrast ratios as a function of marking density (MD) for high and low contrast displays.

MD	LOW	HIGH
55	1.01	1.03
60	1.21	1.45
65	1.35	1.76
70	1.50	2.11
75	1.69	2.58
80	1.91	3.16
85	2.19	3.94
90	2.57	5.05
95	3.17	6.90

For any given distribution of luminance levels in the target we may test the degree to which grouping similar brightnesses is a factor in target detection. For example, both the marking density and the contrast may be equated in two PBB displays, one composed of eight luminance levels and another composed of only two levels. Since grouping by similarity cannot be a factor in a display composed of only two luminance levels, any improvement in performance when the number of luminance levels is increased to eight would attest to the importance of this factor.

If, moreover, the range between luminance levels is increased, then for a given target the contrast ratio is increased. What effect does increasing the range of luminance values have on grouping by similarity? The answer to this question will depend on the exact distribution of luminance levels which comprise the target. For example, suppose we have a display of eight luminance levels. If the target is predominantly composed of one luminance level, then increasing the difference between each level should aid detection: As the difference in luminance between each level increases, the levels become perceptually more distinguishable. However, suppose the critical difference between the distribution of luminance levels of target to background is not along any one particular luminance level but several. In this case, increasing the difference between luminance levels would make it more difficult to group the target dots. Thus, detection may be impeded because the grouping factor has been weakened.

Using the model for noise and signal discussed earlier, Table I lists the theoretical distributions of luminance levels for a target as signal strength increases in a PBB display of eight luminance levels. In this particular model, the difference between target and background along any one luminance level is insignificant (Table II). Rather, the critical difference between the two distributions appears when the differences are summed over the four brightest levels. Thus for this model, if grouping by similarity is an important cue to target detection, increasing the difference between luminance levels would be detrimental, because it would make it difficult to group them.

Effect of Number of Luminance Levels

As we increase the number of luminance levels in a display, the target contrast increases. What effect does increasing the number of luminance levels have on grouping by similar brightness? In order to address this question, we must first know the theoretical distributions of luminance levels for a target with increasing signal strength. This is presented in Table I for STA PBB displays composed of five and eight luminance levels. Listed in Table II is the difference between the percentage of the target signal and the percentage of noise that maps onto each luminance level. For example, for a display composed of eight luminance levels and a target at -2.84 dB (equal to a marking density of 70), 7% of the signal will map onto the brightest luminance level compared to only 2.50% of the noise. With a display of five levels, 11% of the same target signal will map onto the brightest level as opposed to only 4% of the noise. The difference is greater for the five than the eight level display. A comparable difference of approximately 7% between noise and signal is achieved in the eight level display only at the two brightest levels; that is, 12.5% of the target signal will map onto these two luminance levels compared to only 5% of the noise. Thus in the display composed of only 5 levels, the information across brightness levels above black has doubled. That is, information conveyed by two luminance levels in the eight-level display is now conveyed by only one in the five-level display.

If we apply the same analysis to the two brightest levels in the display of five levels as opposed to the four brightest levels in the display of eight levels, we see that this relationship holds. A difference of 14% is obtained between target and noise across the two brightest levels in the five level display, as opposed to a difference of 15.5 % across the four brightest levels in the eight level display. This analysis is depicted in Figure 7 and Figure 8, in which the percentage of the target signal over that of the noise that maps onto each luminance level is plotted as a function of marking density (i.e. increasing signal strength) in a display of eight and five luminance levels respectively (note the percentage that maps onto screen black, level zero, is omitted from both figures). In a display of five levels, the slopes of the two brightest levels are approximately twice that of the slopes of the four brightest levels in the eight level display (refer to Figure 8). In other words, the information conveyed by four levels is now conveyed by only two; thus the difference between noise and target in the five level display is more pronounced along the two brightest levels.

