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HUMAN ENGINEERING DESIGN CONSIDERATIONS FOR THE USE OF SIGNAL COLOR ENHANCEMENT IN ASW DISPLAYS

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November 1990

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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HUMAN ENGINEERING DESIGN CONSIDERATIONS FOR THE USE OF SIGNAL COLOR ENHANCEMENT IN ASW DISPLAYS *

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ABSTRACT

The Lawrence Livermore National Laboratory (LLNL) was requested to examine and define man-machine limits as part of the Office of Naval Technology's High Gain Initiative program(HGI). As an initial investigative area, LLNL's Systems and Human Performance effort focused upon color display interfaces and the use of color enhancement techniques to define human and system interface limits in signal detection and discrimination tasks. This effort is in support of Objective 3.0 of the HGI technical program plan and executed under funding order N0001490MP4B070. The knowledgeable and prudent use of color in different types of display is believed to facilitate human visual detection, discrimination and recognition in complex visual tasks. The consideration and understanding of the complex set of interacting variables associated with the prudent use of color is essential to optimize human performance, especially in the ASW community. The designers of advanced display technology and signal processing algorithms may be eventually called upon to present pre-processed information (signals and noise) to ASW operators and researchers using the latest color enhancement techniques. These techniques, however, may be limited if one does not understand the complexity and limits of human information processing which reflects the assessed state of knowledge relevant to the use of color in displays. Much of the information contained in this report is directly applicable to the ASW research community although many examples are drawn from other fields such as the display of tomographic and CAT Scan medical images for diagnosis, CAD/CAM, and radar. The initial sections of this report discuss various aspects of color presentation and the problems typically encountered, while the last section deals with a specific research proposal required to further our understanding and proper use of color enhancement methods.

Acknowledgements

I would like to personally thank Dr. Richard Doolittle for giving Lawrence Livermore National Laboratory the opportunity and encouragement to support ONT's High Gain Research Initiative and applaud his recognition of the importance of the "systems approach", which includes the human element in any delineation of system limits. I would also like to acknowledge the direct assistance I received from Dr. Harold Van Cott at the National Research Council who graciously sent me a report from which much of the information utilized in this paper is derived. Dr. Van Cott recently served as the Study Director at the National Academy of Science on a Human Factors Workshop Committee to examine the application principles for multicolored displays. Without his assistance this paper would not be possible in the time constraints allowed for this effort.

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1

Introduction

The United States Navy, through the direct efforts of the Office of Naval Technology has embarked upon an ASW research program referred to as High Gain Performance Initiative. This program is focused upon the delineation of limits and boundaries associated with super computer processing, algorithms and models which will eventually yield insights and specific research enhancement of signal processing, signal detection and signal recognition.

In parallel with the effort to determine hardware and software limits is the need to consider directly, the human component and determine the human limits imposed by different ASW technologies, configurations and models. Both in theory and practice it is almost always desirable to define and address those dimensions and variables which impact the human component within the ASW system since human performance constraints can often impact the limitations and performance of the total ASW system as a whole.

A specific example of the importance of the human component revolves around the problem of how to display, in a conspicuous and optimal manner, the fragile and transient signals which are imbedded in high noise environments. To ASW operators engaged in the human activity of target detection using CRT/VDT display technology; the color, shading, format, contrast, and resolution of the display signal presentation would be critical considerations in making confident, unambiguous and consistent judgements. In this example one could deploy some very advanced and sensitive technology to tease out the signal of interest, but if the display format is not human engineered to be compatible with the operators sensory discrimination ability, cognitive expectations and the task being executed, then the human component within the ASW system will be limited and bounded needlessly.

Since color is a dimension of human perception and is a pervasive natural aspect of our world, one may judiciously consider using color enhancement techniques for the human viewer in order to enhance signal nuances and perturbations which would be significantly easier to detect as compared to displays which omit the color dimension.

The effective impact of the use of integrated color dimensions on human performance depends, to a great extent, on a numerous set of

interacting, and complex factors. A three dimensional scheme (Figure 1-1) is used to represent multidimensional facets of different types of color displays. This figure relates the purpose of the display to its content and static or dynamic characteristics.

FIGURE 1-1 Three dimensional taxonomy for color display usage.

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DISPLAY CONTENT

Both chromatic and achromatic displays contain a variety of content, ranging from the simple off or on "idiot light" to the most complex motion picture film or large screen command-control display. For the purpose of this paper, the following three types of display content seem useful to separate: discrete indicators and warning displays, symbolic presentation displays, and imaging displays.

Discrete Indicators

Color coding has stereotypically been used as a situation indicator, with green standing for safety, amber for caution or warning, and red for danger. These color codes have been applied to discrete color lights, sign

fields, and vehicular instruments. Some more complex displays that use color coding for symbolic relationships have tended to avoid the use of these specific colors, reserving them for their traditional meanings. Reserving these colors, limits the range of colors available to the designer in a multicolored display, a problem addressed in this paper.

Symbolic Displays

Color coding has been used extensively for the purpose of grouping like-meaning items and separating unlike ones. In some cases, the grouping is purely symbolic; in other cases, the color coding is intended to portray both categorical differences and geometric relationships. Examples of purely symbolic use are some text-processing systems, which employ color coding to separate inserted text from original text, and command-control-communication displays in which concepts such as friendly versus enemy, airborne versus ground, or division versus battalion versus unit may all differentiate by color codes. In addition, however, such displays may portray the geometric (or geographic) locations of the various items in a plan view display. On occasion, certain of the geometric relationships are also color-coded.

With the advent of 10-bit image processors, the three-primary-color display has the potential for simultaneous display of 2^{30} different colors (combinations of dominant wavelength, purity, and luminance). However, successive pairs of different colors drawn from this set may not be equally distinguishable from one another. If such extensive color resolution is used for discrimination purposes, the result is wasteful and may result in operator errors.

Imaging Displays

Imaging displays range from the complex full-color, wide-screen motion picture to the simple pseudocolor-coded satellite view of a planet, and from dynamic to static modes of presentation.

Other than those imaging displays intended to duplicate our visual perception of a familiar world, there are applications of computer technology to meaningful geometric images in which color is used to code different structures, objects, distances, and the like. All such artificially created color codes have one common objective: to substitute color for dimension of interest to the display designer and user in order to accent differences along that dimension and to facilitate natural grouping and spatial relationships. Thus, for example, pseudo-colored versions of computer-

aided tomography (CAT) and infrared imagery may help achieve easy discrimination of categories of objects, densities, or thermal levels.

