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Color Cathode Ray Tube Displays in Combat Information Centers

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ABSTRACT

Some recent technological advancements with color in cathode ray tube (CRT) displays, the continuing demand to present additional information more efficiently in command and control centers, and the introduction of stored information systems have stimulated renewed interest in color as a coding dimension. This study examines the human factors and engineering considerations as they relate to the central problem of the relative cost effectiveness of color--given the present engineering state-of-the-art--as compared to other coding dimensions for combat information displays and concludes that:

(1) The comparative ranking of color with other coding dimensions is highly related to the task performed

(2) Other situational factors greatly affect the value of color as a coding dimension

(3) There are perceptual problems involving the use of color, but techniques are available to enhance the value of color as a coding dimension

(4) The state-of-the-art for producing color CRT displays is encouraging, but only two tubes seem likely to have application in the near future

(5) Monetary cost estimates have been difficult to obtain, but other more easily ascertained cost factors indicate that for some tasks color will be well worth the cost.

PROBLEM STATUS

This is a final report; this problem will be considered closed thirty days from mailing date of this report unless the Laboratory is otherwise notified by the Bureau.

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PREFACE

This report was prepared to assist in the assessement of the relative worth of color versus other coding schemes in tactical information displays, such as are used in naval combat information centers. It is divided into three chapters and an appendix.

Chapter One is both an introduction and a summary of the major factors, which are further developed in Chapters Two and Three. The chapter relates the usefulness of color in coding displays to the tasks which the users perform and reviews its usefulness in the light of changes in the organization of combat information systems and under the impact of changes in equipment (particularly stored information systems) upon the amount, accuracy, and staleness of the decision-maker's information.

Chapter Two is a survey of selected human-factor experiments which were considered to be germane to the subject. These experiments were directed to finding out the number of discriminable steps which could be used for color coding, the relationships between user's task (such as search or decode) and color as a coding scheme, and the use of color as a redundant and nonredundant dimension to increase reliability, save time, and increase information transfer. The Appendix relates to this chapter and gives further details of a group of these experiments which were considered to be particularly germane to an understanding of the subject. The work surveyed here does not include all applicable work but was limited by the time available to complete the project.

Chapter Three is a survey of the state of the art in color cathode ray tubes. Although other types of color displays exist and are used in combat information systems, the survey was restricted to cathode ray tubes because of their fast response and their applicability as currently used and to stored information systems. Other types of displays such as solid-state display elements may also have applicability in the more distant future.

CHAPTER 1
COLOR CATHODE RAY TUBE DISPLAYS IN COMBAT INFORMATION CENTERS

SUMMARY

INTRODUCTION

Color has been used in the past for certain combat information command and control displays, but cost and engineering feasibility have heretofore prevented more widespread application. However, some recent technological advancements with color in cathode ray tube (CRT) displays, the continuing demand to present additional information more efficiently in command and control centers, and the introduction of stored information systems (e.g. NTDS) have stimulated renewed interest in color as a coding dimension. There are many problems involved in an investigation of the merits of color as a coding dimension for CRT displays in combat information centers, but the focus of this report is on cost effectiveness and feasibility. The central problem concerning the use in such displays relates to color's effectiveness compared to other means of coding or separating infomation, as measured in terms of their relative costs. Cost is used here in the overall sense including complexity, reliability and any restrictions on the selection of personnel who may use colored displays.

The solution of this problem depends upon many considerations. First, is color superior to other coding dimensions, and if so, for what purposes and what is the magnitude of the superiority? Second, are there any human (perceptual) problems involved in the use of color, and if so, what is the nature of the problems and the prospect of overcoming them? Third, what is the present engineering state-of-the-art for producing color for cathode ray tube displays and what are the technological prospects for future production? Fourth, what are the present and projected cost estimates for CRT color production?

Since these questions involve roughly human factors and engineering considerations, two such relatively independent surveys were conducted. The one on human factors presents some of the most relevant studies on color as a coding dimension which seem applicable to cathode ray tube displays. The engineering survey, in anticipation of possible perceptual problems, considers the problems in the state-of-the-art of cathode ray tube color production in terms of the important parameters of range, brightness/contrast/visibility, resolution, and persistence. The discussion which follows attempts to relate the data contained in these surveys to practical applications in the combat information center.

As a general orientation and precursor to this discussion, the following conclusions are presented:

(1) The comparative ranking of color with other coding dimensions is highly related to the task performed.

(2) Other situational factors greatly affect the value of color as a coding dimension.

(3) There are perceptual problems involving the use of color, but techniques are available to enhance the value of color as a coding dimension.

(4) The state-of-the-art for producing color CRT displays is encouraging, but only two tubes seem likely to have application in the near future.

(5) Monetary cost estimates have been difficult to obtain, but other more easily ascertained cost factors indicate that for some tasks color will be well worth the cost.

DISCUSSION

Color coding as a means for separating information

To intelligently assess the value of color as a means of coding information in combat information displays, it is necessary to examine its use in the context of the various competing methods of organizing information by both separating and encoding it. If the fundamental question "why code, separate or organize information?" is asked some insight may be gained. Information is organized - in early states of information processing in a system - by separating to reduce the amount which must be processed in subsequent steps and to simplify these steps by an orderly arrangement of the remaining information. The production of a task related set is the objective. One approach would be to separate information in the earlier stages of a combat information system and then present the decision-maker (DM) with only the information he needs to make a particular decision. Clearly if a single well-defined task is involved and the cost of separating the information is not excessive, this method is highly desirable. However, in CIC and other command and control stations many of the tasks are sufficiently variable that the precise limits of the information needed to perform them are not well defined. Furthermore, the costs of separating this information are considerable and prior to the introduction of NTDS, etc. the cost of providing even one complete display for each DM was prohibitive.

An opposing concept is to present him with a larger amount of information than he may need for a single task and arrange it in such a fashion as to facilitate his separating it into various categories of interest as needed. This may be done by visually coding the information--although other methods of separation such as spatial separation are possible. In combat information displays the importance of position (including geographical) and motion information preempt the use of the spatial dimensions for

such separation. The organization or separation may be regarded as a hierarchical process with division into major categories and subsequent refinement into successively lower levels or finer structure until a precise separation is obtained. Thus separation into air, surface and subsurface with subdivisions under the first of high, medium or low and subsequent subdivision to 25,000 feet versus 26,000 feet might be desirable. Some natural separation by major category occurs as a result of the nature of the surveillance equipment employed although this division is often not that which would be desired by the DM. For example, the combination of submarine target and ASW aircraft information (produced by sonar and radar respectively) on the same display is highly desirable for some DMs. Since higher level DMs are concerned with coordinating units and weapons of own force there has historically been an effort to combine rather than to separate much of the combat information so that the interrelationships of position and motion of the various units may be better comprehended. Another reason for the combination of information which is perhaps not fully appreciated today is the sheer cost in manpower of generating derived displays (vertical plots) necessitating their shared use by several DMs each having different tasks to perform. Newer systems with information electronically stored reduce this cost and make individual user displays feasible. If all the information required by a DM is not available on a single display (plus, of course, his background knowledge) he will be forced to share his visual attention by either looking from display to display if more than one such display is continually available or by switching different categories of information on a single display where this can easily be done. In either case, the result is much the same since his visual attention must be shared and time is lost. Of greater significance is the much greater difficulty of perceiving the relationships of position and motion of the various targets where the eye and memory are required to transpose information from one display to another. This needlessly injects a difficult additional information processing task. The desirability of providing continuously on a single display all the information which the DM needs for his entire task is apparent.

The DM may be provided too much information on this single display since as his information load goes up the time required for him to sort out the information he needs for a particular decision increases and his decision time thus increases. There results a decrement in systems response time which may be critical. In manual CIC Systems (those in which detector-trackers detect and track targets with the aid of grease pencil plots and verbally tell the track information to plotters who manually plot this information) the amount of information available has been low and the principal systems deficiencies have been in errors and delays. Newer CIC systems will change all this. Better surveillance equipment with longer range will increase the number of targets on which information is initially available as well as the precision. The result is a marked increase in the amount of information. Data links will greatly increase the amount which can be exchanged among units as well as its precision and will accomplish this at a speed which will make time delay errors negligible by comparison. The result will be a larger amount of information which the system will handle. More automatic information processing can reduce much of the

manual processing now carried out and will tend to lighten the decision load at some parts of the system; however, there are other complicating factors. The greatly increased cost and sophistication of weapons and their greatly increased destructiveness are forcing decisions to be made at higher and higher levels in the command structure. The greater utility value of the decisions brings with it an attendant desire on the part of commanders to delve into lower level decisions which are "fed up" to them as inputs to their decision processes. The resultant is a higher information load on many decision makers and a system which will become decision limited rather than information limited. An alternative would be to divide the authority and place a greater dependence upon doctrine rather than upon direct ordered coordination. The multiplicity of problems and their broad scope will strongly mitigate against standard solutions or completely computerized solutions especially at high level. The desirable alternative, which has been the approach historically demanded by commanders, appears to be to provide the DM with more information than he really needs because of the difficulty in defining just what he needs. He must have a maximum of help in permitting him to separate this information according to his needs. This is not to suggest that information will not be automatically selected for presentation to the DM or that such is undesirable, but simply that it will be too difficult to draw a sharp line as to what is and what is not needed and that, therefore, such problems will likely be resolved by giving the DM a surplus of information. Laboratory experiments have shown that color coding has the important property that it greatly increases the ability of observers to rapidly select out a particular set of information coded in one color from a much larger set coded in other colors. This appears to be the principal value of color in combat information displays although there are others.

The survey on the human factor aspects of color coding points this out and quotes and refers to laboratory data which indicates its value as an aid in the "search" task which is based upon this ability to separate information categories.

Color coding used as a redundant dimension to increase reliability and decrease response time.

Experiments have shown that, where the same information is redundantly coded in two or more visual coding dimensions, the reliability in extracting or recognizing the coded information is increased and the response time is lowered. By redundant coding is meant the coding of the same information in two or more visual dimensions, e.g., altitude might be represented by a series of, say 10, symbols (perhaps integers) each representing one of ten altitude layers and it might also be represented by a series of 10 colors each similarly representing one of the 10 layers. Altitude could thus be ascertained by observing either color or the symbol. If both series were simultaneously used in a one to one correspondence the coding

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would be completely redundant. If only two colors were used, representing say high and low in lieu of 10, the coding would be only partially redundant. Within abstract situations in the laboratory, color when used redundantly, was shown to markedly increase the reliability of judgments. Response time in recognizing the coded information was also decreased under these conditions of redundant coding. Where the military utility of the decision is high, as it will be in many situations for reasons discussed above, this increase in reliability and decrease in response time could be particularly significant.

An important consideration here is the effect of stress upon the decision maker. It has been shown by studies conducted in this laboratory* that while two displays may be nearly equivalent in effectiveness under conditions of low-stress their comparative effectiveness may change markedly under conditions of stress. This work was not done for color coding but it is believed that this factor may be significant here. Research is needed to relate the effectiveness of color versus other codes under conditions of stress since stress will certainly be present in the command and control decision situations discussed here. It could be that color, which is a fundamentally different visual dimension as discussed below, could be a more stress-resistant coding means than some others. Admittedly the effect of this factor upon operational situations will be difficult to assess.

Color is an efficient dimension to use for coding in order to save display space and increase resolution.

Where the amount of information appearing upon a pictorial display becomes large or crowding in certain areas exists, display resolution becomes very important. Under these conditions, codes which are inefficient in terms of the area of display consumed, create problems. Extensive use is already being made of symbol codes and an attempt to force more information into such codes will certainly increase the area even to the extent of adding additional symbols for a single target. If two separate symbols are closely interrelated to convey information about the same target, ambiguity may result when another target is proximate. Color, however, could be used to add information or redundancy under certain conditions discussed in the engineering survey without requiring additional display area and without introducing the problem of ambiguity. Such ambiguity if it existed would have a significant deleterious effect upon reliability.

Color may be regarded as a fundamentally different visual coding dimension.

Historically, most coding of information has taken the form of space or position coding. Such codes include shapes (circles, triangles, etc)

*Garvey, W. D. The Effects of "Task-induced Stress" on Man-Machine Systems Performance, NRL Report 5015, Sept. 1957

alpha-numeric or similar characters, size codes (area) and pictorial codes (clock codes, etc.). These may be regarded as encompassed by the concept of being generatable by an electron beam or a pointer moving in position (position modulation). They may be (and usually are) stored. Their use requires pattern recognition by the user. The reasons for the predominance of their use is easy to see. They have been readily easy to generate in ordinary use (drawing and writing) as well as electronically and have long histories of use. We are highly trained from childhood in their use and they have natural mnemonic associations based upon a lifetime of training.

There are two other fundamental coding dimensions for visual display. These are intensity and hue. These are easily separated in physical concept corresponding to amplitude and frequency respectively but are not so easily separated in the psychophysical sense in which they are mutually interfering as well as confounded with size to some degree, especially in the case of very small spots. For spots of reasonable size (above visual angles of 20 minutes or one-tenth inch at a viewing distance of 16 inches) the hue-brightness complex is completely separable from the position or spatial dimension and for considerably smaller spots is separable to a high degree. Together they serve to provide in the practical sense a completely separate dimension, involving an apparently different psychophysical mechanism. This tends to limit the amount of information which must be searched to locate a particular list of target information, since pattern recognition is not required in this case. This effect of a really independent dimension and different mechanism in separating information is perhaps what accounts for its effectiveness in the search task.

<u>Laboratory experiments have shown the effectiveness of color as a coding dimension to be highly task related.</u>

The task of the decision maker (DM) or controller, at whatever level in the command structure from equipment operator to Force Commander, will determine how effective color will be as a coding dimension for him. Blanket statements as to the effectiveness in decision making or controlling tasks are not appropriate. Important considerations here are (1) the total amount of displayed information the DM needs, (2) the number and character of the categories of information needed, (3) whether the information must all be available at once or whether it can be displayed in sequence, (4) his visual task consisting of one or more of the operations of search, locating, counting, verification, selection, (5) his visual environment, (6) the amount of information he must transmit to others in the organization or to other echelons, (7) the rates at which the received and transmitted information change, (8) the stress to which he is subjected in his decision making or controlling task and (9) the quality of the display.

To determine color's effectiveness as a coding dimension in a command and control task it will first be necessary to sub-divide the task into appropriate subtasks and to assign some suitable weighting which takes

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account of both its importance and the frequency with which it is performed. These sub-tasks must then be divided into appropriate visual tasks and a value of color as a coding medium for each visual task estimated. If then some estimate of the amount of the DMs critical time spent on each visual sub-task can be made, a suitable weighting can be applied to determine an index of the value of color as a coding medium in the decision task. The concept of critical task or critical time is fundamental, since time spent on each task when the DM is not actively engaged or performing critical functions, is not important. The index will be rough since it can only be as good as the effectiveness of sub-dividing the tasks and assigning the values and weights. Some investigators have divided the display tasks on an arbitrary but somewhat logical basis of "locating", "counting", comparing, verifying and identifying. Further research into the appropriate categories for sub-division appears desirable. The process of developing such an index is depicted as follows:

	SUBTASK		Sub-task Weights		Visual Task Weights	Visual Task Values
T	1	x	W_1	Visual Task 1	x w_{11}	x V_1
				Visual Task 2	x w_{12}	x V_2
				⋮		
A				Visual Task j	x w_{1j}	x V_j
	2		W_2			
S	⋮					
				Visual Task 1	x w_{i1}	x V_1
K	i		W_i	Visual Task 2	x w_{i2}	x V_2
				⋮		
				Visual Task j	x w_{ij}	x V_j

Thus

$$I = \sum_{ij} Wi\ wij\ Vj$$

CHAPTER 1 - SUMMARY

Obviously the Wi wij could be combined into a single term but there is possible advantage in separating them for given sub-tasks may be common to several tasks in which case the wijVj (the weights assigned to the visual tasks and the value of using color in them) will remain the same.