If grouping similar brightnesses is a factor in target detection, then one may expect better performace on displays where the critical difference between the distributions of luminance levels is displayed across fewer luminance levels. Presumably, it is easier for the visual system to group together fewer luminance levels. This compression of the critical difference between the target and background along fewer luminance levels is beginning to take place when we compare the five-level and eight-level displays. Unfortunately, this effect is not optimal in the five level display, because luminance level 2 behaves similarly to levels 3 and 4 (refer to Figure 8) for relatively weak targets. However, one could correct this by altering the mapping of signal level to luminance level in this display. In this case one would predict better performance on the five as opposed to eight level display on the basis of the grouping factor. This prediction is the opposite of what was predicted for contrast: for that we predicted better performance on the eight level display.

However, as noted earlier, grouping by similarity and contrast have an interactive effect in that it is desirable to make those luminance levels which distinguish target from background perceptually more similar while at the same time increasing the contrast between the critical and noncritical sets of luminance levels.

IMPLEMENTING COLOR IN PBB DISPLAYS

This analysis suggests ways in which color may best be used to enhance stimulus cues to target detection.

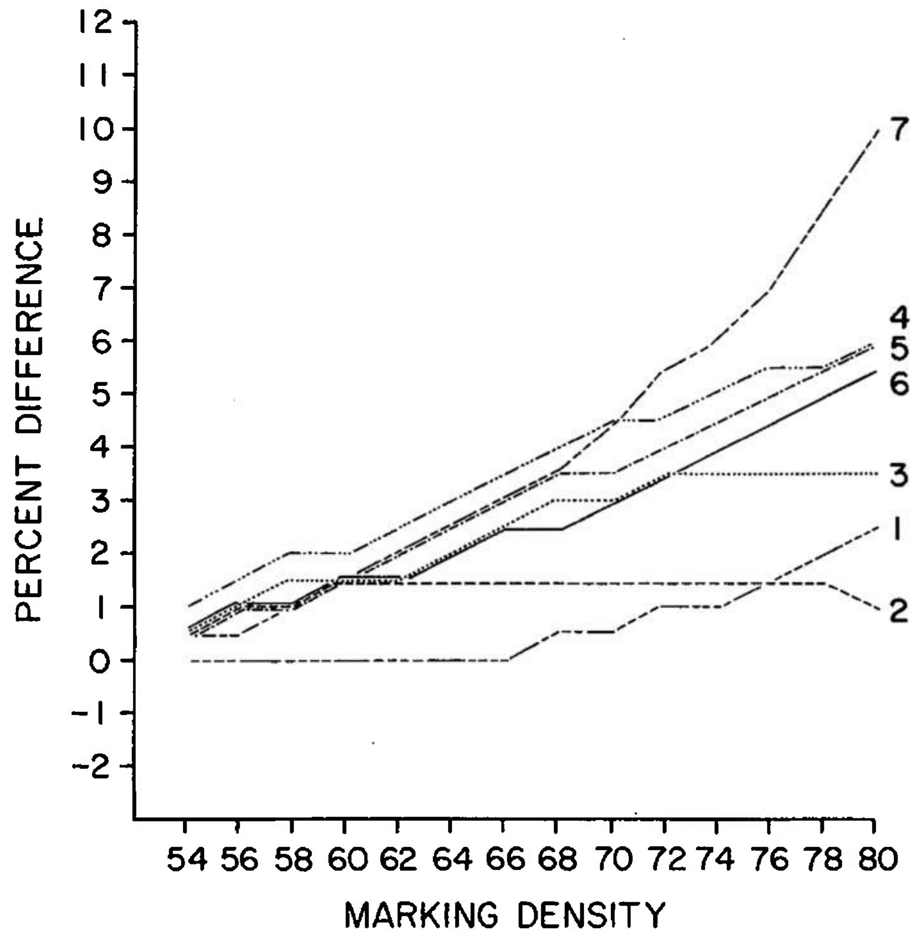

Fig. 7: Display of eight luminance levels. Percent difference between the target signal and the noise which maps onto each of seven luminance levels at each marking density for a PBB display (level zero has been omitted).