THE PURPOSE OF COLOR IN DISPLAYS

Four categories of purpose were considered and particular display designs may serve more than one of these purposes: alerting, discrimination, grouping, and categorical, and organization

Alerting

The alerting function is used to warn the user that some state of a system is out of acceptable range or tolerance. Conventionally, the green-amber-red coding previously discussed is used, although this standard is often violated (for example, in nuclear power control rooms, both red and green lights are used to indicate acceptable conditions). Frequently, the degree out of tolerance is also indicated. An example is a thermometer display that changes color as the amount out of tolerance increases. On more sophisticated displays, one finds large symbols superimposed in a contrasting color to indicate a specific condition to which the operator must be sensitive and respond immediately. For example, a "breakaway X" on a military aircraft vertical situation display is a large symbol denoting that immediate action is required on the part of the pilot.

Discrimination

Under some operational conditions, color is used to improve discrimination among items on a display, by presenting one color symbol against another background color. As early as 1949, Chapanis suggested that the effective contrast for discrimination of one object against another is the quadratic combination of luminance contrast and color contrast. In more recent years, following development of quantitative systems of color measurement, researchers have explored the metrics of color contrast to yield prediction of visual discrimination between objects varying in both chromancy and luminance.

Grouping and Categorical Separation

The use of color grouping and categorical definition of items can be beneficial to a display user. The extent to which the benefits accrue is related to a number of variables in the displayed information, such as the number of

displayed items, the coded symbol legibility, and the logical relationship of the color coding to the immediate task of the user.

Aesthetic and Perceptual Organization

The most complete use of color, at least as measured by the number of different colors used, exists in literal images in which color is employed in its "natural" form to portray an equivalent photographic image in either two-dimensional or perspective view. In this application, color is used to reinforce both object separation and object/scene continuity.

One of the uses of color in dynamic, perspective imagery is found in motion pictures. Scene changes or "cuts" are often selected so that color is used for spatial orientation and perceptual continuity. For example, regions with distinctive colors are presented first in a wide angle scene and when a cut is made to a scene with a narrower field of view, a part of that colored region is

included in order to establish the location of the latter within the former. Thus, a red brick wall may be visible in the initial long shot and then be used as the colored background in the subsequent close-up, its function being to provide a perceptual bridge for the view and to aid rapid comprehension of transition. Cuts are particularly important in video presentations because with the low resolution and the narrow field of view typically provided by small screens, anything that helps comprehension of the large spaces being presented by successive views is desirable. However, the degree to which color actually contributes to the parameters of the process have not been the subject of explicit research.

Artificial color can be used to substitute for natural color in an attempt to emphasize certain objects in the scene. In this application of color, usually controlled by computer, realistic colors are replaced by surrealistic colors to achieve unusual aesthetic effects. Various forms of pop art are the result of this artificial color process.

Pseudo-color is used to achieve discrimination among what would otherwise be shades of intensity in an image. For example, some satellite earth resource images indicate vegetation and water patterns in a color coding scheme that, although logical, is not related to natural colors in the same scene. Pseudo-color is also used to depict stress and temperature gradients in mechanical components designed by computer (CAD).

DISPLAY DYNAMICS

Aside from the content of a display and the purpose for introducing color, there is a third category of variables that may either enhance or compromise the use of color. This category is related to the fixed or changing nature of the display content or color. Static displays are fixed throughout the viewing period, as in color landscape slides, fixed map displays, and pseudo-colored Landsat images. Dynamic displays can vary temporarily to show changes in position over time. An example of the latter is a color-coded weather radar display or a Safety Parameter Display used in commercial nuclear power plants to assess current plant status.

The next section of this report will discuss and define those variables which are known to influence human color perception and color discrimination.

The Current Status of Knowledge

APPLICATION OF KNOWLEDGE OF COLOR VISION

Extensive information available today about the human response to color has potential application to the design and use of multicolored displays. From Newton's discovery of the composite nature of white light to the present day, the field of color vision has attracted researchers from such diverse fields as philosophy, physics, mathematics, physiology, psychology, art, and medicine. The result has been numerous publications and an enormous mass of data (a summary of this material may be found in a publication of the National Research Council, National Academy Press, 1990...Application Principles for Multicolored Displays). Additional information is found in the proceedings of an AIC (Association Internationale de la Couleur) conference on color in computer-generated displays (Cowan, 1986).

Given this wealth of available information, one might assume that its application to the design of colored displays would be straightforward. However, a major recurring theme noted in a recent National Research Council's Human Factors workshop (1990) was the great difficulty found in the interpretation, generalization, and application of the existing information and knowledge. The reasons for this difficulty are many and include: the vast number of variables (e.g., physical, physiological, psychological, social, and contextual) that affect color perception, the many interactions among these variables, and the complexities introduced by individual differences in color vision.

The situation does not mean that generalizing from the existing data to specific applications cannot be done since there are many specific examples (Benzschawel, 1985; Frome, 1984; Kinney, 1979; Silverstein and Merrifield, 1981, 1985; Walraven, 1984). However, the more general the attempt to apply this knowledge, the more variables emerge as relevant, the greater the number of exceptions to be considered, and the longer and more complicated the resulting documentation becomes. For example, the *Color Display Design Guide* (Krebs, Wolf, and Sandvig, 1978) has 200 pages devoted to principles governing the color coding of displays and their applications. Similarly, a volume of over 300 pages was required to cover the fundamental visual, perceptual, and display system considerations for airborne applications of colored displays (Silverstein and Merrifield, 1985). One of

the many research needs, in addition to the proposal presented in Section 4, is a means of organizing and retrieving information from this vast amount of data.

VARIABLES AFFECTING HUMAN PERFORMANCE WITH MULTICOLORED DISPLAYS

A large number of variables directly influence the way an individual perceives and responds to color in displays. These variables include physical parameters and constraints, physiological aspects of human color vision, along with psychological effects and social considerations. Grouping these variables under physical, psychophysical, and psychological topics provides a logical framework for categorization. For some variables, this is relatively easy. For example, temporal stability, gamma correction, convergence, and phosphor decay are all physical in nature. However, many variables subsume two or three of these categories. Even with physical variables, the primary concern is how the eye responds to the physical variation. All the factors that may influence human perception and performance using multicolored displays are listed alphabetically in Table 2-1.