There are problems of display brightness associated with the introduction of color.

These problems affect the utility of color under conditions of high ambient illumination. These problems are not considered important in CIC spaces but may be in above deck spaces. A "transparent" phosphor color tube under development holds promise of alleviating the problems due to brightness for high ambient situations. The technique also has promise in monocolor displays.

With presently available color tubes some problems of display resolution are introduced.

Conventional color tubes, which achieve color separation by suitably directing the electron beam to excite color phosphors which are spatially separated in the display plane, introduce a loss of resolution over ordinary one color displays. Tests would be required to determine if this loss is acceptable. However, as discussed previously, the addition of substantially more information to the display by any form of position coding entails a loss in resolution. This loss may be greater than that introduced by using color.

At the present state-of-the-art, no set of good long persistence phosphors are available.

This necessitates externally stored information to produce color displays of wide color range. Thus, use with stored information systems is possible but when raw information is required it must first be stored in storage tubes (either integral or separate tubes) with their attendant problems and additional complexity.

Where two color presentation will suffice there are two competing two-color storage tubes under development that have attractive possibilities for small displays.

The integral combination of the characteristics of color and storage has obvious advantage. However, these tubes are complicated and presently limited to small displays. The provision of only a second color has marked advantage in display coding for the reasons discussed above.

CHAPTER 1 - SUMMARY

Technical problems in the state-of-the-art devices preclude the shipboard production of color displays of the quality used in the experiments included in the human factors survey.

For the present state-of-the-art a range of not more than four colors can be produced by cathode ray tube displays where 100% reliability of absolute judgment discrimination is required.

All color tube designs involve trade-offs among the various parameters and and a selection and ordering of the importance of the parameters will prove more fruitful than a requirement for maximum performance in all parameters.

The use of color as a means of separating information appears to be the most important use. Thus, a wide range of colors is not necessary and could be sacrificed to obtain the persistence which is required for many applications. For many applications brightness may be sacrificed.

CHAPTER 2
SURVEY OF HUMAN FACTORS IN COLOR CODING

INTRODUCTION

The concern of this survey is primarily with the state of the human factors knowledge relating to the use of color as a coding dimension for visual displays, particularly the cathode ray tube displays. To this end an attempt has been made to gather and review the pertinent published work. In addition, a somewhat detailed summary of the most directly relevant studies has been prepared and is offered as an aid to the reader (Appendix A).

The surveyed literature falls into two areas: (1) the question of discriminability within the color dimension, i.e., the number of steps reliably discriminable as restricted by user capability, operational requirements, and the state of the electronic art; and (2) the question of the utility of a color code used singly or in conjunction with other coding dimensions.

Some limitations of the research on display color coding, and consequently of this survey, should be mentioned. First, the investigators assume viewers of normal color vision and visual acuity. Second, the experimenters are not concerned with problems arising from operator fatigue, adaptation, or vigilance effects. Finally, and with few exceptions, they assume physical conditions (ambient illumination, placement of display and viewer, etc.) to be such as not to introduce unusual perceptual color effects.

To code information to visual displays means to associate the information of interest, usually an aspect of the environment, with some visual quality. This is usually done by binding pairs of selected values, one taken from the environmental and one from the visual dimension. For example, an interesting aspect of the environment, say "speed of aircraft", may be associated with a visual dimension, say symbol shape, by pairing speed in 100 knot increments with the arabic numbers (shapes) in the most obvious way. Thus, 8 would symbolize 800 knots. The aspects of the environment that can be coded, in this sense, are limited only by the number of coding schemes that can be devised.

COLOR DISCRIMINABILITY FOR CODING

Whatever visual dimension is under consideration for a coding scheme, perhaps the first question to be answered is whether there are enough discriminable steps available within the dimension at a sufficiently high level of reliability to meet the requirements of the task to be performed. For any scheme involving multihued displays the designer may find himself squeezed between the number of steps desired and the decreasing discriminability which attends an increase in the number. The first studies to be reviewed deal with the problem of discriminability within color dimension.

CHAPTER 2 - HUMAN FACTORS

Perceptually, color is regarded as having three attributes or dimensions: brightness, hue, and saturation, corresponding respectively to the three categories of variation in light that the eye can distinguish - luminance, dominant wavelength, and purity. Some of the work has been concerned with the discrimination of hue, with brightness and saturation held constant or at least not varied to enhance discriminability.

The earliest work was done under "classical" laboratory conditions and provided a favorable to optimal viewing situation. The judgments were made with a standard for comparison adjacent the test color, i.e., the subject made a null rather than an absolute judgment. The criterion was detection of a just noticeable difference (jnd) 50% of the time. Under these conditions and when restricted to spectral hues, it is possible to make a large number of discriminations. Thus, Wright (1943) found about 150 discriminable steps at 1 to 4 millimicron intervals in the spectral range 430 mμ to 650 mμ.

There has been much work with practical implications for color coding under more extreme conditions, e.g., the recognition of signal lights. These conditions include adverse viewing situations, judgments at near 100% accuracy, and in some cases the identification of the color by a commonly accepted color name. Under these conditions the number of discriminable colors is severely reduced and has been placed at three or four. For operations in Naval CICs, or similar information processing spaces, we are concerned with less stringent but nearer the latter conditions than with the "classical" conditions. The requirement for accuracy will remain very high; discriminations will have to be made without dependency upon standards for comparison and viewing conditions may be better than those for signal lights but short of optimal.

A study by Halsey and Chapanis (1951) was an early attempt to focus on the problem of hue discrimination when subjects are required to make absolute judgments. They worked with the spectral hues. The colors were self-luminous and the luminescence, while varied to compensate for equipment limitations, was not employed to enhance hue differences. Ten hues were found that could be identified with 2.5% error - 430, 476, 494, 504, 515, 556, 582, 596, 610, 642 millimicrons. As expected, an increase in the number of steps resulted in an increase in error: 4.4% for 12 and 27.6% for 17 hues. This study, though "exploratory", foreshadowed the results obtained by later workers. Baker and Grether (1954) list ten spectral hues (the same as those reported above) which, on the basis of the literature, they believe can be discriminated nearly 100% of the time with the light source size at 45' of subtended visual angle and the brightness at 1 millilambert.

A rather elaborate investigation of hue discrimination has been made by Conover (1959) who used surface colors (Munsell) at maximum saturation. He found that the average color-normal individual can identify about nine colors on an absolute basis. A proposed set included eight spectral hues and one non-spectral hue. Another set of thirteen is recommended for subjects with especially good discriminability, and after extensive

practice this latter set, while not identical with that of Halsey and Chapanis, has the same number of spectral hues (10) whose distribution is in some agreement. The wavelength of these hues are: 420, 476, 485, 503, 561, 570, 574, 582, 596, and 610 millimicrons.

Eriksen and Hake (1955) used Munsell colors, i.e., surface rather than self-luminous. The hues were of equal brightness and saturation. They found the number of coding steps to be somewhat lower than ten, about eight. However, they conceded the discrepancy with the Halsey and Chapanis results probably was due to the greater amount of before-testing practice given the subjects of the earlier study. An analysis of the final phases of their work lead these authors to estimate the number of steps obtainable with comparable practice to be near that reported by the earlier authors. The wide variation in ability to discriminate color has been remarked by other investigators in the field and has implication for selection of operators of colored displays to the extent possible.

McAdam (1942) using the ICI (1931) chromaticity diagram -- a device whose space permits the specification of the full ranged chromaticity -- demonstrated the sensitivity possible in color discriminations. However, his work, as Wright's (1943), was done under optimal conditions, null judgments, and in daylight. In 1954, Halsey and Chapanis also investigated the discriminability possible within the ICI chromaticity diagram space, but under conditions more relevant to our concern. Their procedure required the subjects to select from a large number (171) of simultaneously exposed colored lights varying in wave length and purity, those which matched a standard light placed in the center of the display. This is a situation not unusual in operations. Under these conditions they found a set of eight standard lights which could be matched with 100% accuracy, i.e., no colors were ever confused with two or more of these standards. Several sets of six or seven colors were formed to yield over 97% accuracy. Based partly on this work, Muller, et al (1955) reported the development of a 10-symbol alphabet having a high degree of discriminability, 4% error after 30 minutes of training. Both these investigations used self-luminous colors.

A report by Conover and Kraft (1958), addressed primarily to engineers and equipment design specialists, is based largely on the work of Conover (1959), reviewed above. This report discusses some practical aspects of color coding. These authors place at no more than four the number of colors that can be absolutely discriminated when electrically generated on fast phosphers. They find wide differences among color-normal subjects in ability to distinguish hue, the number varying from 5 or 6 to 16, depending upon the individual tested. In both cases the subjects were asked to identify the stimulus with respect to each dimension in which it varied. In this sense they resemble the studies in multidimensional coding to be described later. Finally, they warn that when target size falls below about 20' of visual angle, color perception tends to degrade, i.e., blues are seen as purples, mauves as grey-greens, and purples as yellows and

and browns. This impairment of color discrimination for small fields, described by Willmer (1944) and Willmer and Wright (1945), has been recently studied by Bishop and Crook (1961). They used targets of subtended visual angles of 10', 21', $1^{\circ}26'$, and $5^{\circ}44'$. Their results are in agreement with Conover -- above 21' they found no significant impairment but degradation appeared for those targets subtending 10' of visual angle. Halsey and Chapanis (1954) used targets of 18' visual angle and found no evidence of degradations in color identification. They speculate that this may be due to the subjects task which involved continuous scanning of the display rather than the fixation of the target; the center of the fovea being relatively less sensitive to color than most of the remaining fovea.

The final two studies to be considered in this section investigated color while varying all three of its dimensions (hue, brightness, and saturation) to facilitate discrimination. Both these studies were concerned with the effect of extended practice. Hanes and Hansen (1960) used surface colors (Munsell color chips) and the subjects made their responses in terms of the Munsell notation. Two different sets of 65 Munsell chips were assembled on the basis of preliminary work and two subjects were trained on each set. All four subjects had reduced their errors to 5% or less within 55 hours of training. An additional subject was trained to respond with color names rather than the Munsell notation. This subject reached 3% error in less than 20 hours.

Bishop and Crook (1961) used self-luminous colors. The steps of the three-color dimensions were independently coded and the subjects used the codes in making their responses. These authors conclude that between 50-70 colors can be absolutely identified with extensive training under laboratory conditions. However, for operational systems, assuming moderate training and favorable working conditions, they recommend thirty colors.

Several fairly firm conclusions may be drawn from these studies on color discriminations. With moderate practice and fairly good working conditions some eight to twelve hues (luminance and purity held constant) can be distinguished. The exact number will depend upon the choice and quality of hues, the ambient conditions, the inclusion of white or non-spectral hues, and other factors. However, under operational requirements, the investigators drop their estimates to 5-8 and with the electronically generated targets of the late fifties, the estimates drop to four. Signals should have a subtended visual angle of no less than 20'. Below this size a deterioration in perception occurs for some hues. However, there is evidence that this degradation may not be so serious for scanned as for fixated signals. About 8% of males are color defective and among the color-normal, a wide difference in ability to discriminate color has been noted. Thus, operator selection will be advantageous where possible. An increase in discrimination can be achieved by varying brightness and purity as well as hue. For operational systems, assuming favorable conditions, a thirty-color code may be possible. Under the most extensive practice (over 50 hours) subjects have been trained to recognize up to 60 colors. The effect of very extended practice on the discrimination of hue is unknown. The conclusions above are formed under the assumption that the discriminations are

made as absolute rather than relative judgments. In those cases where a standard for comparison could be provided the operator, the number of discriminations, of course, would rise sharply. Finally, no single study reviewed here has investigated the discrimination of color as generated on a CRT display.

COLOR CODING AND OPERATOR TASKS

A rather large number of coding dimensions (modalities) have been considered by display designers. Loewe (1963) offers a list constructed by himself and two colleagues of some of the more common modalities and the approximate range of the usable coding levels in each.

Coding Modality	Coding Level
Color	3-10
Size	3
Shape: Alphanumeric and Punctuation	50
Abstract	8-16
Suggestive	200-1000
Positions: Linear	3-5
two-dimensional	4-9
three-dimensional	8-12
Orientation	4-8
Line width	2-3
Number (quantity)	4
Flicker	2-4
Intensity (brightness or grey scale)	2-4
Line length	2-4
Line type (dotted, dashed, etc.)	3-4
Focus of distortions	2
Depth	2-3
Motion	2-10

We have already mentioned the case where one coding dimension is associated with an environmental aspect of interest. The other most frequently investigated of these associations follow:

If several aspects of the environment are associated each with a different coding dimension, the coding is said to be nonredundant and multi-

dimensional. If levels of each of two or more coding dimensions are related to the same levels of a single informational variable, e.g., both numeral and color of a red "8" signifying 800 knots, the code is said to have complete redundancy. A third method codes two or more display variables to the informational variable with one or more of the display variables being coded to a finer breakdown of informational variables than the others. For example, the numeral of a red "8" could mean 800 knots, while the red would place the speed in the range Mach 1 to Mach 2. Coding possibilities, of course, are not exhausted by these three simple cases, but the work covered in this review investigates coding relationships that can be classified under one or the other of these three types.

With some arbitrariness, the whole of the operator task performed with the aid of visual displays may be considered to be made up of a "perceptual" part which is covert and prior to a "response" part, usually an overt act, e.g., pushing a button, speaking, etc. The composition of the former for the more complex tasks found in operational settings is unknown. However, some subtasks have been abstracted from these tasks and labeled "decode", "search", "count", "match", "verify", etc. The first two of these "tasks", decode and search, have been singled out for particular attention because they seem to be present so often as a component and sometimes the principal component of those tasks encountered in operations.

Color Coding for the Decoding Task

The decoding task, as abstracted from the laboratory, requires the operator to identify a designated target. The target may be displayed alone or among other signals. In the latter case the target is designated for the operator by some laboratory strategem which brings his attention to the target with a minimum of search. The search, to the extent that it exists, is for a display position, not the target. Essentially, then, the operator, having learned the code(s), is given a target with visual markings and asked to translate these into operational terms.

A few investigators have studied some of the other "subtasks" mentioned above. Whatever the task, the performance criteria have been some measure of time to complete the task and/or a measure of the accuracy of performance. Because the value of color relative to other coding dimensions is dependent upon the task employed in the investigation, the studies to be considered have been grouped on this basis.

The first group of studies* reviewed, while based essentially on a decoding task, employ a response not requiring the operator to translate the coded stimulus to some "real life" terms, but to make a "simpler" motor or verbal response. This is the familiar task frequently found in operations for billets below the top decision-making level.

*Appendix A contains summaries of studies reviewed, with emphasis on methodological detail. Studies marked with an asterisk are included.