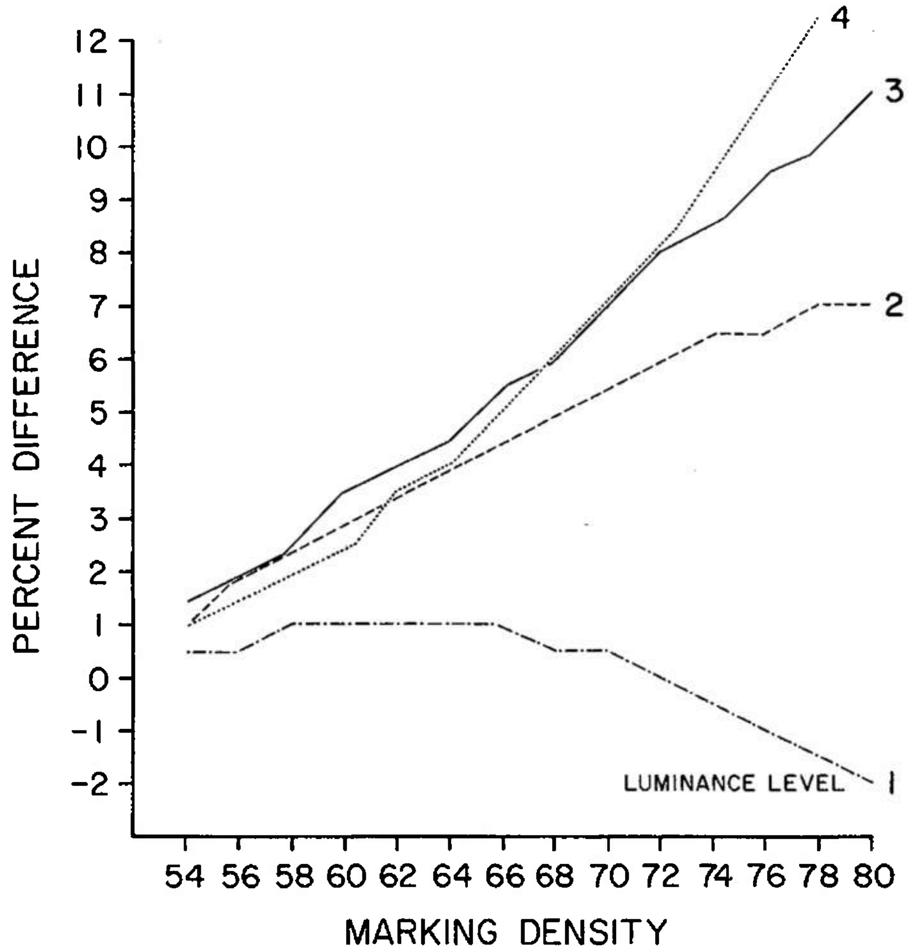

Fig. 8: Display of five luminance levels. Percent difference between the target signal and the noise which maps onto each of four luminance levels at each marking density for a PBB display (level zero has been omitted).

1) MARKING DENSITY

Color may effectively be used to enhance the marking density cue. For example, at each bearing a record can be kept of the percentage of the signal that maps onto a luminance level greater than black over a specified number of display lines. If this percentage is greater than some threshold value, then selected information presented at that bearing over the next specifed number of lines is presented in color. An algorithm employing this basic strategy has been used to enhance target detectability in STA PBB, and it is particularly effective for weak signals at a constant bearing. In such case the marking density at the target's bearing will reliably be above the 50% marking density of the background.

In a chromatic display, the colored signals immediately stand out. In a monochromatic display the difference in marking density is not detectable. The algorithm uses color to flag those bearing whose marking density is consistently greater than the background, thus giving the operator a best guess as to where weak targets are.