Interactions Among Variables

Although the color perceived by an individual depends, more or less, on each of these variables, the interactions among these variables may produce unanticipated color changes. And, since much of the knowledge on color appearance was obtained under controlled experimental conditions, such as a small field, a dark surround, and precisely measured physical stimuli, these interactive effects can pose particular problems.

These complications may be illustrated by an example. The spectral composition of a source of light is obviously a prime determiner of its color appearance; however, the correlation between the spectral composition and color appearance may be destroyed if the light is, for example, too small, too dim, too far out in the peripheral field of view, or viewed under too bright or too highly colored surround conditions.

If the object is too small, its color may be incorrectly perceived even if it is of normally sufficient intensity and is foveally viewed. Not all colors are similarly affected; some suffer a much greater distortion than others. This phenomenon, called small-field tritanopia because of its similarity to that form of color defective vision, is well understood. The spectrum around 575 nm, normally a greenish-yellow, appears white; those spectral colors above

575 nm look yellow-red, while those below 575 nm (including the blues, violets, and yellow-greens) appear blue-green (Thomson and Wright, 1947; Weitzman and Kinney, 1967). The choice of international orange for life rafts and life vests is a direct application of the facts of small-field tritanopia; yellow, the previous choice, is confused with whitecaps when the observer is distant. However, even the specification of the critical size is subject to interactive effects of other variables. The classic limit, less than 10 to 20 minutes of arc, refers to a circular area of that diameter; this configuration results from research conducted on the phenomenon that employed optical systems to provide the monochromatic stimuli. In multicolored displays, the geometry of the visual stimulus may be different, such as an outline drawing or an alpha-numeric symbol. The critical dimensions (construction element, total area, plane angle, solid angle, stroke width) for this type of symbol are unknown. The spatial distribution and integration area are undoubtedly important and, for colored displays, the pixel count is a factor.

TABLE 2-1, Factors That May Influence Perception and Performance in Multicolored Displays

Absolute luminance	Number of colors
Adaption level	Number of task relevant dimensions
Ambient lighting	Phosphor decay
Amount of display information	Redundancy of color code resolution
Brightness	Sequence of colors
Chromaticity	Simultaneous contrast
Color coding	Size
Color contrast	Spectral bandwidth
Color induction	Proximity effects
Convergence	Spectral composition
Diffuse reflection	Spectral reflection
Foreground/background effects	Surround or background
Gamma correction	Temporal stability: additive-spatial,
Glare	temporal, subtractive
Layout, font, grouping	Type of color performance: discrimination
Location in visual field:	recognition, identification
size and degree of eccentricity	User characteristics: age, color
Luminance contrast	vision anomalies, attention level,
Modulation: spatial, temporal,	experience or practice with the
chromatic	display

Individual Differences in Color Vision

A significant problem that may interfere with attempts to apply knowledge of normal color vision to multicolored displays is the extent of individual differences in color sensitivity. Many of the studies in the literature were conducted on two or three subjects. The results, while qualitatively similar between the subjects, do not allow estimates of the deviations to be found in the general population. Moreover, most of the color matching data was obtained by experimental techniques designed to eliminate the confounding effects of macular pigmentation on the matches. Large individual differences in response to metameres may be due to differing amounts of macular and lens pigmentation in the general population (Ruddock, 1972).

Another possible source of deviation among subjects is the possibility that absorption spectra of the photopigments may vary slightly from one color normal person to another. For example, Alpern and Pugh (1977) have data suggesting that differences in the maximum of the long wavelength photopigment vary over a 7 nm range. Mollon (1982) has summarized a number of studies that suggest this possibility and reviewed possible sources of error. Confirming evidence from molecular genetics was recently presented by Nathans, Piantanida, Eddy, Shaws, and Hogness (1986).

When color vision is studied in larger fields (approximately 10 degrees in diameter), individual differences are greater than those found for smaller fields. The contribution of the rods in fields of this size provides an additional source of variance, and even more complex interactions are suggested by the data of Palmer (1985). These remarks refer to color normal individuals and do not include the marked deviations known to exist in the appearance of colors to color defective individuals (see the Appendix). When more data is available for large groups of subjects, they may reveal differences of real significance for applications to multicolored displays among color normal individuals.

3

Emerging Design Principles For the Use of Color Displays

Color is being used in many modern applications to simulate the real world, to provide pleasing arrays, to provide continuity in motion pictures, or to enhance portions of a small signal in the context of much visual noise in the display. The inclusion of color in a visual display is rarely obtained without additional cost. Color displays, whatever their mode of generation, generally cost more to purchase, maintain, and use, than do their achromatic or monochromatic counterparts. Thus the provision of color in a display should be associated with some measurable or at least definable benefit. In some applications, the benefit may be largely aesthetic or subjective, while in others it may be directly related to user and system performance. In performance-related applications, two criteria must be met: (1) the addition of color must provide some measurable improvement in performance in at least some operational conditions and (2) there must be no decrease in performance under any critical operational condition. With respect to the purposes for which color is employed in current multicolored displays (e.g., alerting the operator to some change of system status, improving discrimination among items on a display, grouping and categorical separation, and aesthetic and perceptual organization), it is important to apply color effectively so that these two performance criteria are met.

Research to date has led to a number of design principles for the use of color in displays. In this section we review the research and principles and provide exemplary applications.

Principles of Color Appearance

The requirement that the colors perceived by the viewer are the ones intended by the display designer is basic to the use of color for any purpose.

To meet this first requirement, the desired physical stimulus (the appropriate spectral radiant power distribution) must be produced on the display and the observer must respond to this distribution as anticipated. The first requirement is a topic of concern.

The second requirement, the appearance of the physical stimulus, is the direct result of the information processing performed by the human visual system in response to the physical stimulus. Much is known about this processing; the color appearance of different radiant power distributions under specific conditions has been extensively studied. Expectations concerning the appearance of different spectral power distributions generally stem from direct foveal viewing of the light under neutral or darkened surround conditions. However, the colors perceived by the viewer may be different from those expected by the designer due to unknown or unanticipated responses by the human visual system.

While the delineation of adequate laws for specifying color appearances on displays requires detailed knowledge of display characteristics and purposes, generalities can be formulated from knowledge of the human visual system. The most important considerations are presented here; the reader is also referred to the Reference and Bibliography sections for more information through the references listed.

The most varied and highly saturated colors are perceived when the stimulus is foveally viewed and presented against a somewhat darkened surround. Too great an external illumination will cause the colors on the display to appear dark and unsaturated. In addition, too highly chromatic an external illumination may cause deviations in color appearance due to chromatic induction (Benzschawel, 1985; Walraven, 1984).