CHAPTER 2 - HUMAN FACTORS

A study by Reed (1951)* is typical of a number of studies involving color coding done prior to 1952. It was designed around a card-sorting task with each card of the deck bearing a single symbol coded on one of two levels for each of four dimensions: hue - red and green; shape - triangle and circle; size - large and small; brilliance - dull and bright. Subjects sorted these two-value codes into two bins for each dimension separately. Sorting on hue and shape proved both faster and more accurate than shape or brilliance alone, but the advantages were small. The sort had a basal time of 0.41 sec/card. Discriminations on hue took 0.08 sec longer; shape 0.10 sec longer; the two others were somewhat slower. Hue and shape sorting also produced fewer errors; hue about 1 percent, size 2 percent, and brilliance 3 percent. These findings foreshadow those of other investigators that color and shape are superior coding devices in speed and accuracy for tasks involving discriminations made while scanning successive signals.

Muller (1955)* used a 10-step color code as one of two coding dimensions, the second being spatial, in an experiment designed partly to "compare the relative compatibility of visual and motor responses to different types of visual stimuli". Motor responses to both codes were made on a 10-finger keyboard (two congruent semicircles corresponding to the natural placement of the fingers) with the keys numbered 1-10. Verbal responses to both codes consisted of announcing the appropriate number into a microphone. The colors, each associated with a number 1 thru 10, were exposed one at a time as patches in the center of the display. The spatial code consisted of ten small lights positioned to correspond to the keyboard positions used for the motor responses.

Each code was tested under both response modes and, because a second purpose of the experiment was the effect of verbalization as a factor affecting transfer from one response to another, each of these four conditions was tested by a group pretrained with the verbal response and a group pretrained on the motor response. Thus, the final design had eight groups undergoing both training and transfer trials.

The significant result of concern to us is that the spatial code was superior to the color code on both training and transfer trials whether coupled with the verbal or the motor response. The results were in terms of both average reaction time per stimulus and information transmitted per second. The average reaction time to a single color patch for the last of the transfer trials was about 1.5 sec, when the response was verbal, and 1.0 sec when the response was motor. The corresponding reaction times to the spatial code was about 0.5 sec lower.

The author cautions that "the inferiority of all responses to the color symbols may be due in part to the fact that absolute discrimination among colors becomes difficult for many people when more than eight or nine symbols of approximately equal brightness are used".

Finally, the particular spatial code used in this experiment, especially when paired with the particular keyboard arrangement that produced the most markedly low scores, would seem to have limited applications.

This experiment brings to light another effect important in the coding of visual displays - there is a critical relationship between the way information is encoded both as stimulus and for response. For example, the motor and verbal responses to the color code gave similar results but motor responses coupled with spatial code gave superior results.

The effect of this interaction, called Stimulus-Response (S-R) compatibility, on performance was further studied by Alluisi and Muller (1956)* who compared seven 10-step visual codes paired with both motor and verbal response tasks under forced and self-pacing conditions. The visual codes were color, an ellipse-axis ratio alphabet, three different inclination codes, the conventional arabic numerals, and a set of arabic numerals derived from an eight-element straight line matrix. The response tasks were similar to those imposed in Muller's (1955) experiment. Under the self-pacing conditions, the rate of information presentation was determined by the subjects - under forced pacing the presentations were at a fixed rate to which the subjects had to accommodate. The symbols forming the coding alphabets appeared on the display one at a time. The results are given in terms of the average information transmission rate.

The color and ellipse-axis ratio codes under the conditions of this experiment were poorest, the numerical codes best, with the inclination codes giving intermediate results. This was true under both response modes and for both pacing conditions. The rate of information transmission for color was only 69% that of the conventional arabic numerals under the self-paced motor response conditions. (The actual rate of information transmission under this condition was 3.97 bits/sec). The inferiority of color to both the numeral codes is of this order of magnitude for the other three conditions - self-paced with verbal response, and force-paced with both motor and verbal responses.

The results of this experiment generally support other findings relative to S-R compatibility. For example, although color was markedly inferior to numerals under the same conditions, under forced-pacing the color code paired with a verbal response is actually superior to the numeral codes coupled to the motor response. The S-R coupling seems of undoubted importance for the read-out task studied, as well as other tasks. For tasks where this coupling is found to be important, an optimum S-R pairing will have to be sought. While at present, prediction of performance for different S-R pairing is not possible, the authors offer two guidelines. They say. . . "relative S-R compatibility tends to approach a maximum when (a) the stimulus and response sets correspond to one another in a direct physical sense, and when (b) the pairings of stimulus and response elements agree with strong population stereotypes, where such stereotypes exist".

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The compounding of dimensions with varying redundancy (completely redundant in two or in three dimensions) to achieve greater accuracy and/or speed of discrimination was investigated by Eriksen and Hake (1955)*. They coded twenty levels in each of the individual stimulus dimensions - hue, brightness, and size (area) to provide three separate sets of stimulus material. Each of the levels corresponded to one of the numbers 1-20. They then prepared three additional sets of twenty, in which each dimension was paired with each of the other two and a seventh set in which all three dimensions were present. They tested each of these seven sets by getting subjects to verbally respond by giving an absolute judgment of the number (1-20) corresponding to the stimulus level. The results were treated in terms of information theory using a method developed by Garner and Hake (1951). In this the amount of information transmitted by a series of stimuli along a dimension(s) is interpretable as the number of stimuli that can be selected from this dimension(s) to yield perfect discrimination using absolute judgments. They found that hue, as a single dimension yielded 3.45 discriminable steps, size - 7.19 steps; and brightness - 5.06 steps. The discrimination was considerably better for the three double compounds and best of all for triple compound for which 17.28 steps were discriminable. The average (in percent) correct judgment showed the same superiority of compounded dimensions over simple ones. On this latter measure, although hue as a simple dimension was better than either size or brightness, it yielded only 53.4% correct judgments, but when combined with both brightness and size the percent of correct judgments reached 96.5%.

Color, when compounded with brightness and size in a completely redundant way, resulted in a very large improvement in the accuracy of discrimination for the perceptual task imposed and the most of response used.

The limited number of usable steps within most coding dimensions led to suggestions for enlarging a code by increasing its dimensionality, i.e., combining dimensions to form a single coding alphabet. Two experiments by Anderson and Fitts (1958)*, the second an extension of the first, throws some light on this method of code enlargement. Color served as one of two compounded dimensions, numerals the other, with combinations of these two forming a third. For the second experiment, the elements of the single dimensioned alphabets consisted of nine digits and nine color patches; the enlarged alphabet was made up of the 81 possible combinations of these numerals superimposed on the color patches. These alphabets were tachistoscopically presented (0.1 sec exposure) with message length (number of symbols) and number of elements (steps in code) varied to produce different amounts of transmitted information. The results of the two experiments were consistent - the use of the color-numeric code was significantly superior to either color or numerals used alone. Numerals, a form of shape-coding, permitted a higher maximum information transmission than did color.

Specifically, the multidimensional code transmitted up to 13.6 bits per exposure, the numerals alone transmitted a maximum of 14.9 bits and color alone 10.4 bits. The authors suggest that this type of coding may have practical applications for displays where the total display area is

limited or when it is desired to make the most advantageous use of central vision.

For the group of studies reviewed above, color, as a means of coding information, did not show any consistent superiority over other coding methods. In fact, for many situations amenable to unidimensional non-redundant coding, where the task additionally is of the read-out or decoding type, some other coding device such as the Muller-Alluisi spatial arrangement may prove definitely superior. Also, color does not seem to surpass in speed and accuracy of discrimination either numerals or geometric shape, although in this regard it seems superior to brightness and size. However, used with other coding methods it offers possibilities for either increasing the discriminability or the size of a coding alphabet.

Color Coding for the Search Task

The following studies have all been based on search type tasks described earlier. It is often desirable for the user(s) of a complex visual display to locate quickly and accurately the members of a particular subclass from a field whose members are coded along a single dimension. A possible way of enhancing the speed and reliability of the search is to impose an additional code from a different dimension on the critical subclass. Following the classification given earlier, this is partially redundant coding since the second code is not essential to finding the target. It is this question, the extent to which redundant coding facilitates visual search, that underlie most of the studies in this group.

Eriksen (1952)* presented his subjects with a synthetic display consisting of a 49-cell matrix; one symbol per cell. The task was to locate six targets among 42 symbols and 7 blanks. Eriksen coded his targets (7 levels each of four dimensions - hue, size, shape, brightness) both on the four dimensions individually and on the ten possible compound combinations. He found that in a homogeneous field, one in which the objects varied in only one dimension (hue), a target defined by one level of that dimension (red) could be located as rapidly as a multiple-defined target in a field varying in several dimensions.

In a later study using the same methods (1953)* investigated single-defined targets in a field varying in several dimensions. By comparing data from the two experiments, Eriksen came to the conclusion that with comparable field heterogeneity, multiple-defined targets could be more rapidly located than those single-defined. For both these studies, targets defined on only the hue dimension in a homogeneous field were located more rapidly than those single-defined on each of the other three dimensions for similar fields. Moreover, for multiple-defined targets, the presence of hue in the combination had a tendency to produce shorter location times.

Green, McGill and Jenkins (1953)* reported a series of experiments which significantly involved the use of color. The task was the location

of targets among varying numbers of signals. Size (large and small) and color (yellow and blue) were used to code the signals, each of which was also uniquely identifiable by a particular number. The display was a large table top on which the signals (chips) could be moved about. "Cluttered" versus "uncluttered" displays were investigated; the former having a green grid, miscellaneous red markings and color-size coded signals; the latter consisting of numbers on a homogeneous background. In both cases the targets were identifiable by number only, and that search time was roughly the same for the two displays. Next, under varying conditions of target density, the subjects were told the color-size coding of the target subclass, in addition to the numerical identification. The speed in which these multiple-defined targets were found was nearly proportional to the number of signals in the target class and largely independent of the total number of signals on the display. This finding was further tested in an experiment for which only the color of the target subclass was specified in addition to its numerical identifier. The previous results were confirmed. The authors state, "...the results suggest that search time decreases if the elements are separated into categories by some visual code such as color, so that only numbers of a certain category may be considered as alternatives".

Green and Anderson (1956)* sought to confirm, with two experiments, Green, et. al's earlier findings (1953) and to investigate those of Eriksen (1952-53) relative to the interaction between search time and degree of heterogeneity of the visual field. The subjects in both experiments looked at a matrix of 60 cells into which two-digit numbers could be placed. The design of these experiments permitted an evaluation of the presence of colors other than that of the target subgroups for its effect on searchers who were either aware or unaware of the subgroup's color. The results of these experiments are a substantial verification of the earlier findings that a partially redundant color code is useful. The search time, when the searcher is aware of the target subgroup color, depends primarily on the number of signals in the subgroup. A minor effect for those unaware of the color was also found. For these searchers, search time was somewhat longer on multicolored than on single-colored displays. If this conclusion is correct, it has implications particularly for multicolored displays with more than one use or user. The advantages gained from the use of the code by an aware user might be more than offset if: (1) the code were only infrequently relevant to the display use (task); (2) the code was irrelevant for several other users of the display; (3) the code was irrelevant to some very critical uses. This line of investigation (the effect of color coding target subgroups on visual search time) has recently been furthered by Smith (1962)* who modified the Green and Anderson (1956) experiment principally to include a greater range of signal density, 20-100, and color levels, 1-5. The results he obtained largely substantiated those of Green and Anderson. When more than one color is used and the target's color is known, the search time is markedly shorter than if its color is unknown. For a series of displays with 20 signals in the target's subgroup and an increasing number of signals of a nonrelevant color, the target, when its color was known, was found with only a slight increase in search time. With only 20 signals all of the same color search time was about 4 sec,

while with 100 signals (80 of nonrelevant color) search time had only increased about one sec. Smith points out that "if color permitted absolute visual separability between classes of displayed items the average search time for these five-color displays would be only one-fifth as great as when it is unknown". His data shows a lengthening search time for targets of unknown color over those of known color when the percent of signals in the target class is a constant 20%. The targets of known color are found in roughly one-half the time at a display density of 20, and in less than one-third the time for a display density of 100.

There is one major difference between Smith's results and those of Green and Anderson. Green and Anderson found that nonrelevant colors produced a decrement when the target color is known and, as we have noted, Smith did not find this decrement. This possible disadvantage of redundant color coding should be resolved.

An experiment reported by Muller, et al (1955)* compared the efficiency (speed and accurace) of a 12-step color code with an inclination or clock code consisting of a circle with a radius line positioned at one of 12 inclinations. The two coding dimensions were investigated separately, i.e., the display presented signals coded on only one dimension at a time. While the coding scheme was simple, the search task was perceptually somewhat more complex than any so far reviewed. The subjects were asked to search for and report any "conflicts", i.e., any groups of two or more signals bearing the same code, on a display with a signal density varying from two to twelve. The color code proved markedly superior to the inclination code for both time to process the display and errors made. An analysis of the data from this experiment supported the hypothesis that, at low signal densities (up to eight or ten) the time to process information in check-reading tasks involved "sequential comparisons of sub-parts of the display". The simplest operations consistent with this hypothesis seemed to be the discrimination and comparison by operators of successive pairs of targets to determine whether similarity did or did not exist. The time to process the display when plotted as a function of the number of target pairs showed a linear increase in time required up to 10 signals (45 pairs) for color and eight signals (28 pairs) for the inclination code. Beyond these points the processing is slower suggesting a different or additional processing component. It required about 5 sec to process an eight signal color display and about 11 sec to process the inclination code on a display of the same density. For higher display densities the speed advantage for color seemed to grow; it required about 12 sec to process 12 color signals and over 30 sec for the inclination code.

In a further experiment Muller, et al (1955, p 103)* investigated these same two coding dimensions using a tachistoscopic (0.1 sec) presentation rather than a response-terminated exposure and, in addition to the "conflict" reporting task of the earlier experiment, imposed an additional task requiring the subjects to report all signals on the display. The two dimensions were again tested separately. Target densities did not exceed eight. Under these conditions and with somewhat different performance measures than for the first experiment, no pronounced differences were

found between coding dimensions. However, for the "conflict" reporting task, some superiority was found for the time-limited (tachistoscopic) presentation over the response-terminated condition of the first experiment. These different results led to an additional session using only the color code and reverting to the response-terminated exposure. The results for this session agreed with the earlier findings for the "conflict" reporting task. The research thus far reviewed has been concerned with coding symbols to one dimension at a time or with aiding one coding dimension by adding a second in a redundant manner.

Promisel (1961)* used 7 levels each of color and shape to code targets for a search task where, for one experimental condition, the symbols were coded to two dimensions independently, i.e., nonredundantly. Under this condition, called double-coded, the signals competing with the target (a red circle) offered competition equally divided between color and shape. That is, half the competing targets were red and of some shape other than circular, half were circles of some hue other than red, but, neither dimension alone served to identify the target, and thus both were necessary. For the other conditions (partially redundant) the target had competition in only the color dimension, that is, there were other red signals but no other circles. In this condition the circle was sufficient to identify the target. Although somewhat faster location times resulted under the double-coding condition, confounding of the two dimensions in the design made a straight-forward analysis of their comparative search times and errors impossible. However, there was some indication in the data that, for those targets showing the shorter search time and fewer errors, hue was the critical factor.

Search times for varying target numbers, 0-8, and competing signal numbers, 0-32, and a signal density of 40, ranged from approximately 8 to 10 sec for the partially redundant condition and about 1 sec faster for the double-coded condition. The number of errors was low under both conditions and the difference was not significant.

This group of experiments, all having a large search factor, give strong support to two conclusions. First, for tasks requiring rapid and accurate scanning of multi-signal displays, the "set" for color acts as a filter which allows operators to pass the nonrelevant signals with only minimal attention. This permits the searcher with a knowledge of the code to process the display with a rapidity and accuracy more nearly dependent upon the number of targets in the category of interest than upon the total number of signals displayed. The effect of ancillary information and background material can also be greatly minimized by color coding. Second, compared with some more common coding dimensions such as shape, size, brightness, and an inclination code color gave evidence of superior filtering qualities, in the above sense, and may prove unsurpassed in this respect when tested against a fuller range of competing coding methods.