2) CONTRAST

We have used the term "contrast" to refer to two different applications in monochromatic displays. The first is the usual definition, the ratio of the luminance of the target to that of the background. If experiments show that this ratio reliably predicts perfomance in monochromatic displays, then it will raise questions as to the necessity for color to enhance target detection. Moreover, since different colors have markedly different brightnesses, a poor choice of colors would render this cue ineffective.

We have also used "contrast" to refer to differences between luminance levels in a PBB display. In this case, contrast is used to aid in grouping similar brightnesses. Color coding of information is applicable in this situation, and is discussed next.

3) GROUPING SIMILAR BRIGHTNESSES

It is my opinion that the degree to which grouping similar brightnesses is a cue to target detection will dictate the effectiveness of color coding information in the STA PBB display. Eight colors may easily replace the eight luminance levels of the monochromatic display so that the differences between the eight levels are perceptually more distinguishable. However as discussed earlier, the degree to which it is desirable to make the levels perceptually more distinguishable is a function of the degree to which the differences between target and noise information may be represented by a single level.

This suggests that the sonar operator should be able to select the color coding scheme. For example, the system could be programmed to seek out differences in the distributions of various groups of luminance levels at selected bearings. The operator could then use this information to change the color scheme on the display. He could choose to represent several levels in one bright color, while displaying information across the other levels as darker colors. In this manner a target whose distribution of levels differs from that of the noise along the selected levels, will more readily be detected. Upon detection, the operator may switch to a new color set in order to enhance the difference between other distributions of quantized levels associated with another possible target.

SUMMARY

Targets on the PBB sonar display have been shown to exhibit three distinct stimulus attributes which may form the basis of detection by the operator. These may now be studied to determine which characteristic is most frequently or effectively attended to, and which, therefore, should be enhanced to produce the greatest improvement in operator performance. Future studies will manipulate these characteristics independently.

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APPENDIX I

EFFECT OF SCREEN RESOLUTION

Thus far I have used the term "contrast ratio" in the traditional sense to mean the ratio of the luminance of the target to that of the background. In a classical brightness contrast discrimination task, both the surround and the target, which may be a thin contour or circular disk, are uniform in brightness. Although the shape and size of the target may influence the obtained threshold, the perception of form is not thought of as entering into the task of detecting the target. However, suppose our PBB display is similar to the display in Figure 9. In this display either the resolution of the CRT screen is poor or the number of pixels per bin is so large that a weak target at a constant bearing would appear as a vertical column of distinct dots. That is, black portions of the screen are interspersed between the dots that compose the target. The detection of this target seems to entail more than just brightness contrast, because the target is detected despite the perceived discontinuities in brightness along the target's bearing. Neither the target nor the background is of a homogeneous brightness level, and the visual system must connect the dots in order to perceive a target. In this case the detection of the target entails form perception and grouping similar brightnesses is applicable.

The effectiveness of marking density, contrast, or grouping by brightness, is dependent upon both the CRT resolution and the number of pixels per bin. For example, if the number of pixels per bin is small and the resolution of the CRT great, the visual system may be unable to resolve adjacent bins. In this display a target would appear as a thin contour whose overall brightness was different than that of the background. Although the brightness of the target may appear to vary, the changes would appear more gradual since the brightness of any segment of the target would actually be a function of the brightness of several bins of information as opposed to one bin. In this display, contrast would be directly appplicable to target detection. In fact, the cues of both marking density and grouping similar brightnesses would reduce to average luminance. Thus, the applicabilty of any of these cues is dependent on the display format. The question immediately arises, given the nature of the PBB diplay, which cues and display formats are more advantageous to target detection?