The phenomenon of small-field tritanopia has been described previously. If a color is to be recognized correctly, one must be sure that it is either large enough to avoid the tritanopic effect or, if small, that is one of the few colors (yellow-reds or blue-greens) that would not be confused.

Considerable evidence has been amassed that the blue system of color vision has poorer spatial and temporal resolution than do the red and green systems (Frome et al., 1981; Kelly, 1974). This has led some experts to discount the use of blue entirely for symbology on multicolored displays. In view of the many interactions, a more reasonable approach is to consider the application. If the information must be presented in small or brief form, it is best to use luminance or shape differences to encode it. Larger and longer

symbols can be color-coded, with red-green differences being more effective than blue-yellow (Benschawel, 1985).

If symbols on display are to be viewed with peripheral vision, color must be used with caution. The closer to the fovea, the more likely the colors will be judged the same when they are viewed directly; the farther out, the more likely they will be seen as white or very unsaturated (Burnham, Hanes, and Bartleson, 1963; Kinney, 1979; Moreland and Cruz, 1958). The loss of color vision in the peripheral retina can be compensated, to some extent, by an increase in size (Gordon and Abramov, 1977). The increases in size that are required, however, make this an impractical solution for some purposes.

Highly saturated colors of equal luminance will often not appear equally bright. For example, monochromatic reds or blues may appear several times brighter than colors of less saturation. The phenomenon, called the Helmholtz-Kohlrausch effect, has been extensively studied and is well understood. Techniques are available to make different colors on a display appear equally bright to the human observer (Kinney, 1983; Ware and Cowan, 1984).

A large variation in the luminance of a colored light will often result in a change to its color appearance (the Bezold-Brucke effect). Some colors are more affected than others and the direction of the change differs in different portions of the spectrum. The general rule is that the spectral colors tend to shift in appearance toward blue and yellow as their intensity is increased. Thus yellow-reds and yellow-greens appear bluer. Moreover, these hue shifts can occur when the perceived brightness of a colored light is manipulated rather than its physical intensity (Walraven, 1984).

Another change in perceived hue occurs when white light is added to colored light. This is, of course, a common method of obtaining a less saturated color, but it also results in hue shifts for some colors, known as the Abney effect. Unsaturating a blue, for example, may cause it to appear violet. The differences, while frequently small, could be important in applications in which it is essential that the hue remain constant despite variations in saturation (Walraven, 1984).

Evaluating the Use of Color in Displays

For the most part, the use of color in displays has been assessed by objective methods. Thus, accuracy of response may be compared for targets of different colors, or, more generally, for colored targets versus monochrome. Many ramifications are possible: color may be the only

dimension in which the targets differ from non-targets, or it may be combined with other attributes such as brightness, size, and shape. The number of colors employed, the specific color set, and their contrast with the background illumination are all variables that can be manipulated.

The time required for successful visual search has figured prominently in research evaluating the effectiveness of color in displays. In it the subject searches for a specific target in an array; the time required to locate it may be simply until the subject says "stop", identifies some distinguishing feature, or indicates success by pointing at or touching the target (Christ, 1975). Another measure used in visual search is the tendency to look at irrelevant objects, assessed objectively by the number of fixations on targets of the wrong attribute (color, size, shape, etc.) relative to those made on objects that share the defining characteristic (Williams, 1967). Again, a number of experimental manipulations are possible. An experiment by Carter and Carter (1981) provides an example. Subjects searched for a self-luminous three-digit target among other similar three-digit targets on a dark background. The variables included the number of other objects on the screen that shared the target's color, the total number of objects on the display, and the color difference between the target's color and that of the other objects. Each of the variables had a profound effect on both search time and relative fixation times.

Much of the information on the types of tasks for which color is effective in improving performance is derived from studies using these methods. For example, of the 42 studies comparing color codes and achromatic codes reviewed by Christ (1975), all used either accuracy of identification or search time as dependent measures of performance.

Subjective methods have also been used to assess color in displays. Subjects are asked to rate subjective pleasantness or personal preference for specific colors or for color versus monochrome. These methods almost universally result in support for the use of color. Subjects reported that the use of color seemed to make tasks easier and more natural. This is true whether or not there is any measurable change in performance with color (Christ, 1975; Kellogg et al., 1984).

While these objective and subjective methods have been generally successful in providing information on the use of colors in displays, a need for non-traditional measures for complex applications involving the total performance of the human-machine system was emphasized in the workshop. Color may have an impact on the total task by reducing operator workload and yet not show a measurable effect if assessed with respect to those tasks

involving only the color display. For example, Krebs and Wolf (1979) found performance improvements for a combined performance score for both tasks was computed (Figure 3-1). The advantages of color increased with increasing task difficulty. Luder and Barber (1984) also used a multi-tasked environment with similar results, thus emphasizing the need to assess total performance of a human-machine system in a complex task, in order to reveal the advantages of color.

FIGURE 3-1 Effect of different methods of color coding on tracking performance.
Source: Krebs and Wolf, 1979.

Use of Color for Grouping and Categorical Separation

Color is widely used to unify parts of the visual field. For example, this function is apparent in colored weather maps and in colored medical imagery. One of the largest effects of color found in perceptual research is the reduction of search time by color coding. This effect depends on color to unify items of the target color so that they can be scanned to the exclusion of other items on the display.

Visual search has been extensively studied, and a number of principles for the effective use of color in visual search have evolved. First, if color is to be effective in helping a viewer find a symbol on a display, the symbol's color must be known to the viewer. Without such knowledge, performance is poorer on a multicolored display than on a monochrome display (Krebs and Wolf, 1979).

Second, the advantage provided by color increases as the density or the clutter on the display increases. The principle is illustrated in Figure 3-2, which compares search times for monochrome and colored displays composed of varying numbers of symbols (Green and Anderson, 1956). In a simple uncluttered display, color contributes nothing to performance, while its greatest advantage is in the display of highest density. Under appropriate conditions, the use of color can reduce search time by 90 percent in a display of 60 items (Carter, 1982).

FIGURE 3-2: Effects of color coding as a function of display density.
Source; Green and Anderson, 1956.

Third, the average search time increases linearly with the number of items on the display that share the target's color, assuming again that the target's color is known to the viewer. For instance, average search time increases by about 0.13 seconds for each three-digit number of the target's color in the display area. The slope is steeper for more difficult targets (Williams, 1967). The linear effect of the number of items on the target's color is the most powerful determinant of search time in a colored display (Carter, 1982).