Multi-Task Experiments

The results reviewed thus far have, with one exception, been based on

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either one of two tasks, "decode" or "search". Three recent studies investigate the effect of color coding for different tasks. Hitt (1961)* abstracted five tasks from an unidentified system and gave them descriptive labels; "locating", "counting", "comparing", "verifying" and "identifying". The first and last of these, from Hitt's task descriptions, appear to be similar to the "search" and "decode" tasks with which we are already familiar. Hitt selected five 8-step codes to be compared on these tasks. In addition to color they were: conventional arabic numerals, upper case letters, geometric shapes, and an inclination code. The response task was a pencil-and-paper test to be completed, while the display, containing symbol densities of 40 to 120 and a simple coding dimension, was exposed for examination. Hitt found that, in general, colors and numbers were superior in terms of his measure, "number of correct responses per minute". The number code was slightly, but not significantly, superior to color for the "counting", "comparing", and "verifying" tasks, while color held a comparable advantage over numerals for the "locating" task. The identifying tasks produced the one clear difference; numerals were distinctly superior to color and the other codes.

Because of the importance of the perceptual task for performance, Hitt sought to uncover the more basic factors underlying the five tasks by factor analysis of the task intercorrelations (Thurstone's 1947 centroid method). This analysis revealed two basic factors which were labeled "search" and "recognize". The "locating" task was heavily weighted with the first of these factors and lightly weighted with the second, while the factor loadings for the "identifying" task were the reverse of this. Both factors contributed substantially to the other three tasks, with "search" contributing high loadings on "verifying" and "counting". This finding supports and helps explain the discrepant results obtained with different coding dimensions, particularly color and shape, for the two tasks which have dominated the earlier work.

Christner and Ray (1961)* followed Hitt with an experiment which was in many respects similar and to an extent confirmatory. They used five tasks bearing the same descriptive titles and of apparently similar constructions. The response task was, like Hitt's, a questionnaire, sections of which were to be completed while the display was exposed. But the display was more "realistic". Whereas Hitt had used a 5x8 matrix with symbols distributed in the cells, Christner and Ray used a modification of a map on which the irregular boundaries were preserved and color coded and the other map details (cities, rivers, etc.) were omitted. Moreover, Christner and Ray used only three 8-step codes; numerals similar to those used by Hitt, color and geometric shape, both somewhat different from those used by Hitt. The results show some differences from Hitt's, the most important of which is the clear superiority of color over the other two codes for both the "locating" and "counting" tasks. The numeral code was, as for Hitt, superior to the other codes on the "identifying" task. There were no differences between codes for either the "comparing" or "verifying" tasks.

Christner and Ray, following Hitt, sought by factor analysis to find factors basic to the five tasks they employed. Their analysis, too, un-

covered a "search" and a "recognition" factor plus one which was identified as "remembering". In the main the distribution of loadings for these factors did not differ substantially from Hitt's: "identifying" (decoding) is high on "recognition", low on "search"; locating, counting and verifying are, to the contrary, high on "search" and low on "recognition". "Comparing" differs from Hitt's analysis, being low on both, but has a moderate loading of a "remembering" factor. The display difference is only one of the dissimilarities which could account for these differences in results. In the evaluation of both these experiments it must be remembered that the performance measures incorporate and hence reflect the time and skills required to complete the response task, i.e., the rather cumbersome pencil-and-paper test which had to be completed during each display exposure. Christner and Ray recommend color coding for those "locating" and "counting" tasks which they associate with the search factor, and numerals for tasks like their "identifying"task which seem largely based on a recognition factor.

For many uses it would be desirable to portray symbolically a complex tactical situation on a single display. This would reduce the time and error inherent in correlating the information from several displays with, usually, several different formats. But the great volume of information needed to portray such complex situations leads to increased symbol density and/or symbol modifications, both detrimental to the speed and accuracy of display processing. As a solution to this problem, it has been suggested that several informational dimensions be encoded to the same set of symbols by means of several additional independent visual coding dimensions, independent in the sense that each visual code is related to only one of the environmental dimensions.

Newman and Davis (1961)* investigated the effectiveness of this type of multi-dimensional, nonredundant display coding. Their encoded symbols were 36 modifications of nine basic geometric figures similar to a set developed for the Naval Tactical Data System. The additional coding dimensions were: color and flashing rate, both at three levels; and brightness, at two levels. They employed twelve conditions of encoding differing in the level at which the four dimensions were fixed. Condition "G", for example, consisted of twelve geometric symbols encoded for three levels of color while holding brightness and flashing rate constant at one level. However, irrespective of the number (3 to 36) of geometric symbols on the displays, there were always 36 different symbolic "items" present, i.e., the quantity of information was held constant. Two tasks were employed, essentially "search" and "recognition". For the latter the coding dimensions were related to a "vocabulary" drawn from familiar environmental variables, e.g., fuel state, aircraft type, etc. Both tasks were tested with and without symbol overlap.

Newman and Davis' results suggest that, for either task, if speed of response is to be emphasized, the symbol-plus-color conditions will yield the best results and those conditions combining levels of all coding dimensions were poorest. Fewer differences were found between the conditions

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for errors on both tasks. The authors' conclusions are that "...for tasks involving rapid response to a stimulus, such as detecting and/or tracking assignments, the encoding dimension(s) of the information requiring prompt action is of great importance. On the other hand, the analysis of variance for errors shows that when the primary criterion in a task is accuracy, as it is in an identification position, then the encoding dimension would not seem to exert too great an influence except when it is more than likely that spatial overlap of informational items will occur".

It is interesting to notice that the decrement in performance in this study occurred when other coding dimensions were added to the favored combination despite the very small number of steps for these added dimensions. Of course, different additional dimensions might give different results. The performance with three flashing rates prompted the authors to warn against their use. Finally, it must be pointed out that assuming a falling-off of performance with an increase in nonredundant coding dimensions beyond the symbol-plus-color schemes, the value of adding an independent dimension to represent a very critical informational variable might offset the loss of speed and/or accuracy incurred.

The three studies of this section are based on several subtasks abstracted from the more complex activities of some actual operations. Both searching (locating) and decoding (identifying) are among these abstracted tasks. Compared to other coding methods, color coding resulted in superior performance for those tasks associated with searching. For those tasks highly dependent upon decoding color was inferior to numerals, and no better than other coding methods.

Subsequent statistical analysis seeking to uncover the more basic factors accounting for the results obtained with these various tasks yield two factors identified as "search" and "recognition" (decoding). These two, with perhaps a third labeled "remembering" are found to influence most highly a comparing task and seem to be the principal contributors, in varying amounts to the several tasks.

CHAPTER 2 - HUMAN FACTORS

SUMMARY AND CONCLUSIONS ON HUMAN FACTORS

One important concern with the use of color as a coding dimension in naval combat information center displays is the ambient conditions which are likely to prevail. Evidence shows that the discriminability of color differences is affected by the surrounding physical conditions as well as the number of steps to be discriminated. It is probable that some naval command and control spaces can provide conditions which permit an 8-10 step color code with reliability approaching 100%. This 8-10 code consists of discreet steps along the color (hue) dimension with a constant level of brightness or with brightness and/or saturation varied at each step to enhance the color difference, and assumes a fairly stable color reproduction. If brightness is used as an additional coding dimension, it will tend to reduce the reliability of the color code, and if there is less than optimal color reproduction, the number of steps in the code may have to be reduced to three or four.

It is possible that three or four reliably discriminated steps may provide an ample number of categories for the necessary operational parameters, but if more steps are absolutely necessary there is evidence that with training and/or personnel selection the number of discriminable steps could be expanded. The results on training were obtained with varying lengths of time, but these were not extensive. The evidence of large differences among subjects in the ability to discriminate color supports the statement on personnel selection. All the above discussion assumes subjects with normal color vision and visual acuity.

Eight to ten steps may seem like a small color coding alphabet, but only two other coding dimensions, alpha-numeric and geometric symbols, both shape codes, provide more steps. Other common coding dimensions are size, brightness, flashing rate, various inclinations, clock and configuration codes, and a spatial code.

Another important consideration about color as a coding dimension is the task to be performed. In the earlier studies on color coding, the tasks could be grouped roughly as "decoding" and "searching". These are simplified abstractions derived from concrete operations. For the search task, there was strong evidence that color offered a distinct advantage. Specifically, color-coded objects can be found with a marked reduction in search time and with no loss and perhaps some gain in accuracy. For the decoding task, however, there was no evidence of a consistent advantage for color. In fact, color was markedly inferior to a spatial code for a read-out task and transmitted less information than numbers during brief exposures, but did give better results than brightness or size. A few recent investigations have been designed to take account of the task variable. Some studied complex operations which were factor analyzed into several different tasks, including searching and decoding. These studies showed that a number code is superior for decoding, while the superiority of color clearly emerges as the tasks are increasingly weighted with the search factor. Color coding, therefore, seems to hold greatest promise for those tasks

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having a significant search component.

Many of the functions performed in naval operations are similar to or involve searching and decoding tasks. Tasks described as counting and matching are similar to search tasks, while those described as read-out or sorting are similar to decoding. Some functions are relatively simple while some are complex. The detecting of new targets is an example of a relatively simple task heavily weighted with search. For such tasks, the color coding of a highly important information variable, which might be in storage in the system, such as, friend-foe, detected, or surface-subsurface-air, in a multi-dimensional and nonredundant way could prove to be most helpful to the operator (detector-tracker). Sub-categories could also be color coded in a redundant way to permit the operator to sort on sub-categories, and this could be done with a small number of coding steps.

The important activity typically associated with higher level decision making, such as, threat evaluation, weapons assignment, and tactical planning, are examples of complex functions which are not easily subdivided into tasks. In these functions, the decision maker has more freedom to structure these acitvities to his own needs and to the demands of the situation. His time and attention must be shared by other activities, such as discussions, consultation of other sources of information, receipt and issuance of commands. The higher the decision making level the more urgent will be the demands of other responsibilities. For such activities, the visual display has become indispensable as an aid for keeping track of the dynamic tactical situation. The decision maker, in his repeated returns to the display, must quickly bring his comprehension up to date, and it is probable that this process of reorientation has a large search component. While searching a display may not claim a large portion of the top level decision maker's time, his search time should be reduced as much as possible because of the importance of other components and responsibilities.

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CHAPTER 3
SURVEY OF STATE OF THE ART IN COLOR CATHODE RAY TUBES

This survey describes briefly eleven different cathode ray tubes, pointing out their most important features and discussing the important display parameters of color tubes, namely: (1) range of available color practically attainable; (2) the closely interrelated parameters, brightness-contrast-visibility; (3) resolution (available versus required) and, (4) persistence and storage requirements. It concludes with a discussion of the different problems encountered where display of raw surveillance information is required. Because of the marked limitations in the persistence of available colored phosphors, a storage tube is required, either integral with the color tube or a separate tube.

The tubes discussed here are in various stages of development and production. Only the RCA TV tube and the Chromapix (chromatron) can be considered as available off the shelf.

There are several ways of classifying color tubes. The following table lists the important characteristics of eleven tubes. A number of the tubes operate on a basic principle of separating the colored phosphor in incremental bits arranged in the plane of the display in various manners, such as dots or stripes, and depend upon the eye (by reason of its limited resolution and its ability to integrate over space) to combine these increments into the desired colors. Others produce color by arranging the phosphors in layers which are sequentially excited by varying the penetration of the electron beam and depend upon the eye's ability to integrate over time. Where more than one gun is used, the usual problems of keystoning and its correction are introduced.

The color generating cathode ray tubes presented in this tabulation were selected to illustrate the more important operating principles of the various tubes.

Full description of these tubes is not presented here. Some details will be found in the discussion of the parameters considered most important to color coding and greater detail may be found in the references. None of these tubes was designed specifically for color coded displays for command and control use. The following comments are intended to clarify the meaning of the column headings in the chart. Conventional beam control, as used here, means merely that the electron beam is deflected toward a given point on the screen and is focused to a small cross-section at this point by the usual electrostatic or electromagnetic means and is intensity-modulated. The generation of more than one color on the viewing screen requires something more than this. Thus, only two of the tubes selected for this chart have "conventional" control of the electron beam. One of these is the Prismachrome or Geer tube. The basic principle of this tube is the geometric orientation of the phosphors with respect to the guns so that each gun illuminates only the desired phosphor. The two-color Prismachrome utilizes two guns each offset 45° from the main axis of the tube and a glass viewing screen grooved to form parallel prismatic ridges. The surfaces of the grooves facing one gun are coated with red

Table 1
Characteristics of Eleven Types of Color Cathode Ray Tubes

COLOR CATHODE RAY TUBES Selected to represent operating principles	PHOSPHOR ARRANGEMENT			BEAM CONTROL					OTHER OPERATING REQUIREMENTS						ESTIMATE OF CHARACTERISTICS		
	Dots	Stripes	Layers	Conventional	Beam Indexing	Beam Bending	Controlled Acceleration	Post Deflection Focus and Acceleration	Number of Writing Guns	Storage Grid, Flood Gun System	Shadow Mask	Special Viewing Plate	Bombardment Induced Conductivity	Multitube and Optics	Range for color coding (number of discriminable steps)	Brightness (ft Lamberts)	Resolution - Lines per inch
Prismachrome		x		x					2			x			3	55	55
Sunflower			x	x					3			x		x	4	50	400
RCA TV Tube	x								3		x				4	25	34
Chromatron		x						x	1						4	50	34
Penetron (thin layer)			x				x		1						4	30	400
Penetron (transparent)			x				x		1			x			4	2	400
Apple Tube (Philco)		x			x				1						4	50	34
Goodman Tube		x			x				1						4	50	34
Aiken Flat Tube			x			x			2			x			3	60	400
Hughes Storage Tube	x							x	1	x			x		2	150	55
RCA Storage Tube			x				x	x	2	x			x		4	100	55

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phosphor and those facing the other gun are coated with green phosphor. Intensification of each electron beam, independently, will produce the associated color, red or green. Intensification of both beams simultaneously will produce the additive combination (yellow) if both beams are directed to the same spot on the tube face. With other special face plates, tubes with seven guns could be constructed to produce six colors plus white. These tubes are bulky but comparatively rugged. The other tube using "conventional" beam control is listed in the chart as Sunflower. Actually, this is two or more tubes, each with different color phosphor and a special optical system to superimpose the individual color spots on a viewing screen. Keystone correction is provided by the optical system.