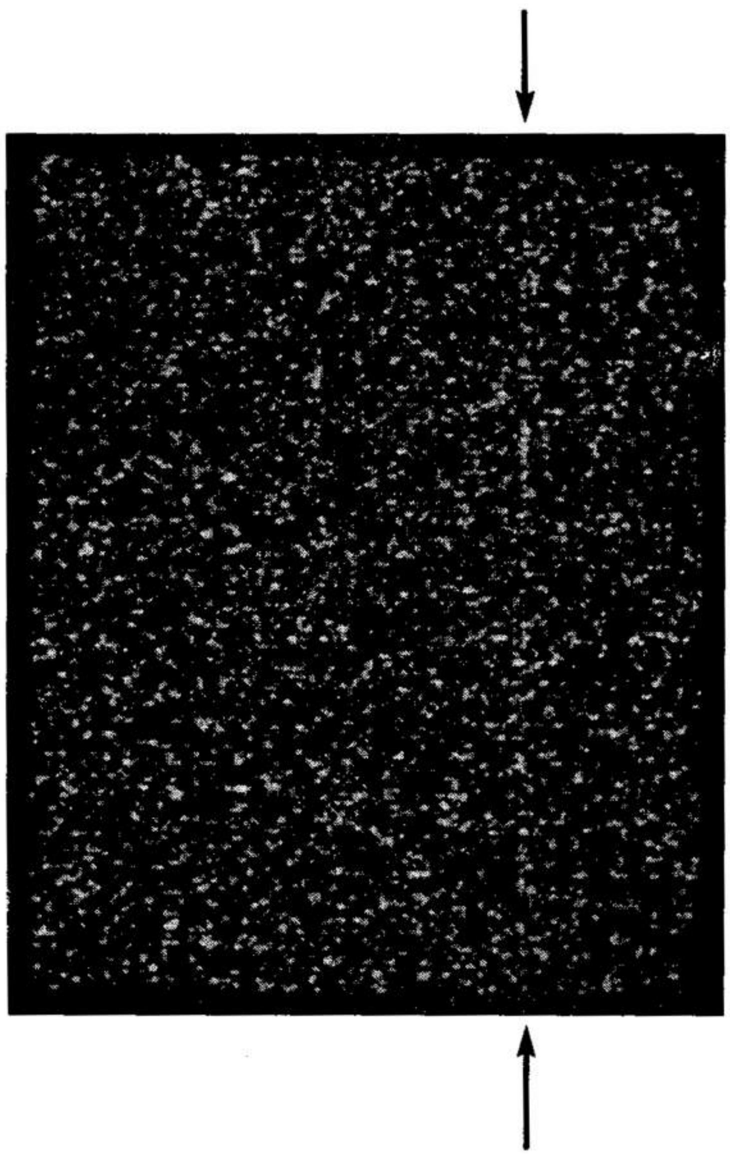

Fig. 9: The arrow points to a weak target at a constant bearing. Contrast alone cannot account for the perception of this target. (Note the low luminance levels were not captured by the photograph and printing process.)

APPENDIX II

THE PROBLEM OF MEASURING THE AVERAGE LUMINANCE OF THE TARGET

In my analysis of contrast ratio, I computed the average luminance of the target and background. That is, the distribution of luminance levels has been computed, and the luminance readings obtained from measuring individual pixels have been used to calculate the target's mean luminance. Do these computed values correspond with the measured values? In order to determine this, targets were generated whose distributions of luminance values exactly reflected the computed distributions for 200 lines of STA PBB. The average luminances of these targets were measured as discussed above. However, several limitations in our equipment and technical difficulties with CRT screens in general made an accurate measurement of the average luminance of the target difficult.

The eight luminance levels were obtained by measuring a single green color dot. The smallest aperture of the photometer, 2 min, is larger than a single color dot, and the measurements thus underestimated the luminance of the dot. However, between two vertically aligned green color dots there was a small area of black screen. When the photometer was 2 ft from the screen, the 2 min aperture covered a circular area composed of a single color dot, the black area of screen above and below it, and the edges of the adjacent green dots. Thus, some light from adjacent green color dots entered into the measurement creating a source of error. Another problem which arose concerned a focusing error of the electron beam. Each color dot received stimulation intended for neighboring pixels, thus increasing the overall luminance measured. To obtain an estimate of this error, the luminance of a black vertical line one pixel in width was measured in a background of noise. The average luminance for this target was .47 fL. This marked an increase of .345 fL when compared to the luminance of the black screen, .125 fL. In Figure 10, both the theoretical and obtained contrast ratios are plotted against increasing signal strength for the low contrast displays of eight luminance levels. If the .345 fL error is subtracted from both target and background luminances, the theoretical and actual contrast ratios agree to the first decimal place.