Fourth, items not of the target's color have virtually no effect on search time if their color is sufficiently dissimilar from the target's color, for example, a red and a green (Carter, 1982). Thus a display designer can avoid decrements in search performance due to non-target colors by selecting a color code that maintains adequate separation in color space among colors. Separation or similarity of colors, one to another, can be represented by quantitative color difference formulae (see the Appendix) for this purpose (Carter and Carter, 1981; Neri, Luria, and Kobus, 1986).

Items of a color similar to the target's color (i.e., a red and a red-orange) will have a deleterious effect on search time. This effect is additive to that of some target-colored items: formulae predicting search time can have separate additive terms combining the contributions of target-colored and other-colored items on the display. The coefficients of other-colored items will be zero for colors far removed from the target color in a uniform color space (Williams, 1967).

Similar conclusions have been reached in another study (Neri, Jacobsen, and Luria, 1985). A matching task was used to evaluate performance with 10 different sets of seven colors each. The larger the color difference between the most similar colors in a set, the shorter the reaction time, and the fewer errors made on the color matching task.

One of the most effective applications of color in displays is to organize or to unify different parts of the visual field. It is used in color weather maps, color medical imagery, computer-enhanced pictures, and many other applications. One of the pronounced and most useful results of perceptual research is the reduction in search time achieved by the use of color coding. This effect depends on color to unify items of the target, so that they can be scanned to the exclusion of other times in the display. Color is a useful cue for doing a fast, simple, initial parsing of the visual field. This facility may stem from the fact that color information is one of the first attributes to be extracted in processing the visual image. Since there are few restrictions on the choice of colors, sometimes color is used simply because it

is available. The more colors, the better is a common philosophy, although it is an uneconomic and untested solution.

The use of color for organizing data is an application for which there is a great need. For example, Earth Observational Remote Sensing Systems generates an overwhelming amount of data. The Landsat system, in its first generation configuration, produced frames of imagery that contained approximately 7.5 million pixels in each of four spectral bands. These have been produced continuously since 1972. A down-link data rate of about 30 megabits/second is needed to deliver the data to earth. In the second generation system, the spatial resolution has more than doubled and the spectral bands increased from four to seven, requiring a data rate of 85 megabits/second. Future systems being planned will involve many more spectral bands and substantial increases in the complexity of data. A significant problem in the field has been how people can successfully make use of such a volume of data. The issue is much more complex than the interface with the imagery itself, because of given data set consists of seven interrelated images in different spectral bands. Furthermore, the use of such data might involve, for example, merging newly collected Landsat data with existing geographic information expressed in visual imagery.

Color, by its very nature, seems to contain an answer to this interfacing problem. Colors exist in a three-dimensional volume of hue, brightness, and saturation, allowing relationships among data to be expressed in a variety of color schemes that could not be done in a single dimension of monochrome. Furthermore, color space is not essentially isotropic: it has significant internal structure. The achromatic axis is special, as are the red-green and yellow-blue axes. There is an increasing amount of imagery that is inherently multidimensional, such as in the multiband Landsat, and it is natural to display it in color, which is also multidimensional.

Despite the apparent rationality of such an approach, unanswered questions remain. For example, are there advantages to be gained by paralleling the data dimensions with intrinsic color dimensions? Insofar as a priori metric can be established in the original data, one could try to preserve it in the metric of the color space. And insofar as meaningful axis can be established in the original data, one could try to map them onto the perceptual axis of color space. As a simple first pass, a principal component analysis could be performed on the original data, mapping the first component onto luminance, the second onto the blue-yellow axis, and the third onto the red-green axis. There is some evidence (Buchsbaum, 1987) that this is a useful way of thinking about how the human visual system decomposes natural images.

Likewise, the planes corresponding to the equilibrium hues could be used as landmarks in color displays. For example, if a variable is coded onto the range red-to-yellow, passing through orange in the middle, the perceptual consequences may be quite different than if it is coded onto the range orange-to-yellow-to-green, passing through yellow in the middle. In the first case, the end-points are poorly defined. Again, there is little data to indicate the usefulness of this or other approaches for choosing colors to organize multidimensional data.

Other unanswered questions concern the choice and the number of colors to be used in displays of this type. There is a limit to the number of colors that can be employed and still retain their advantage over monochrome to organize the data and make them more comprehensible. Evidence that this number is small and suggestions for the choice of colors themselves are discussed in the section below on specific colors to be used for coding. In the Landsat observation, the limit may be approached or exceeded in the future generation systems; for example, one current prototype has 128 spectral bands. Another problem stems from the limited number of hues, intensities, and saturations that can be discriminated absolutely.

Colors as an Aid to Discrimination

Color, to the extent that it provides contrast, has been shown to improve the discrimination among items on a display. To assess the degree of discrimination, some means of measuring or specifying the amount of contrast among colors is required. Several studies have measured color contrast (between equally bright or equally luminance colors) by determining the equivalent luminous contrast. For example, acuity was used as the dependent variable in one study; the amount of luminance contrast was found that produced the same letter acuity as achieved with letters formed by hues of equal brightness (Eastman Kodak, 1944). In another study, apparent contrast between equally bright color pairs was measured by asking subjects to compare the appearance of color differences to luminance differences (Post, Costanze, and Lippert, 1982; Snyder, 1982). In a third type of study, the perception of a minimum border between two colored fields was measured, either by comparison to a border formed by luminance contrast (Kaiser, Herzberg, and Boynton, 1971), or by measuring the duration that a minimum boundary was visible (Frome et al., 1981).

Two conclusions can be drawn from these various studies: (1) luminance contrast is a much more effective determinant of visibility than is

hue contrast, and (2) hue contrast can aid discrimination, but only if the hues are widely separated in color space and there is little luminance contrast present, i.e., less than 10 percent (Lippert, Farley, Post, and Snyder, 1983). Furthermore, there is evidence that red-green contrast is more effective than yellow-blue contrast in improving visibility (Frome et al., 1981; Kaiser and Boynton, 1985; and Boynton, 1976, 1978).

The Alerting Function of Color

In order that the alerting function be successful, several principles must be followed. First, the more sparing the use of the warning color, the more effective it is as a warning (Krebs and Wolf, 1979). This principle can be expanded to the use of a warning color on adjacent displays. For example, the use of red to map an area on one display may interfere with its alerting function on an adjacent display (Frome, 1984). The system designer must consider the whole system in choosing color codes.