The other tubes in the chart require extra beam control in one way or another to produce a multicolor display. The RCA TV tube, often called the shadow mask tube, is so designated because a thin perforated mask is positioned in the path of the electron beam in front of the phosphored view plate. This tube utilizes three guns, spaced 120° apart around the main axis of the tube, and a view plate on which red, green and blue phosphor dots are deposited in small triangular groups. The shadow mask is aligned to provide each trio of dots with an associated perforation. In operation, the beams from the three guns are magnetically controlled to converge at a certain hole of the mask for a given set of deflection voltages. The angle at which each beam strikes a particular hole determines the phosphor dot excited. The shadow mask and phosphor dots are so oriented that each gun can strike phosphor dots of only one color, regardless of which part of the view plate is being scanned. Each gun is assigned to one primary color. The color developed at any aperture depends on the amount of beam current emitted by the three guns as the beams pass that aperture. Thus, numerous colors can be produced by mixing the three primary colors. The shadow mask tube is reported to be sensitive to slight variations in the earth's magnetic field. Two-and three color Chromatrons (Lawrence tube) have been built. The three-color tube employs thin parallel stripes of red, green, and blue phosphors arranged on the view plate in an alternating red-green-blue-green pattern. A wire grid system is established parallel and close to these stripes so that each blue and red stripe is shielded by a grid wire. All wires shielding one color are connected together so that two sets of grids are formed. Varying the voltages on the two sets of grids gives an extra "last minute" deflection to the electron beam from a single gun in the space between the grids and the stripes and selects the color. When the voltages on the grids are of proper magnitude and equal, the unshielded green phosphor stripe is excited. When one grid wire set is positive and the other negative, the electron beam bends around the positive grid wires and strikes the phosphor beneath. Proper programming of the grid voltages causes excitation of any phosphor or group of phosphors. A voltage between the grid wires and the screen results in acceleration and focusing of the beam (post deflection focusing). Thus, extra deflection, focusing, and acceleration of the beam occur near the end of the beam path. The Penetron (Transylume) cathode ray tubes have color phosphor deposited on the viewing screens in thin layers. The layer(s) closer to the viewed surface of the screen are excited in response to higher accelerating voltages than the layer closer to the gun, so that color selection is accomplished by controlled acceleration of the electron beam. The difference in the accelerating voltages for successive layers of phosphor is of the order

of 4 or 5 kilovolts. In order to achieve a dot sequential multicolor display, the accelerating voltages applied to the beam must be modulated as the beam scans the screen and deflection control must be varied simultaneously to neutralize the beam "stiffening" which results from greater acceleration. Frame sequential programming could be used to reduce the modulation rate or multiple guns (one for each color) with independent beam deflection and acceleration control might be developed. The Penetron is a comparatively rugged tube. When transparent phosphors are used with this tube, a special viewing plate is required to withstand the high temperatures involved in processing the phosphors.

Philco has developed a color CRT called the Apple Tube in which three primary color phosphors are deposited in narrow vertical stripes on the tube face. For each three-color group of phosphor stripes, there is a special additional stripe which is used for precisely locating (indexing) the writing beam. Two beams are used: one for writing and one for developing the indexing signal. The two beams are generated by the same gun and are precisely oriented with respect to each other so that the beams track each other. As the two beams scan horizontally, the indexing beam generates a signal which is used to synchronize the intensification of the writing beam in accordance with the desired pattern.

The Goodman tube is also a beam indexing CRT in which the screen is made up of narrow vertical stripes and is scanned horizontally. Instead of a special indexing strip between groups of color stripes, however, the first color stripe also contains a phosphor which emits invisible radiation. In operation the electron beam progresses across the screen and strikes the first phosphor stripe which radiates a short burst of energy (the indexing signal). This signal is picked up by a scintillator and is converted to a voltage pulse which in turn causes the beam to be intensified as it passes over the appropriate color stripe(s) in the next group. Color selection is made by delaying the time of intensification of the beam by the proper amount.

The Aiken flat tube was selected for inclusion in the chart to represent the principle of "beam bending". This term is used rather than deflection to indicate that the beam is made to turn 90° corners by changing the potential on two or more of the row of deflection plates near which it is passing. The two-color, two-gun Aiken tube envelope is rectangular in shape and only a few inches thick. The viewing screen is a thin glass plate which has one color phosphor on one side and another color on the other side. One gun is assigned to each side. Control of the beam impact point is accomplished by sequentially varying the potential on the various deflection plates. Selection of either color is accomplished by intensifying the appropriate beam. Three-color Aiken tubes have been considered using a Prismachrome type view plate and three guns. The color storage tubes (Hughes and RCA) write the desired pattern on a storage grid rather than directly on the viewing screen. A writing gun is used for this purpose. A selective erase gun is also used. These two tubes are described in greater detail in the discussion of persistence.

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CATHODE RAY TUBE PARAMETER CONSIDERATIONS

Most of the Experiments which demonstrate the superiority of color as a coding dimension have been carried out under "laboratory" conditions. When comparing color coded displays to alphanumeric, suggestive or abstract shape coded displays, the laboratory displays are at once complete, concise, easily seen and free of noise, clutter, and flicker. Colors are bright and of high purity and stability. Shapes are distinct and legible. Obviously, a coded display using Munsell colored paper cut-outs pasted on cardboard (the usual experimental display) and depicting a real situation is not practical aboard ship despite the high quality and great variety of colors.

Technical problems in electronic state-of-the-art devices preclude the production of color displays of the quality of Munsell paper cut-out displays. Although electronic devices are available to produce the required color displays in real time, the quality of the display produced is degraded because of presently unsurmounted, interrelated problems in range (number of colors used in the color code), brightness/contrast/visibility, resolution, persistence, etc., depending upon the design of the device.

RANGE (Number of Colors)

The best information available is that the range of a color code must be reduced from about eight equally discriminable colors for Munsell surface color displays to no more than four for electronically (CRT) generated color displays if nearly perfect decoding is required. This reduction appears to be necessary because (1) in some devices the eye is depended upon to mix the red, green, and blue "primary" colors and to perceive them as magenta, yellow and cyan, (2) the resolving capability of the eye in terms of lines per inch is better than the resolution obtainable with available dot cluster and stripe color screens, (3) color perception is not constant but changes with adaptation of the eye to varying light levels and is influenced by other colors in the visual field and by previous color fixation, (4) lack of uniformity and stability in exciting the phosphors of the screen (because of CRT construction and control circuit problems) results in lack of uniformity and stability of the precise color brightness, hue, and saturation emitted by the phosphors.

Further reduction of range may be necessary if the individual "spots" of the color coded display subtend a visual angle of 20 minutes or less. For instance, if a spot one-tenth of an inch in diameter is viewed from a greater distance than 16 inches, normal color vision may degrade to tritanopic-like vision. One-tenth of an inch is rather large for a spot size on a ten-inch screen. It is approximately the minimum size for an alphanumeric character in this usage but is more than ten times as large as necessary for position marking. The literature is insufficiently complete to make the determination needed here, but it is known that when colors are produced as small sources (subtending a visual angle of less than about 20 minutes) and are viewed by direct fixation, blues may be perceived as blue-green, mauve and gray-green as green, and purple as yellow or brown. Thus, it would seem that a decision-

maker who searched his CRT display and found the information he was looking for encoded in color, even though the color was blue or contained blue (such as purple), would be able to decode without error so long as he did not fix his gaze upon that spot. It would also seem reasonable to assume that if no blue-emitting phosphor were used on the screen, no tritanopic-like effects would be possible. On the other hand, greater range may become feasible with the further development and discovery of phosphors for color CRT's and with better control of the devices. Recent reports state that the latest version of the transparent phosphor "Transylume" (Penetron) CRT is capable of 3000 line pair resolution, daylight visibility and full color range. Other CRTs using the same (medium-short persistence) phosphors, arranged in dots or stripes rather than layers, may be capable of the same range with greater brightness but with less resolution.

While it is necessary that a full range of colors be available to reproduce scenes in "living color" on the home TV receiver, the full range may not be necessary for a color coded military display. Depending upon what use is to be made of the color code, a much restricted range might be adequate or even preferred. Consider the use of color to code the "targets" of a radar indicator display into the all-important military categories -- foe, neutral, and friend. These categories are of interest to all hands, especially to members of the CIC and command and control teams. Because color coding has found application in many everyday systems (red meaning stop, danger or bad; yellow meaning caution or normal; and green meaning go, safe or good) only a little orientation would enable almost anyone to symbolize red, yellow and green as foe, neutral, and friend, respectively. Thus, near perfect decoding could be expected even in tense situations. As restricted as the electronically generated color code may be at present, it compares favorably with the range of most other coding modalities, such as size, flicker rate, brightness and motion, and, if properly used, is very effective.

BRIGHTNESS/CONTRAST/VISIBILITY

The light output or brightness of a small area of a CRT screen is directly related to the energy input (electron beam intensity) to that area, the efficiency with which the phosphor converts this energy to light, and the "efficiency" with which the light is directed toward and transmitted to the viewing surface of the tube, provided that the capabilities of the phosphor to convert and dissipate the energy are not exceeded. Thus, in the four-inch RCA 6866 direct view storage tube where the monochrome phosphor layer is "continuously" excited by virtue of a storage mesh and flood gun, "written" areas may have a brightness of 1750 foot-lamberts which does not deteriorate for 10 seconds after writing has ceased. This brightness has been adjudged by some as adequate for "daylight" viewing. Except for storage tubes, however, the written areas of the screens of most color CRTs are not continuously excited, but are reintensified at regular intervals for very brief periods by the beam. For example, the RCA shadow mask tube, 21AXP22-A, used in color TV receivers obtains a white light (in a centered five-inch circle) brightness of 20 foot-lamberts with three

electron beams of more than 400 microamperes each and with accelerating voltages of 25,000 volts. The screen of this tube is made up of triangular groups of phosphor dots--three dots per group; one each of red, blue, and green emitting phosphor. Group centers are approximately 0.03 of an inch apart. Three electron beams, one assigned to each color, converge and traverse the rows of dot-trios at "writing" speed of approximately 150,000 inches per second. Thus, each phosphor dot of each trio is reintensified (in a still picture) every 33 milliseconds during approximately one-third of a microsecond. The short length of time which each phosphor dot is exposed to the energy of the beam and the fact that only about 15% of the beam energy gets past the shadow mask and strikes the phosphor, account in part for the low light output. Aluminization of the screen reduces the back-scatter loss of light, but the filterglass face plate absorbs 23% of the light in the direction of the viewer and the protective window, necessary to avoid the hazards of X-ray radiation and implosion, absorbs about 39% of the remainder. The 20 ft-lamberts of nonflickering brightness, if available on a cleaned-up CRT display, would be highly preferable to the flash and fade spots of a conventional radar indicator and the much subdued or very special lighting which has been characteristic of CIC, even without color coding. Provided that specular reflections were avoided and sufficient contrast maintained, enough lighting could be provided so that ancillary information displays and equipment in the space would be visible. With 300 ft-lamberts brightness, a color CRT display is said to be visible in a normally lighted room. This brightness could be attained with a shadow mask tube for a limited number of spots with "jump" scanning (and its complications) or with a three gun Chromatron recently developed. The new tube circumvents the problems in beam switching which the single gun Chromatorn had (by using three beams) and improves contrast by having black stripes between the red, green, and blue phosphor stripes of the screen. The 300 ft-lambert brightness is obtained by virtue of the fact that approximately 85% of the cross-section of the beams strike their respective phosphors and that time sharing of the beam is not required. The problems of beam convergence and registration, inherent to all CRTs with a gun for each primary color, have not been completely circumvented.

Brightness has been sought as a means of imparting good visibility to the information bearing symbols of CRT displays used in spaces where the ambient lighting is sufficient, say, to read a printed page. Symbol visibility is principally determined by the contrast between the symbol and its background. Where there is ambient illumination, the reflection of this from the relatively opaque conventional and fine-grained, thin layer CRT phosphors raises the level of brightness of the symbol's immediate background and therefore requires additional light energy at the symbol to achieve contrast. Also some phosphors are mildly excited by visible light. As the ambient light rises, the reflectance due to ambient light rises so that contrast (and visibility) approach zero as the light per unit area reflected from the background becomes equal to the light per unit area output of excited phosphor.

In the case of transparent phosphors, the relatively small amount of phospher used is capable of producing only a low light output when excited but the

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light reflected by the background is negligible so that visibility of the written spots defies intense ambient illumination. The reason behind this, of course, is that the phosphor is invisible until excited. Ambient light in almost any amount passes unseen through the face plate of the tube and the phosphor and is absorbed in the dark interior. There is the problem of making all interior surfaces of the tube light absorbing, however. Full exploitation of this phenomenon could result in providing color-coded CRT displays on the bridge (where natural, visual clues important to the well being of own ship) are available.

It appears that with selected CRT devices, satisfactory visibility of color-coded displays in normally lighted spaces is within the state of the art.

RESOLUTION

Retinal resolution of the human eye, a measure of visual acuity, is the capacity of the eye to see precisely a pattern of detail. Retinal resolution may be measured in minutes of arc of visual angle subtended by the minimum separable distance between two targets. The minimum separable distance between lines, as in a grating, has been found to be about one minute of visual angle with adequate viewing conditions (sufficient illumination and contrast). Another measure of acuity, the minimum perceptible width of a line is considerably less, however, being of the order of one-half to one second of visual angle. At a comfortable viewing distance (for the normal eye) of 17.2 inches, one minute of visual angle is approximately 0.005 inch; one second, about 0.00008 inch. If viewed from 8.6 ft, one minute amounts to 0.03 inch; one second, 0.0005 inch. Thus, if an area of white paper were shaded with very fine black lines, 200 per inch, the lines would not be seen. Under "ordinary" conditions the area would appear light gray, unless it were viewed from a distance less than 17.2 inches and the viewer was able to "accommodate" to the lesser distance. If the area were shaded with lines wide enough (0.0025 inch) to occupy half of the area, the individual lines still would not be seen but the area would appear to be darker gray. If the lines were 0.015 inch in width and 0.015 inch apart (34 lines per inch) but viewed from a distance of 8.6 ft, the area would appear to be the same shade of gray as above and individual lines would not be distinguished.

Since the above discussion is based on threshold values of acuity determined by experimenters, it implies that more than 200 lines per inch resolution is not necessary for directly viewed TV picture-type displays. In fact, considerably fewer lines per inch (120-130) yield adequate resolution for direct viewing. The standard TV raster is 511 "TV" lines (256 lines and 255 spaces). If 128 lines per inch were a requirement for TV receivers the raster height could be only two inches. A 10-inch high raster viewed from 7 ft or a 20-inch high raster viewed from 14 ft would appear to have the same resolution as the two-inch high raster even though the number of lines per inch on the screens would be one-fifth and one-tenth, respectively, of those on the two-inch raster. Resolution of the eye is not appreciably altered if the lines per inch are in color rather than in black.

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Although the TV raster has not replaced the FPI and is not likely to in the applications of interest here, the resolution of cathode ray tubes, including color tubes, is generally given in lines, TV lines, line pairs, or lines per inch or per millimeter. The tubes using short persistence, fine grain, thin layer phosphor screens without storage or collector grids between the gun and the screen and relatively low beam current have a screen resolution of 400 lines per inch or better. Resolution in these tubes is usually limited by spot size, which in turn depends upon beam current, focusing, phosphor efficiency, brightness requirements, diffusion (phosphor layer thickness), etc., and, in the case of multi-beam and controlled penetration color CRT's, upon registration. Except for registration most of the factors affecting spot size are common to both monochromic and multi-color CRT's and, therefore, are of secondary consideration here. Increased spot size because of diffusion in thick, long persistent phosphor is not a factor in any of the promising multi-color layer screens because the layers are not thick and the phosphors are not long persistence. Long persistence phosphors are not used for multi-color screens because the range of hues of long persistence phosphors is very limited. Multi-beam tubes in the conventional funnel-shaped envelopes have overcome the problems of beam convergence (and registration) at least in part, by the use of a collimating "grid", but fringing (mis-registration) may still exist at the outer edges of the screen. The two-beam, two-color Aiken thin tube is reported to have very good registration. By using post-deflection acceleration, the single gun Transylume tube has overcome the problems in deflection (and registration) which are created by beam "stiffening" when the beam acceleration is increased in order to increase penetration (and change the color). The wire mesh which is necessary to accomplish post deflection acceleration probably reduces the resolution capability of the tube and a voltage-modulater synchronized with the color modulation is necessary. Because of the magnitude of the voltages involved (of the order of 5 kv) the modulation rate is limited to several hundred kilocycles. This may be sufficient for color-coded military displays, if not for commercial TV application.