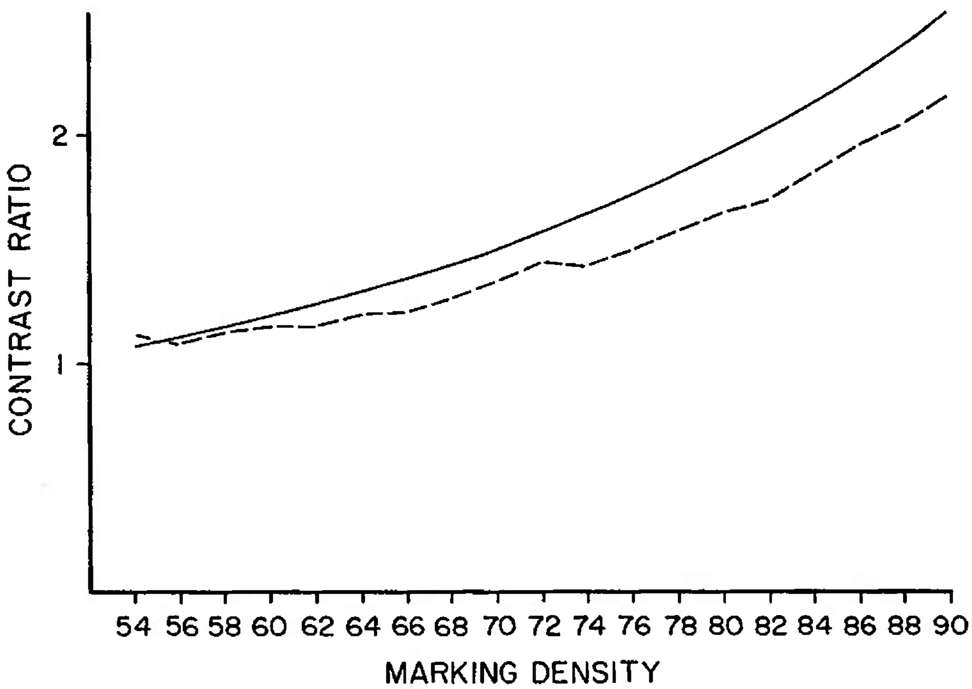

Fig. 10: Theoretical contrast ratio (solid line) and actual contrast ratio (dashed line) as a function of marking density. Both the marking density and distribution of luminance levels in the target were controlled.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NSMRL Rep. No. 1057	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AN ANALYSIS OF STIMULUS DETERMINANTS OF TARGET DETECTION IN PBB DISPLAYS		5. TYPE OF REPORT & PERIOD COVERED Interim 6. PERFORMING ORG. REPORT NUMBER NSMRL Rep. No. 1057
7. AUTHOR(s) JOSEPH DIVITA		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Submarine Medical Research Laboratory Naval Submarine Base New London Groton, Connecticut 06349-5900		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 65856N M0100.001-1022
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Submarine Medical Research Laboratory Naval Submarine Base New London Groton, Connecticut 06349-5900		12. REPORT DATE 1 Aug 1985 13. NUMBER OF PAGES 27
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Medical Research and Development Command Naval Medical Command, National Capital Region Bethesda, Maryland 20814		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Marking density; contrast ratio; grouping similar brightnesses

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Targets on passive broadband sonar displays may be detected on the basis of three distinct stimulus attributes--target contrast, target marking density, and by grouping of similar brightnesses. Previous research has failed to isolate and systematically manipulate these variables. Methods of doing so are proposed in order to determine which of these stimulus attributes underlie target detection. Enhancing the proper variables should improve target detection.

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