Second, the colors chosen must be in number and as discriminable from one another as possible. Krebs and Wolf (1979) suggest that no more than five colors should be used and an optimum number would be three or four. The restrictions on the number of colors employed for alerting functions stem from the attempt to eliminate errors of color confusions under as many conditions as possible. Specifications of colors for coding, such as signal lights at sea, aviation colors, and colors for traffic control, are generally available. Figure 3-2 depicts such a set of specifications, for signal lights at sea (Commission Internationale de l'Eclairage, hereafter CIE, 1975). These recommendations are being updated to include restricted specifications to minimize confusions among color defectives.

FIGURE 3-3 Recommended color boundaries for signal lights shown on the CIE chromaticity diagram. Source: Commission Internationale de l'Eclairage, 1975.

Using Colors for Realism in Computer-Generated Imagery

An increasingly popular role of color in displays is in computer-generated images. Color may be used for aesthetic purposes, as in pop art and TV advertising, or to mimic the real world, as in simulators used for military training. In either case, computer-generated images are currently very costly in terms of computer time. Major reasons for this high cost are lack of knowledge of the degree of realism required for different applications and of principles to employ color effectively to achieve this level of realism.

In some cases, the maximum photographic level of realism is not required or even desirable. Wire frame images or simple diffuse shading may be sufficient to depict the surfaces desired. Moreover, high levels of realism can actually yield diminishing returns. Added realism increases potential ambiguity; the viewer may see the wrong thing. A photographic image of a polished metal object, for instance, would include mirror-image reflections of its surroundings due to specular reflection. In such a circumstance, these superfluous reflections could distort the viewer's understanding of the geometry of the object.

An example of these unresolved problems is found in real-time flight simulation, in which there is an increasing demand for more realism. If the simulator is to be most effective, the pilot's training on it must transfer to real-world behavior. Unanswered questions abound in this area, including the degree of realism required for effective transfer of training (Jones, Hennessy, and Deutsch, 1985). Much of the terrain for a flight simulator can be modeled with only diffuse reflection, because much of the real world has a matte appearance. However, some features, such as water, pavement, and other artifacts, exhibit considerable specular reflection as well. Correct interpretation of these features may require specular information that is not generally provided in simulators. In addition, although color shading is an effective way of achieving realism and giving an impression of three dimensions, there are no guidelines to govern how many colors are needed or how many colors can be perceived by the observer. The current procedure is generally to provide physical fidelity; that is, to simulate as much as possible the physics of light reflected from the real scene. However, this can be a very costly solution.

This paper has brought up several specific questions concerning the use of color to simulate reality for which there are, at present, no adequate

answers. They involved shaded images, the importance of highlighting and diffuse and specular reflectance, and the dynamic use of color.

Shaded images are often used to simulate the perception of three-dimensional objects and can produce a very compelling impression of depth. The quality of such images depends on the number of simultaneously displayed colors available, and on the number of individual picture elements (pixels) in the image. Typically a computer-aided design (CAD) display of just a few years ago consisted of a raster-type cathode-ray tube (CRT) with 256-512 lines and as few as 65,000 pixels. With palettes of only 4 to 16 colors, realistic shaded images could not be produced. However, today's displays can have 1,536 lines (more than two million pixels) and over one billion colors.

The question of "how many colors will suffice"? is unanswered. The use of too few colors causes boundary artifacts to appear between colors (called *contouring*) when the objective might be a smooth imperceptible transition between colors. This objective can generally be met with 4,096 colors (4 bits per gun) or even fewer. At the other extreme, the subjective quality, called perceived realism, seems to require more colors. Some in the computer animation industry believe that full color requires 24 bits or 16.8 million colors. Some indeed claim to see improvements between 24 and 32 bit images. Others argue that 16 million colors are excessive and point out that the most demanding case would require no more than one color per pixel; 16 million colors cannot be displayed simultaneously on any current display because there are not enough pixels. It is also argued that the viewer cannot perceive that many colors. Limb, Rubinstein, and Fukunage (1977) report a maximum of about 50,000 distinguishable colors.

Other techniques are being tried to increase realism without adding additional colors. Heckbert (1982) used look-up tables for colors that were determined by their statistical distribution rather than by equal intervals in the color space. He created images with only eight bits per pixel that compared favorable with images of 15 and even 24 bits per pixel. Pixel averaging techniques, which further mutilated contouring effects and created more effective colors without increasing memory requirements, improved images even more.

Raster displays suffer from a potential problem in that all elements must be composed entirely of horizontal line segments. The resulting stair-stepped or scalloping aberration associated with oblique lines can be mitigated by a greater raster density or by techniques involving recalculation of certain pixels (anti-aliasing algorithms). Both techniques result in higher

costs. While this is not a consideration specific to multicolored displays (it occurs in monochrome as well), the question of whether there are color dependencies in these techniques should be addressed. The differential sensitivity of the eye to spatial, temporal, and orientational variations in different colors suggests that color dependencies might exist.

Another question involves the degree to which specular and diffuse reflections need to be presented in the CAD images for the perception of realism. All materials are characterized by some combination of specular and diffuse reflection, the former being important for the perception of glossy surfaces, for three dimensionality, and quite probably in air-to-air flight

simulation. However, diffuse reflection is relatively easy and inexpensive to simulate, while specular reflection requires more colors and more computer time. In addition, the simulation of specular reflection, whose luminance ranges in the real world may be 1,000 or 10,000 to 1, may require greater luminance ranges than are generally found in CRTs. The trade-offs between the expense of computing specular reflections and the perception of reality are unknown.

One recent paper was cited as addressing this point. Different pictures with different degrees of fidelity were shown to subjects who were asked to rate them for realistic appearance. The minimum number of pixels required for faithfulness of the perception in a sphere was derived from the results (Atherton and Caporeal, 1985). This technique in human evaluation of image quality may prove useful in answering other questions about the simulation of reality.

The relationship between color and perception of motion is another issue in the simulation of reality. One important function of color in the perception of the world is to indicate, in a normally cluttered environment, which parts of the field of view belong together and will move together. Size, motion, and color interact together in object segregation, and the color effects on perceived organization can be substantial, as is indicated by the Ishihara color vision tests and by numerous search investigations. There have been few experiments dealing with the effect of color in organizing moving arrays, and, paradoxically, color does not seem to be a prime determinant of perceived motion. For example, apparent motion can occur between different colors, rather than the same color, when the configuration allows for either perception (Johansson, 1950; Ramachandran and Gregory, 1978). An analysis of the functions that color does serve in segregating still and moving objects from their surrounds and backgrounds is necessary.