When the phosphor is arranged in dots or stripes rather than layers, however, resolution does suffer. Although diffusion may be reduced by virtue of the spaces between dots or stripes, the present state-of-the-art practical limit for producing the phosphor screens and the matching storage grids is about 100 dots, stripes or mesh openings per inch. If three "primary" color phosphors are used (in order that a "full" color range is available) the space between centers of dots or stripes of a single color is approximately three-hundredths of an inch. Thus, the resolution for a single primary color (and for any hue obtained by mixing colors) is about 34 lines per inch. For two-color dots or stripes (and a range restricted to, say, red through yellow-green) the resolution may be 50 to 55 lines per inch - still less than half of that desirable for a direct view color-coded CRT display. Assuming a maximum dot size of 0.01 inches (no overlapping of dots) there would be 0.01 inches (120 seconds of visual angle) between dots of a color. The Handbook of Human Engineering gives 180-200 seconds of visual angle as the minimum separable distance between self-luminous points on black and so indicates that individual dots could not be distinguished. However, comments of observers of color tube demonstrations have found their way into the literature and these indicate not only that the self-luminous points (of the CRT variety) are individually dis-

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tinguishable but that the hue of area made up of different colored spots appears to change as the eye tires (or accommodates). The adequacy of surface color "dot" resolution is easily checked, e.g., newspaper picture shading is accomplished by varying the size of dots which are arranged in rows and "colums" about 60 dots per inch, whereas higher quality pictures in the better magazines use the same method but employ 120 or more dots per inch.

There are other factors which militate against the use of dots (or stripes) which are fixed in position on the CRT screen which are intended for use as a coded military display:

(1) The movement of targets on a PPI scope, for instance, would have to be in steps, the minimum step being to the next closest dot. If a 10-inch scope were being used with 200 mile range and no off-centering, then 0.01 inches equals 0.4 miles. Thus, errors in range and bearing are created because of the structure of the viewing screen. Although these errors may be insignificant (depending on usage), they are unnecessary because layer screens with high resolution could be used.

(2) If coding symbols were to be used with a "dot" screen, a greater space on the screen would be occupied by the symbol than if a "layer" screen were used. A 5x7 matrix of dots has been suggested as the minimum necessary to build up reasonably legible alphanumeric symbols. The larger size of the individual symbols creates problems in crowding the display, reduced legibility (due to overlapping of symbols) and masking, perhaps of an important new target such as a missile fired from an aircraft or submarine.

(3) Dot (and stripe) screens are used in cathode ray tubes for no other reason than to give the tubes color capability. Since there are other color tubes which appear to be as near to operational use as the "dot" screen tubes and do not sacrifice resolution for color, this trade-off, in itself, would not seem warranted. The direct view two-color storage tube uses the so called "dot-and-donut" screen but trades-off resolution for persistence and brightness, rather than color. Loss of resolution in this tube is primarily a result of the unavoidable lack of fineness of the storage grid. Hughes Aircraft is developing under contract a 150-line storage mesh and matching two-color screen. Unless substantial gains in the art are made by this effort, however, the color capability of this tube is likely to be somewhat less than desirable for color coded military displays. Also this type of tube is relatively much more expensive and considerably less rugged than the conventional CRT (because of its internal structure) and the associated power supply and control circuits are more complex. This means even more cost, if cost is interpreted in general terms to include down time, installation space, and more extensive training for operation and maintenance.

(4) Although no data has been found to substantiate this, it seems reasonable to assume that color mixing by the eye would present less of a problem with small self-luminous spots which are superimposed than with the same spots placed adjacently. Also, it would seem that better discrimination of hue

would be possible with the superimposed spots where fringing occurs and where the spots subtend a visual angle of less than 20 minutes (approximately one-tenth inch), i.e., where viewing screen space is conserved by use of small color coded spots rather than alphanumeric or other shape coding.

(5) Assuming not only that a color coded PPI display would be needed in CIC but also that it would be desirable to operate the display off-center, it appears that resolution and hue discrimination (of a small spot) would vary from region to region of the screen for almost any obtainable geometry of phosphor dots or stripes.(Off hand a "dot-and-donut" arrangement looks best; radial sector-shaped stripes look worst. Much depends upon the relative sizes of spots, dots and stripes).

Two ways have been found to use more than one layer of phosphor, superimposed with respect to the viewer, in order to present a multicolor display to the viewer. In the two-color, two-gun Aiken flat tube, the layers of phosphor are deposited one on each side of a thin rectangular glass plate to form the viewing screen. The two guns are also mounted one on each side of the screen at a lower corner of the edge. The beams from the two guns travel and are deflected and focused in synchronism so that they impinge on opposite sides of the screen after having made two right-angle bends. Although no values can be given here, these tubes are reported to have high resolution and high brightness (because they have no interfering internal masking or grid structures). If transparent or very thin phosphor layers were used, it is assumed that three distinguishable colors would be available for use in a color coded display. Other advantages claimed for these tubes are freedom from normal stray magnetic fields and smallness of size relative to the useful screen area. One disadvantage is that control of the high electrostatic deflection voltages may be difficult and complex. Another type of color cathode ray tube, more nearly conventional than the Aiken tube is the Penetron or Transylume (Panaura Corporation) which uses the idea of controlled-penetration of two or three phosphor layers to produce a multicolor display. The results obtained using the recently developed transparent and thinly settled, small particle, phosphor layers are impressive. Color range with two layers is at least three colors, discriminable on an absolute basis. Resolution can be very high - more than 20 times our arbitrarily set value for direct view color coded military displays. The light output of the penetron is low. As explained previously, this does not necessarily mean that the visibility of the written spots on a transparent screen is low. The low light output is due, at least in part, to the very small quantity of phosphor material which is present in a small area of a transparent phosphor screen. In other words, a small mass of the material which converts the beam energy into visible light is capable of converting only a limited amount of energy in a given time. The small quantity of material may also account, in part for the fact that no transparent, long persistence phosphor has been found. The process of forming a transparent phosphor screen is to evaporate the material onto a transparent substrate and then to bake it on. The temperature necessary for proper processing of the "standard" color phosphors is so high as to preclude the use of the glass ordinarily used for CRT face plates. Perhaps quartz glass could be used, but this would be very expensive. If more phosphor is distributed over the screen by settling a small

particle material in a thin layer, resolution is reduced (but not enough to threaten our arbitrary minimum) and brightness is increased greatly. The thinly settled phosphors are not transparent - they are nearly white, when not excited. Thus, some advantage in visibility is lost with loss of transparency in spite of the fact that white, as a background "color" for black, blue, green and yellow symbols is unsurpassed. Red on green appears to result in poorest legibility. From the standpoint of visibility, color and brightness contrast are much more important considerations than background color, however.

Screens using P16 (violet) phosphor deposited by cataphoresis have been made with 2000 lines per inch resolution and with an increase in radiant efficiency. Perhaps this process could be used to advantage in depositing other color emitting phosphors.

From the preceding discussion it is concluded that color imposes no requirement in resolution which cannot be met.

PERSISTENCE

No long persistence phosphors have been found which could be used to produce a satisfactory range of colors for CRT color coded displays. To obtain a reasonable range, short or medium short phosphors must be used for color displays and these must be energized continuously or intermittently at rates above the threshold of flicker perception, if the display is to be flicker-free. The TV "frame" rate of 30 frames per second is a practical minimum value of reintensification rate - not too far above the threshold of flicker perception but far enough to avoid most of the eye fatigue associated with flicker. The upper limit of reintensification rate is continuous intensification, of course. The rate at which "blips" are received from a given radar target and displayed on a PPI scope is not greater than the rotation rate of the radar antenna. This may be between 3 and 30 rpm or between 600 and 60 times too slow to avoid flicker. The two CRT devices sketchily described below can be used to circumvent this difficulty and have limited multi-color capability as well. Each has a built-in memory in the form of a storage grid.

The Hughes two-color direct view storage tube with selective erasure being developed under Navy contract and the RCA two-color multi-mode display storage tube being developed at RCA expense represent the state-of-the-art in color storage tubes. The Hughes tube is capable of displaying stored information in either of two colors or in intermediate hues, and of selectively erasing that information. The operating principle is based on the fact that flood electrons which pass through holes in the storage grid when the storage surface potential is near cut-off, fall within small areas on the viewing screen opposite the storage grid holes; whereas flood electrons which pass through the holes when the potential is near maximum, fall on larger areas of the viewing screen. The viewing screen consists of two phosphors in a "dot-and-donut" arrangement. One, the red emitting phosphor, occupies small areas in register with the storage grid holes, while the other (green) occupies areas surrounding the first. Thus, when the storage surface potential is near cut-off and a spot is written on the

storage grid which allows about 40% of the available flood electrons to pass, the elemental spot size on the screen will be smaller than the red dot and the hue emitted will be reddish orange at a brightness of perhaps 140 ft-lamberts. When the storage surface potential is further from cut-off but other conditions are the same as above, the spot size may be large enough to cover the green donut as well as the red dot so that the hue emitted would be a mixture of red and green and would be perceived by the eye as yellow-green at a brightness of 330 ft-lamberts. Minimum viewing time (after writing has ceased) without noticeable shift in hue, would be one minute unless the spot is intentionally erased sooner. Selective erasure is accomplished by bombardment induced conductivity (BIC), a process by which the insulating material used for the storage grid is made to leak by electron bombardment of the written area so that the positive charge of this area leaks off and the flood electrons no longer pass through.

The RCA color storage tube is capable of simultaneously displaying stored information in one color (red) and "transient" information in another color (green) and is also capable of selective erasure (and of "black trace" operation). The operating principle of the red display is similar to that of the Hughes tube but with the exception that a two-layer screen is used (rather than a "dot-and-donut" screen) and the color emitted by the screen is controlled by control of penetration of the layers. Thus, the electrons which excite the red phosphor have been accelerated only enough to partly penetrate the first layer they reach (the red layer) and so lose their energy to the red phosphor. The electrons which excite the green phosphor have been given a greater acceleration (about 3500 volts, depending on layer thickness) by a third, higher-energy gun and, therefore, completely penetrate the red layer and go part way through the green layer before being stopped by collision and releasing their energy. If these electrons penetrated to the interface between the two layers, i.e., if some of them stopped in the red layer and some in the green layer, both colors would be emitted but the spot on the screen would appear to an observer as a single hue intermediate between red and green, such as orange or yellow. The electron beam from the third gun can be adjusted to "shoot through" the storage grid, as above, and produce a green spot as long as the shooting continues or it can be adjusted and deflected to erase positive (red control) spots already written on the storage grid. BIC is used in either case. In the "shoot through" case, the adjustment is such that the charge which would normally build up at the spot is just balanced by BIC "discharge" (leakage) during the shooting but leaves the charge of the spot unchanged. In the selective erase case, the charged spot is discharged by BIC action.

It should be noted that in both of these tubes only one color (red) is given persistence by the storage grid and that the signal to write the spots on the storage grid must be of uniform strength, if the brightness of the displayed spots is to be uniform. In the Hughes tube, the hue as well as the brightness may vary with signal strength since small signals will result in dim red (small elemental spot) displays while large signals show up as bright green (larger elemental spot) displays. Therefore, these tubes are intended for use in displaying information which is stored external to the tube. It should also be noted that both of the tubes use electrostatic deflection which sets a practical maximum limit of about 7-1/2 inches on the useful screen diameter.

Again, neither of the tubes is an "off-the-shelf" item, being still in the development stage, but both provide persistence which is compatible with the rate at which signals are returned from radar (or sonar) targets.

Color CRTs other than the storage tubes have no built-in means of providing persistence above the flicker rate and the written areas must be reintensified from an external source at rates above the flicker rate if flicker is to be avoided.

RAW RADAR, PPI AND COLOR DIRECT VIEW STORAGE TUBE

It appears from the foregoing that no single CRT device is immediately available which could be used to present a raw radar PPI display to a decision-maker if some information on the display has to be coded in color. This is supported by the fact that the "raw radar" stipulation implies a slow target reintensification rate, which in turn injects a requirement for persistence. However, persistence in all color CRT devices, except the storage tubes, is available only with an external means of reintensification. The color storage tubes on the horizon (Hughes and RCA) can provide persistence in one color. Either of these tubes could be used to present a raw radar PPI display in one color (with much better spot brightness characteristics than the conventional flash and fade display and, perhaps, with satisfactory resolution). External control circuitry would be necessary to erase the scope a few degrees ahead of rewriting. A proper amount of partial erasing could provide target history (speed and heading vector). Such a display has been demonstrated. Neither device, used in the manner just described, has great potential as a color coded display, the extent of the color coding capability of the Hughes tube apparently being to call up one category of information in one color or another category in another color but not to superimpose the two. The capability of the RCA tube to present a color-coded display with raw radar in one color would not end here. With the arrival of stored data systems (such as NTDS) to provide an external means of reintensification, the RCA tube would be capable of displaying coded information in at least one other color and, therefore, would be on the threshold of presenting color-coded information so that it could be used in the most advantageous way - to reduce search time. With the further development of controlled penetration, phosphors and phosphor processing, storage grids, storage grid insulating material, jump scanning, control circuits and signal processing (to name a few needs), the decision-maker could have on his PPI, on demand, not only a cleaned-up NTDS display with targets catagorized to his needs by color but with raw radar as well.

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APPENDIX A
SYNOPSES OF REPORTS ON COLOR DISPLAY

Alluisi, Earl A. and Muller, Paul F.
Rate of Information Transfer with Seven Symbolic Visual Codes: Motor and Verbal Responses
WADC Tech. Rpt. No. 56-226, May 1956

Purpose: To determine the information transfer functions of seven symbolic visual codes with respect to speed and accuracy of both motor and verbal readout under both self-pacing and forced-pacing conditions.

Method: Two experiments were conducted differing essentially only in the kind of response required. For both, the subjects viewed a display formed of a 10 inch diameter opal glass screen in the center of which the symbols appeared one at a time. The seven codes, consisting of ten symbols each were as follows: (1) conventional arabic numerals, used for comparative purposes, (2) symbolic arabic numerals, using symbols formed from an eight-element straight line matrix, (3, 4 and 5) three different inclination codes, (6) an ellipse-axis ratio code, and (7) a color code. The ten colors, produced from Wratten gelatin filters, included a grey and a violet. The colors were presented as circles of 1/4 inch diameter and the other codes were scaled to the same dimension. These symbols were made to appear in the center of the display screen by passing light through the photographic transparencies.

In one experiment the subject responded by pressing one of ten finger keys for each of a set of ten symbols. The keys were arranged horizontally in two semi-circles to correspond with the natural placement of the finger tips and were numbered 1, 2...9, 0, from left to right. The method of the second experiment differed from that of the first only in the use of a boom microphone instead of finger keys, the subject responding by speaking into the microphone. The verbal and motor responses were paired with self-paced tasks giving four experimental conditions. For the self-pacing conditions, a new symbol was presented just after the subject had responded to the preceding symbol; for forced-pacing, symbols are presented at a selected rate and the subject must respond at this rate if he responds at all. The rate of information presentation used in the forced-pacing tasks varied from 2-6 bits/second, in unit steps.