The Choice of Colors

The seemingly simple questions of which colors should be used on a multicolor display is fraught with complications and unanswered questions. It is essential to know beforehand the purpose for which the display is to be used. A simple alerting function requires fewer and different colors from those needed to simulate reality. In selecting color for coding purposes, questions concerning specific colors, number of colors, and possibilities of color continua for continuous quantities must all be addressed.

Specific Colors to be Used for Coding

The theoretical and practical limits to the number of categorically different colors that can be employed are based on information available for surface colors, rather than emissive ones. It is obvious that there is still much to be learned from the study of surface colors. For example, the mechanism of color constancy, which allows these colors to remain remarkably stable despite changes in the spectral character of the illuminant, is an important aspect of the perception of surface colors. A number of differences in the perception of surface colors and emissive colors may affect the use of color for coding. Video displays allow both the illusion of surface colors and the perception of disembodied colors floating on the face of the screen or superimposed on the real scene.

From a survey of the literature on naming of surface colors, three lines of converging evidence were discussed indicating that the upper limit of surface colors that can be employed without error in the ideal condition is exactly 11. That is, there is a potential set of 11 real reflecting colors that, under appropriate viewing conditions, will never be confused by people with normal color vision. The first type of evidence comes from color names. Evans (1948) cites a study of word counts of 17 most popular colors in that era. Of 4,416 color terms used, 4,081 (92 percent) were counted for by 12 names (white, black, blue, red, gray, green, brown, gold, yellow, pink, silver and purple). Similarly, Chapanis (1965) describes an experiment in which subjects were asked to select from a large array of Munsell chips, those that were the best examples of a variety of color names. Consistent selections were made for white, gray, and black, and for orange, yellow, red, green, and blue. Purple and violet were used consistently but a further analysis

showed that these terms were used to name almost exactly the same colors. Taking this into account, the list of consistently employed names included pink and purple also.

A second line of evidence is provided by a study of confusions among colors. Halsey and Chapanis (1954) examined 342 colors of equal brightness produced by transillumination against a darker surround. A test color was presented with 171 of the others, randomly chosen, and subjects were asked to select those that "satisfactorily matched" each standard. The safest set of colors for coding, those for which there was no overlap among the confusion contours, are shown in Figure 3-4. Although color names were not employed in their study, green, yellow, red, purple, violet, blue, white, and pink are probably the best descriptors. This study shows that, if adaption levels are controlled and only colors brighter than the surround are used, as many as eight can be employed for color coding in video displays. Because stimuli darker than the surround were not presented, gray, black, and brown could not be seen.

FIGURE 3-4; Confusion contours for eight standards. Each line encloses colors that were confused with the standard a given percentage of the time. Source: Halsey and Chapanis, 1954.

A different type of evidence comes from a cross-cultural study (Berlin and Kay, 1969) concluding that color names develop in a seven-stage order in the history of a given language. Figure 3-5 shows this order with the same 11 colors: black and white are the first names to evolve and the blends - purple, pink, orange, and gray - the last. In another naming study, Battig and Montague (1969) had 442 subjects write down the names of as many colors as they could think of in 30 seconds. Violet was one of the colors named. Otherwise, the 11 colors most often named first are those of the Berlin and Kay list.

FIGURE 3-5 The order in which the use of color names have developed in language. Source: Ratliff, 1976.

The 11 colors then can be grouped as bright, unique colors (white, red, green, yellow, and blue), bright blends (orange, purple, and pink), and dark colors (gray, black, and brown). Two of the names from the word counts (gold and silver) are excluded because they are "object substance" names (Evans, 1948). The remaining names are the same as those that emerge from the cross-cultural analysis. Oddly, orange is missing from the word count list, and purple was uncommon. Perhaps this is because these colors can be completely described as combinations of red-yellow and red-blue, respectively (Fuld, Wooten, and Whalen, 1981; Sternheim and Boynton, 1966). This list thus comprises the achromatic colors, the psychologically unique colors, and three blends. The reason for the lack of a commonly accepted name for the blue-green combination is not known. While 11 colors appear to be the limit for surface colors, there are a number of reasons why the number of colors are not confused on a video screen is less than this limit. An important one is the requirement for reliable and consistent color production and calibration. A second reason is that color-coded characters in many video displays are almost always brighter than their background, thus eliminating brown, gray, and black. It would theoretically be possible to employ all 11 discriminable colors in the video display, particularly if it were designed to appear as a surface. To achieve this effect, the video display could be produced on a thin surface and viewed under appropriate surround

conditions so that the colors changed under ambient illumination as if they were reflecting surfaces.

Additional experimental work is needed to verify and extend these speculations. It would be useful to determine the chromaticities of the 11 surfaces that, under a given illuminant, are the optimal representatives of the given color. A next step would be to alter the spectral character of the illuminance and determine for each color the best example from all possible metameres from the standpoint of resistance to color change.

Carter and Carter (1982) presented another approach to choosing specific colors to be used for coding. They used the conventional idea of color as a three-dimensional space and suggested that, if the space were perceptually uniform, then colors (represented by points in space) could be chosen to be as far from each other as possible in this space. They had

previously shown (Carter and Carter, 1981) that, as the distance between color points increases, discriminability of color codes is improved. In this conception of the problem of choosing colors, the capabilities of the display to be used are taken into account as boundaries on the achievable colors in color space. Carter and Carter offered a computerized algorithm to choose high-contrast set of colors tailored to the capabilities of the device to be employed. The merit of this system warrants further investigation.

Color Continua

If color coding is to be used to depict spatial variation of continuous quantity, such as stress or temperature across a surface or position in depth, there are a number of possibilities for the color continuum. One could use the spectral continuum from violet, through blue, green, yellow, orange, to red; the range of perceived brightness such as white, yellow, blue, black; or a range based on color temperature, red (cooler) to blue (hotter) or on a perceived temperature, as red (hot) to blue (cold).

An intuitive arrangement, using the spectral continuum, for coding three-dimensional representations may be presented with red on top, orange as the next layer, etc. Another intuitive scheme is the use of saturation variations of a single hue to depict changes in intensity, the most intense shown as the most saturated.