Ten subjects were used in Experiment I and nine of them were also used in Experiment II. The tenth subject for this latter experiment was recruited from the laboratory staff. Experiment II followed Experiment I for all subjects. The subjects worked in pairs with one of them engaged in the experimental task while the other practiced responses (Exp. I) or recorded errors (Exp. II). Records of both speed and accuracy of response were taken. These were reduced to a "rate of information transmission" measure which was used in the presentation of results.

Results: The two numerical codes were superior and the color and ellipse-axis ratio code poorest for all four response conditions. Performance was best with verbal responses under the forced-pacing condition and poorest with motor responses under the same condition; the self pacing condition yielding intermediate results.

Anderson, Nancy S. and Fitts, Paul M.
Amount of Information Gained During Brief Exposures of Numerals and Colors
J. Exp. Psychol, 1958, 56, 362-369

Purpose: To examine the relation of information transmitted to information coding and amount of information displayed.

Method: Two experiments were performed under much the same conditions, the second being confirmation to the first.

Experiment 1: Twelve subjects, in groups of four, viewed an opening in a screen behind which the shutter of an exposure apparatus could be seen. Messages, composed from three alphabets, were given .1 second exposure through the opening. The three alphabets used were: nine black numerals, 1.2 cm x 2 cm, "0" through "9" excluding "1"; nine homogeneous color patches, 2.5 cm x 3.2 cm, and the black numerals superimposed on the color patches. The colors were selected to be equally discriminable and were assigned common names. Message length for the two simpler alphabets, color patch, and numerals were 3, 4, 5 and 6 symbols leading to an information content for the messages ranging from 9.51 to 19.02 bits. The message length for the color-numeric alphabet was held constant at three symbols but the information per symbol was varied by varying the size of the set of alternative color symbols, 9, 6 or 3, used in combination with the nine numerals. This gave three-symbol messages of 19.02, 17.25 or 14.25 bits respectively. After training, 10 test sessions were held with each of the groups, five with the simpler alphabet and five with the more complex one. For the simpler alphabet each session consisted of 36 test messages for each type of symbol and each of four message lengths. Before the session with the color-numeric alphabet the subjects were informed of the size of the symbol set to be used in each series of trials. An alerting signal sounded three seconds before each message exposure. Subjects were told to fixate a dot on the display shutter behind which the message would appear. The subjects recorded their estimates of the messages, giving symbol and symbol position in sequence for each trial.

Experiment 2: Because performance with the color-numeric symbols were found to be highest for the maximum information messages employed in Experiment 1, whereas performance in reporting messages of similar information but comprised of less complex symbols had apparently passed a peak and begun to decrease, it was decided to conduct a second experiment including messages of higher information content while retaining some of the lower information conditions of Experiment 1 for comparison purposes. The alphabets were identical to those used in Experiment 1 except that only the most complex condition (9 numerals superimposed on 9 color patches) were used with the color-numeric alphabet.

APPENDIX A - SYNOPSES OF REPORTS

Messages were of three levels of information content, 12.68, 19.02 and 25.36 bits per message, formed by using 4, 6 or 8 simple symbols or by using 2, 3 or 4 combined symbols per message. All procedures were identical to those followed in Experiment 1. None of the twelve subjects had served in Experiment 1.

Results: The results of Experiment 1 were confirmed by those of Experiment 2, i.e., for all common conditions, the latter gave comparable results to those obtained in the former. Performance at first increased and then decreased as information content per message was systematically increased, reaching different maxima for each of the three coding schemes studied. The use of shape-coded symbols permitted higher maximum information transmissions than did color symbols and the use of color-numeric symbols gave an even greater maximum amount of information. Maximum average information transmitted by the color, numerals and color numeric codes were 10.44, 14.94, and 18.64 (bits per .1 second exposure) respectively.

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Christner, **Charlotte W.** and Ray, Horace W.
An Evaluation of the Effect of Select Combinations of Target and Background Coding on Map-reading Performance - Experiment V
Human Factors, 1961, 3, 131-146

Purpose: To evaluate the effectiveness for several operator-tasks of the combination of certain selected coding dimensions for targets and for backgrounds on performance in the reading of cartographic displays.

Method: Five subjects viewed a large number of variations of a basic display each drawn on 30 x 30 inch cardboard. The basic display was an abstraction of the map of an area (West Central Asia) which included 30 smaller sections. The area was chosen because it was believed unfamiliar to the subjects and the borders of its smaller sections were of typical irregularity. Background and target codes were superimposed on this basic display. The five backgrounds were: color, all gray, white, patterned, and different shades of gray. Each of these five backgrounds were combined with three target codes; colors, numerals and inclosed shapes, to form 15 background-target combinations.

Five colors were selected for background coding. Their value/chroma rating was 8/4 (Munsell notation) and the hues were red, yellow, green, blue and purple, all 2.5 Munsell. Eight colors, all different from those used for background, were used for target coding. Eight numerals (1 to 8) and eight inclosed shapes (triangle, heart, etc.) were also selected for target codes on the basis of previously demonstrated effectiveness. The color targets appeared as 1/2 x 1/2 inch squares and the other two codes were adjusted to fill white matching squares. All squares had a 1 mm black border.

In addition, the targets were coded at two levels each of three complexity conditions; (1) number of targets on display (60 or 120), (2) number of coding levels (4 or 8), and (3) clustering, the total number of targets clustered in several groups or dispersed. The 120 displays constructed from the 15 background-target combinations and 8 complexity conditions were each tested for five operator-tasks.

APPENDIX A - SYNOPSES OF REPORTS

The experimental tasks assigned to the subjects, the completion of a 15 question form for each display, was designed to sample five subtasks considered basic to map reading. These subtasks were labeled: identify, locate, count, compare and verify. Three of the 15 questions related to each of the subtasks.

Three performance measures were taken; time to complete, error and number of response scores, all related to the three question subtasks. A rating scale was also included to investigate the subjects preferences for the various coding conditions.

Results: Background codings did not differ significantly over all target codings and all tasks. Target codings, however, showed some superiorities; color for the locating and counting tasks, and numbers for the identifying tasks. No differences were found for the comparing and verifying tasks. An analysis of factors (Thurstone's Centroid Method) was made on the intercorrelations of the five tasks to investigate the basic factors accounting for the variations existing between them. Three factors were extracted by this method and were identified as "search", "recognition", and "remembering". The locating and counting tasks were highly loaded with "search" factor while the identifying task had its heaviest loading on the "recognition" factor. The rating scales revealed a pronounced preference for colored targets.

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Eriksen, Charles W.
Location of Objects in a Visual Display as a Function of the Number of Dimensions on Which the Objects Differ
J. Exp. Psychol., 1952, 44, 56-60

Purpose: To determine the speed with which objects could be located on a visual display under two conditions: (1) When the various classes of objects on the display differed from one another on only one of four visual dimensions of form (F), hue (H), size (S) and brightness (B); and (2) when the classes differed from one another on two or on three of these dimensions.

Method: The display was a 3 ft square, flat white in color and ruled off into 81-4-inch squares by means of black lines. The squares on the outer border were never used. For each trial, 42 of the inner 49 squares were randomly selected to display the objects. The unused squares were filled with blank white cardboard. A 1/2 inch circular electrode was located at the bottom of each of these small squares and cards bearing symbols were hung from a small hook at the top of the square. The display was perpendicular to the subject's line of sight. A panel hid the display from subject until a catch was released. The panel dropped, giving subject a full view of the display and tripping a microswitch which started an electric timer. The subject's task was to locate the objects of the target class from among the various classes on the display by touching a stylus to the electrodes beneath the appropriate cards. A sample of the target class was mounted to the left of the display and the subject was told to locate the six objects of the display that were the same as the sample. The subject's score was the time it took him to locate them all. When this had been accomplished, in any order, the timer was automatically stopped. There were seven classes within each of the four dimensions: H and B, given in the Munsell notation, were distributed over the Munsell series; F--circles, triangles, etc.,

and S-- varying from 4/8 inch to 10/8 inch. One class from each dimension was selected as the target class. The experiment was divided into two parts with 30 different subjects, having normal color vision and visual acuity, participating in each.

The first part of the experiment was to determine the speed of location when the classes of objects on the display varied only in one dimension at a time. As a control measure each of these dimensions was tested under three conditions. Under condition 1, two non-target classes were on the display; under condition 2, four non-target classes; and under condition 3, six non-target classes. For all three conditions the total number of objects on the display was kept constant at 42 by manipulating the number of the last added class from 30 for condition 1 to six for condition 3. The other classes, including the target, contained six objects.

In the second part of the experiment the speed in locating the target class was determined when the classes on the display varied on two or on three visual dimensions. Each of the 10 compounded dimensions, formed by the possible combinations of the four single dimensions taken two and three at a time, were tested under the three conditions of the first experiment.

Results: Mean locations time for the four single and the ten compounded dimensions were: For the single dimension - H proved significantly faster than F, and both H and F are significantly faster than B or S. With the exception of one reversal, between FS and BS, the rank ordering of the compounds correspond to an average of the location times of the single dimensions involved.

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Eriksen, Charles W.
Object Locations in a Complex Perceptual Field
J. Exp. Psychol., 1953, 45, 126-132

Purpose: Two experiments, both investigating the time required to locate targets against different field heterogeneities (number of coding dimensions along which the objects in the field differ) are reported. In the first, the target definition (number of coding dimensions on which the target can be identified) was varied with field heterogeneity; in the second, target definition was held constant, field heterogeneity varied.

Method: The display, associated apparatus, and the general experimental situation was the same as that described above (Eriksen, 1952).

The first experiment was a repetition of the author's previous experiment (Eriksen, 1952) but using different instructions to the subjects. Instead of being shown a sample of the target they were made explicitly aware of its complete definition, i.e., subjects were informed of each characteristic by which the target could be identified. In addition, the 16 subjects were divided into two groups of eight each, with one group given a "set" for hue and the other a "set" for form. Twelve conditions of field heterogeneity were used; hue, form and the five double, four triple and one quadruple compounds to be formed

from the four coding dimensions, hue, form, size and brightness, used. Each of these 12 conditions was used with a different target definition, e.g., if the field involved two dimensions the target could be identified by characteristic values on both these dimensions.

The procedure for the second experiment was like that of the first except that the targets were singly defined, that is, the targets were always six circles, while the field heterogeneities were those eight of the compound which included form from the set of 12 used in the first experiment.

Results: Target objects defined only on the hue dimension can be located as rapidly or more rapidly on a relatively homogeneous field, varying only in hue, than multiple defined targets on a heterogeneous field. This result held for the form group and both results support the findings of Eriksen (1952).

A "set" for hue resulted in a shorter location time than a "set" for form but this difference had not reached .05 significance under variance analysis.

Under comparable field heterogeneity, target objects that were multiply defined by assigning them unique values on several dimensions were located more rapidly than objects defined on only one dimension.

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Eriksen, C. W., and Hake, H. W.
Multidimensional Stimulus Difference and Accuracy of Discrimination
J. Exp. Psychol., 1955, 50, 153-160

Purpose: To determine whether (1) stimuli can be more accurately discriminated from one another if they differ on two or three dimensions, than if they differ along a single dimension. And, (2) if the discrimination accuracy for such multidimensional stimuli can be predicted from the discriminability of the component dimensions of hue, size (area) and brightness.

Method: Discrimination was determined by the method of absolute judgments, i.e., subjects identified by number (1-20) a set of individually presented stimuli. Seven different sets were prepared: one for each of the dimensions (hue, brightness and size) taken singly, one for each of three pairs that can be formed from these dimensions, and one for all three taken together. For the sets combining dimensions the stimuli could be uniquely specified on any dimension in the combinations. The stimuli were mounted in the center of 3 inch white cardboard squares. The subjects (6, with normal vision) were run individually. Each subject made 100 judgments of each stimulus of each of the seven stimulus series. The steps for both the hue and brightness are specified in Munsell's notation and are equally spaced over the range of the Munsell scales. Size was varied in 1/8 inch square steps, from 1/8 inch square to 20/8 inch squares.

Results: Discrimination accuracy for each of the seven stimulus series is given by two measures; (1) a measure interpretable as the maximum number of

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stimulus values that could be selected from a series of stimuli if errorless discrimination were desired, and (2) the average percentage of correct responses given to stimuli within each series. As a single stimulus series, hue yielded one more discriminable step (8) than size (7) and three more steps than brightness (5). The average percentage of correct judgments when these dimensions were used alone were for hue 53%, for size 47%, and for brightness 41%.

All three of the single series showed improvement in accuracy when combined with any one other of the series and the combination of the three showed the greatest accuracy. Thus, when used alone hue yielded about 8 absolutely discriminable steps. When combined with brightness or size the number of steps was increased to 12 or 13 and in combination with both brightness and size the number was 17. There were parallel results when the compounding of dimensions was measured by the percentage of correct judgments made. When the stimulus series were used alone, 40%-50% of the judgments were correct; in combination of two's, 60%-85%; and the three together gave 96% correct.

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Green, B. F., McGill, W. J. and Jenkins, H. M.
The Time Required to Search for Numbers on Large Visual Displays
Massachusetts Institute of Technology, Lincoln Laboratory
Tech. Report No. 36, August 1953

A report of several experiments, three of which are directly relevent to the evaluation of color for coding displays.

Experiment No. 5
Purpose: To compare search time for "cluttered" displays with search time previously found (Exp. 1 of same series) for uncluttered displays.

Method: Displays were projected on a table with the targets (three digit numbers) enclosed in a circle 42 inches in diameter. Target densities were 25, 50, 75 and 100. For each trial, immediately before the display was projected, the subject was told to find a particular number. The search was considered completed when the subject said he had found the number. Time to complete the search was the measure taken. Color was introduced in the form of background clutter, i.e., polar coordinates in green, other items in red. In addition the targets were of two colors, yellow or blue.

Results: When compared with results obtained with uncluttered displays under similar conditions, the cluttered displays showed no pronounced differences.

Experiment No. 6
Purpose: To study the effect on search time of the presence of other signals of a different color.

Method: Same as for Exp. No. 5 except (1) both yellow and blue signals in equal numbers appeared on the display, and (2) the subject was told before each trial the target's color-category. Thus, half of the targets served as additional background clutter.

Results: The results of Exps. 5 and 6 were compared. The comparison showed that adding numbers of another color to those of the color being searched does not greatly increase the time needed to search the latter category. The results suggested to the authors that "...Search time decreases if elements are separated into categories by some visual code such as color, so that only members of a certain category must be considered as alternatives".

Experiment No. 7
Purpose: An extension of Exp. No. 6, to clarify the effect of the number of alternatives.

Method: The changes in procedure from Exps. 5 and 6 were as follows: (1) Three different signal types were used; large yellow and large blue (same size) and small yellow. The search time for each type was tested at two densities, 25 and 50. (2) Two mixtures of these signal types were tested: large blue and large yellow, 25 of each, and large blue and small yellow, 25 of each. For each mixture three conditions were used: search for blue target, search for yellow target, target color unspecified. Under all conditions there were 50 signals on the displays.

Results: The results generally confirmed the expectations following Exp. No. 6 i.e., if color was specified the search time was essentially that found for a 25 signal one-color display, with color unspecified, the search time was about that for a 50 signal one-color display.

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Green, B. F. and Anderson, Lois K.
Color Coding in a Visual Search Task
J. Exp. Psychol., 1956, 51, 19-24

Two experiments are reported aimed at investigating "the effectiveness of color coding as a function of the relative number of symbols of each color, and as a function of the number of different colors used".

Experiment No. 1
Purpose: "To measure the effectiveness of a two-color code as a function of the relative number of symbols of each color".

Method: Signals were 60 two-digit numbers arranged in random order on a 6x10 matrix. The two colors, prepared from Kodachrome transparencies were green and red on black background. Three conditions were used: In the "set" condition subjects searched a 60 signal matrix with 0, 10, 20, 30, 40, 50, and 60 red or green targets. They were told the color-category in addition to the number of the target. In a "non-set" condition the same procedure was used except the subjects were not told the target color. In a control condition the same procedure was again used except that symbols 10, 20, 30, 40, 50, and 60 were all one color and remaining matrix positions were blank. Time to find target was the measure taken. Subjects were 20 enlisted men with normal acuity and color vision.

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Results: The average search times for the "set" condition were slightly longer than for the control condition but markedly superior to the "non-set" condition. The authors conclude "...the average search times in the set condition depend mainly on the number of symbols with the target-color, but are also affected slightly by the presence of wrong colored symbols".

Experiment No. 2
Purpose: To measure search times for displays with varying numbers of colors.

Method: The displays were similar to those used in Experiment 1 but included yellow and blue numbers in addition to the red and green. As for Experiment 1, three conditions were used. The control condition was essentially the same as in the previous experiment except that the numbers of symbols on the displays were 15, 30, 45 or 60. In the "set" condition the displays contained 30, 45 or 60 symbols of which 15 each, of two, three or four colors, respectively, were used. The subjects were told the target color. The "non-set" condition was identical with the "set" except that the subjects were not told the target color. For both set and non-set conditions there were always 15 numbers of the target's color. For all three conditions in those cases where less than 60 signals were displayed, the remaining positions were blank.

Results: When the subjects knew the target's color, their search time depended primarily on the number of symbols of the same color as the target. As more symbols of a different color are added to the display, however, the search time becomes slightly longer indicating a minor effect due to the presence of signals not of the target's color. When subjects did not know the target's color, search time depended primarily on the total number of signals on the display.

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Hitt, William D.
An Evaluation of Five Different Abstract Coding Methods
Human Factors, 1961, 3, 120-130

Experiment 4
Purpose: To ascertain the relative effectiveness of five different abstract target coding methods for the performance of five operator tasks.

Method: Five subjects viewed 20x13 inch rectangular displays mounted on 30x22 inch cardboard posters, each display having eight columns and five rows. The coordinates for the 40 cells so formed were identified by 1 inch red numerals on the upper and lower borders and 1 inch red letters on both sides. The test symbols appearing in the cells were 1/2 inch for the longest dimension.

The five different coding methods selected were: numerals, letters, geometric shape, color, and an inclination code. The 8 hues used with the color code were: black, red, blue, brown, yellow, green, purple and orange. No attempt was made to keep saturation and brightness constant. The eight levels of the five codes were related to eight items within each of five target categories (aircraft type, industrial sites, etc.) believed to be representative of

inputs to intelligence centers. To the five target codes two other display variables were added; "number of coding levels" (2, 4 or 8 steps) and "target density" (40, 80 or 120 per display).

Five different operator tasks appearing basic to visual display reading were included as an additional independent variable. These tasks were: identify, locating, counting, comparing and verifying.

The experimental task was to complete a pencil-and-paper test (25 questions, 5 for each task) for each display poster. The code category/target category combination was kept constant for any experimental session. Upon a signal from the subject the experimenter raised a blind that covered a display poster and simultaneously started a timer. When the subject had completed the five questions relating to one task he again signaled the experimenter who lowered the blind and stopped the timer. The subjects were practiced in the code category/target category for the day before each session.

Performance measures recorded were: number of correct responses and speed of response, both for completion of the 5 question subsets.

Results: A search for factors underlying the operator tasks (Thurstone's centroid method) produced two basic dimensions identified as "search" and "recognition".. The "locate" task was closely associated with the former while the "identify" task was associated with the latter. The other tasks had mixed loadings on these two factors. In general, color and numeral codings were superior to the other coding methods. Numeral coding proved clearly superior to color for the "identify" task while color was ranked first (but not significantly better at the 0.05 level) on the "locate" task.

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Muller, P. E. Jr., Sidorsky, R., Slivinski, A., Alluisi, E. A., and Fitts, P.M.
The Symbolic Coding of Information on Cathode Ray Tubes and Similar Displays
WADC Tech. Report 55-375, October 1955

This report summarizes the results of several investigations conducted as part of a program to determine the feasibility of symbolic coding for CRT. Two of the experiments described are directly revelant to display color coding.

Experiment No. 9 (Page 93)
Purpose: To obtain data on performance in a complex check-reading task and to compare efficiency of check-reading as a function of the type of code and the number of targets to be checked.

Method: The two types of coding symbols compared were (a) inclination, consisting of 1/4 inch diameter circles each containing a single radius line at one of 12 spaced clock positions, and (b) color, consisting of 1/8 inch circles filled with 12 colors produced by passing light through Wratten gelatine filters. The signals were presented on a simulated CRT scope face. Nine target densities were used, 2, 3, 4, 5, 6, 7, 8, 10, and 12 with 10 arrangements at each density for a total of 90 arrangements for color and 90 for inclination.

Upon presentation of the display the subjects were to determine and report verbally all conflicts, i.e., any two or greater number of targets bearing the same code. Subjects were six males with normal vision. Measures were time to complete checking process and number of correct reports.

Results: For this task the color code used proved markedly superior to the inclination code for both information processing time and per cent of error.

Experiment No. 10 (page 103)
Purpose: To compare performance on inclination-coded displays versus color-coded displays presented tachistoscopically.

Method: Stimuli was the same as for Exp. 9 except that the patterns for 10 and 12 targets were not used. The targets were presented for 0.1 sec after which two response tasks were used. For Task A the subjects reported verbally the exact code category of all symbols displayed, for Task B, the number of conflicts and the number of targets involved in each. Three measures of performance were taken: (1) number of correct trials, (2) response latency, and (3) total response time.

Results: The only marked difference between the two codes was for response latency (delay in initiation of report) for both Tasks A and B. Color coding with this measure for these two tasks was clearly superior.

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Muller, P. F., Jr.
Efficiency of Verbal versus Motor Responses in Handling Information Encoded by Means of Color and Light Patterns
WADC Tech. Report 55-472, Dec 1955

Purpose: (a) To compare the relative compatibility of verbal versus motor responses to different types of visual stimuli, and (b) to determine the effect of verbalization as a factor affecting the ability to transfer from one type of response to the other.

Method: The subjects, 96 volunteer female students, viewed a panel upon which two sets of stimuli could be presented: (a) ten, half-inch diameter ruby lights, positioned so as to correspond to the spatial placement of the ten finger tips, and (b) ten one-inch diameter circular patches of color projected onto the back of a back-tilted opal glass screen. Two types of response were made to both these two sets of stimuli: (a) a motor response requiring the pressing of the appropriate key of a ten positions key-board with the keys placed, as was the set of ruby lights, in two semi-circles corresponding to natural finger-tip placement, and (b) a verbal response through a boom microphone suspended from headphones. The task was self paced with the response serving to introduce the next symbol. The ten colors used were obtained by projecting light through Wratten gelatin filters (numbers listed) including a grey and a violet. The colors varied in saturation and brightness as well as hue.

The four conditions described above (2 types of stimuli for 2 types of responses) were used with both verbal-response and motor-response pretraining, giving eight experimental conditions in all. Twelve different subjects were

assigned to each of these conditions. Each group worked through five pre-training trials followed by five transfer trials. Each trial consisted of 100 stimuli.

The measures of performance recorded were the delays in response and errors. Both response time and information transmitted per second are treated in the analysis.

Results: Performance with the ten color symbol sets associated with ten numbers was inferior for response time and information transfer, to the spatially placed symbols also associated with numbers. This result held for both motor and verbal responses. With color symbols, motor and verbal responses are comparable. With 10 color steps the subject's response time leveled off after 5-6 trials of 100 stimuli each. This final response time was about 1 second for the motor response and 1.25 seconds for the verbal.

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Newman, K. M. and Davis, A. K.
Multidimensional Nonredendant Encoding of a Visual Symbolic Display
[illegible], Report No. 1048, July 1961

Purpose: To examine, while holding the total quantity of information to be displayed constant, whether it could be advantageous to reduce the number of symbols by substitution of other encoding dimensions such as brightness, color and flashing.

Method: The subjects faced a 36 cell matrix (6 rows x 6 columns). Thirty-six geometrically different symbol types were available but although 36 symbols were always used, the number of symbol types varied from 3 to 36.

Three additional encoding parameters were used: (1) brightness level; bright and dim, (2) flashing rate; steady, 2 c/s & 4 c/s, and (3) color; red, yellow and green. These encoding parameters were combined with the symbol types to form 12 experimental conditions each resulting in displays having 36 qualitatively different signals, e.g., condition "j" consisted of 4 symbol types, one brightness level, 3 flashing rates, and 3 colors.

The subject's tasks were to search or decode. For the search task the subject was shown a replica of the target after which the display was illuminated. He reported its location by means of alpha-numeric symbols placed on the margins of the main display. For the decoding task the subject learned to associate the codes with a meaningful vocabulary, e.g., passenger-freight, American-TWA, and targets were decoded by use of this vocabulary. The experimenter designated the target using the marginals after which the display was illuminated. The subject then proceeded to decode. For both tasks a response time was recorded. This "time" was from display illumination to completion of task. Errors were also counted.

These 12 conditions were tested in each of four parts of the experiment: (1) Search for target with a signal in each of the 36 display positions. (2) Decode target with a signal in all 36 positions. (3) Search for target with

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two overlapping signals in each of 18 randomly selected positions, and (4) Decode target with two overlapping signals in each of 18 randomly selected positions.

Ten rated Navy men familiar with visual displays and all having normal vision acuity and color discrimination served as subjects.

Results: The non-redundant use of two or three colors improved both speed and accuracy significantly, especially speed. However, the combination of several levels of the three different encoding dimensions was detrimental to performance irrespective of the task, particularly when three flashing rates were used.

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Promisel, David M.
Visual Target Location as a Function of Number and Kind of Competing Signal
J. Applied Psychol., 1961, 45, 420-427

Purpose: To investigate operator performance with double coded visual displays as a function of the following variables: The number of target signals on the display, the values of the hue-shape combinations used as target signals, the number of competing signals on the display and the distribution of this competition between the hue and shape dimensions.

Method: The subjects viewed a three-foot square display board which had been ruled by black lines on flat white to form an 81 cell matrix, each cell 4 inches on a side. The inner 49 cells were used for the display of signals. The signals were printed on cards which were hung on a hook, one to each of the cells. They were formed from the 49 possible combinations of seven shapes and seven hues. The shapes were: circles, hexagons, diamond, triangles, crosses, stars and squares. The seven hues were selected from the areas of most sensitive color vision. The authors give the Munsell notations.

For each trial, 40 signals were placed in randomly chosen positions, the remaining nine positions left blank. The subject's task was to find among these 40 signals those that matched in both shape and hue, a sample signal displayed for the duration of the trial near the display board. The time to complete the search and the number of errors made were recorded for each trial. Of the 49 signals described above, 5 were used as targets: a red circle, green-yellow triangle, yellow-green hexagon, blue-green star and a blue square. The number of these that matched the sample target among the 40 signals varied from trial to trial and could be 0, 2, 4, 6 or 8. The number of competing signals, i.e., signals that matched the target sample in either hue or shape but not both, was also varied. The number could be 0, 8, 16, 24 or 32. The distribution between these competing signals was also varied. For one of two conditions, the competing signals were evenly divided between those that matched the targets in hue or in shape; for the other condition, all the competing signals matched the targets in hue.

Results: The number of targets on the display was the variable showing the greatest effect. The relationship between number of targets and search time

approached linearity. Analysis suggested that hue rather than shape was the critical factor in lower search time and number of errors. Task time increased with an increase in competing signals. There appeared to be no difference in task time under the two conditions of distributions for competing signals.

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Reed, J. B.
The Speed and Accuracy of Discriminating Differences in Hue, Brilliance, Area and Shape
Mt. Holyoke College; Psychophysical Research Unit
Contract Nonr 131(01), Special Devices Center Tech. Dept. 131-1-2, Sept 1951

This report describes two experiments. The first, comparing four coding dimensions, is of immediate revelance to the color-coding of displays. Although a card-sorting method is used, the author is clearly concerned with implications for the design of visual display.

Purpose: To compare four visual coding dimensions: hue, brilliance (saturation), area, and shape for speed and accuracy of discrimination.

Method: Subjects (5) sorted a deck into a two-compartment box. One symbol was printed in the center of each card. Each symbol was coded in four dimensions with two levels of each dimension; shape, a triangle or circle; area, large or small; color, red or green, and brilliance; light or dark. The subjects sorted the deck for only one dimension at a time, e.g., red and green, but each subject sorted the deck four times, one time for each dimension. A record was kept of time to sort and number of errors made by each subject for each trial.

Results: Sorting on hue or shape was about equally fast and accurate. These two dimensions were somewhat faster and more accurate than size and markedly faster and more accurate than brilliance.

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Smith, Sidney L.
Display Color Coding for a Visual Search Task
Mitre Tech Series, Report No. 7, (AD 283, 971) June 1962

Purpose: To study effects of display color coding on visual search time when the displays varied in signal density, number of colors used, color of target, color of background (black or white), and knowledge of target color given in advance or withheld from the subject.

Method: The subjects viewed a projected display with an overall field of 12 inches square. The field was partitioned into 13 columns and 27 rows for a total of 351 positions. The display positions were randomly filled with varying densities of three-digit numbers. The digits were 1/3 inch high and 1/6 inch wide. There were 5 density categories; 20, 40, 60, 80 and 100. There were 5 categories of target color; red, blue, green, orange, and black (on white background) or white (with black background). The individual displays, 150 in number, were so constructed with respect to these two categories that three sets of displays could be formed: (1) a single-colored set of increasing display density, (2) a comparable set also of increasing density but having all five

colors in equal numbers on each display, and (3) a set with increasing number of target colors associated with increasing target density.

The subjects went through the 150 displays twice, once with and once without foreknowledge of target color.

At the start of a trial, the experimenter told the subject the first two digits of the target number and a panel indicator displayed either the target color or a statement, "color unknown". When the subject had found the target he pushed a button. The time from display exposure to button pressing was recorded for each trial and is the measure used. There were 12 subjects, all with normal color vision.

Results: Neither particular target color, background color, or the interaction of these two factors was significant. Search time increased steadily with increasing display density. For multicolored displays, search time was considerably shorter when the target color was known than when unknown. With a constant number of signals of the target's color present and the target-color known, the search time was increased only slightly over a series of increasing signal density and was considerably lower than search time for the same series with target color unknown. When color of target is unknown, search time for single colored displays are not significantly different than for multicolored displays.

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13. ABSTRACT

Some recent technological advancements with color in cathode ray tube (CRT) displays, the continuing demand to present additional information more efficiently in command and control centers, and the introduction of stored information systems have stimulated renewed interest in color as a coding dimension. This study examines the human factors and engineering considerations as they relate to the central problem of the relative cost effectiveness of color—given the present engineering state-of-the-art—as compared to other coding dimensions for combat information displays and concludes that:

(1) The comparative ranking of color with other coding dimensions is highly related to the task performed

(2) Other situational factors greatly affect the value of color as a coding dimension

(3) There are perceptual problems involving the use of color, but techniques are available to enhance the value of color as a coding dimension

(4) The state-of-the-art for producing color CRT displays is encouraging, but only two tubes seem likely to have application in the near future

(5) Monetary cost estimates have been difficult to obtain, but other more easily ascertained cost factors indicate that for some tasks color will be well worth the cost.

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