In practice, pseudo-colors are frequently used to depict temperature gradients. This relationship may be appropriate because of long-standing

associations between color and temperature (red with warmth and blue with cold). In fact, this association between color and temperature is one of the few psychological effects of color to be replicated over the years (Payne 1964). The red-to-blue spectrum may be equally appropriate for associating most-to-least gradients in depictions of pressure and stress or, generally, any gradient of activity or potency. In studying the meaningful connotations of colors, Osgood (1971) found systematic effects of color on the judged activity or potency of the objects with which they were associated. Regardless of the object being judged, those depicted in colors toward the red end of the spectrum were judged to be "passive". Some of these associations between color and attributes of objects may be cross-cultural (Oyama, Tanaka, and Chiba, 1962).

However, there have been very few empirical evaluations of such schemes, and in at least one the outcome was unexpected (Frome 1984). In this application, color was employed to spatially separate but relate information in a CAD display: everything on each layer of a printed wiring board was displayed in a single color. To evaluate possible color schemes, six sets of hue/value combinations were selected and sample lines in each color were displayed to designers who were asked to specify which should be used for each layer. Surprisingly, there was good agreement that red should be the top layer, green the bottom, and aqua the interior layer. Before, the study many

people wrongly guess that the designers would use intensity or brightness as the code for layer. The underlying basis for their choices is not known; one hypothesis is that the lowest level is most closely associated with the base material of the printed circuit board, which in virtually all cases is green. More research on this topic is required in order to develop a reasonable rationale for the choice of a code for color continua.

4 A RESEARCH AND DEVELOPMENT PROPOSAL

**Submitted to:
The Office of Naval Technology**

**Developing Advanced Assessment Methods and Acceptance Criteria
for the Use of Color Enhancement of ASW Displays**

by:

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Abstract

We propose to develop an experimental observation system to record and analyze user-computer interactions with ASW (WRAP) generated displays. This observation system can be used in the design and evaluation for user interfaces which use color to enhance human detection, discrimination and target recognition. A diversity of different colored display interfaces can be analyzed, ranging from complex signal patterns to simple comparisons between noise and signal presentations. The focus will be on measuring user productivity and performance. We will compare productivity under different environmental and color pattern conditions, and with different user interfaces to computer applications having the same functionality. We will seek to identify key human detection parameters, and understand how they interact with different ASW display formats. This proposal involves the assembly of appropriate hardware and software components in a passive, non-obstructive configuration, so as to generate contamination free, human performance data. The aim of this research is to

engaged in ASW signal detection tasks and determine which set of key interacting variables, and the required magnitude, are needed to optimize man-machine detection performance.

I. Background

Over the past 15 years, computer generated displays have become common in ASW detection and recognition tasks. However, its acceptance has not necessarily brought an improvement in human performance. In fact, the displays generated by the WRAP model are quite complex and difficult, at best, to interpret without the costly expense of intensive training and practice.

A great deal of work in the Navy requires computer usage; and a significant amount of the work is done in signal processing. Scientists, engineers, and ASW operators, deal with computer technology, primarily workstations and personal computers. These people use the computer tools at hand to perform their jobs. However, the integration of the WRAP Model and super computer into the ASW environment may not optimally improve detection performance unless we understand the basic principles of signal enhancement needed by the human eye and brain. In particular, it would be useful to determine, for applications of similar functions, what works best and what hinders communication through these user interfaces, comparisons being made in terms of user detection, hits, false alarms, correct rejections, etc., or, in other words, human performance.

Our proposed system will allow us to conduct experiments while the user attempts completion of certain tasks. We will obtain physical, behavioral and physiological data about the user in terms of specific and general ASW applications. All the data will be analyzed, correlated, and presented in terms of significant effects and interactions. The experience we gain in repeating experiments will validate the metrics selected and uncover key determinate, and interactive factors.

We also will be able to evaluate user interface and ASW application prototypes developed and provide specific and general rules for expected and measured performance improvements. This feedback would be especially helpful and have the most impact with those applications intended for large numbers of users or where the consequence of user actions is critical to mission success.

Research is currently under way in the areas of computer-human interface and human factors in many universities and industries. Some diverse areas of the industrial research are: airplane cockpit operations, network-based products and services, video games, spreadsheets, and weapons command and control systems. Yet, inadequate attention has been paid to evaluating and improving many of these interfaces. At ONT, the primary emphasis tends to focus on model development and software development, with little attention paid to improving human performance in aiding the accomplishment of a specific function. The lack of quality in the user interfaces, although noticed, has been generally accepted (exceptions can be found in design of real time control systems [Banks85]). The costs in awkward usage and correction of problems have been high. Some examples of in-house developed systems intended for many users that have had significant user interface problems, discovered only after a certain amount of practical usage are: supercomputer operating system shells, real-time access and control systems. The most effective way of evaluating usability is by observing usage [Monk88].

While it is common in industry to see applications tested in a Usability Testing Lab [Poto90] before product distribution, the Navy, currently has no such dedicated facility. We propose to serve this function. Our laboratory could provide special equipment to record and test people performing tasks with different software products, in a test room with video monitors, video controlling equipment, video tape recorders and possibly personal computers to log and record data. Our proposal to develop advanced assessment methods and metrics for color interface design and evaluation is also very germane to the software engineering process currently used in ASW research. Typically, software development begins with a problem to be solved and a requirements specification. The requirements describe the system to be built quantitatively in terms of measurable attributes. These represent system constraints. They are necessary because they provide the clarity of purpose needed in finding the appropriate solution to the problem. After the system has been built, it can not be determined whether or not it meets its requirements specification unless all attributes have been made measurable in practice. Often a complex concept of "usability" is a requirement. Principles of software engineering management require this to be broken down, until a set of simple attributes is defined, each one which can be measured. Thus the concept, "usability", as a whole becomes measurable [Gilb88]. Our proposed system will bring to the Navy, new metrics for the user interface and the capability for advanced performance measurements. This is essential if the Navy desires to engineer software which meets its "usability-performance" requirements.

II. Goals

This proposal is to initiate work in user interface evaluation and improvement by putting together an observation system made up primarily of off-the-shelf hardware and software components. The system will be used to take physical, physiological, psychological and performance measurements of the user in non-obtrusive ways and will record what is happening, in real time, within the application's user interface. The integration of the observation system components is to be done by the engineering and computer sciences researchers. They will make the system portable so that it can travel to the user's work area. Research psychologists will have primary responsibility for the design and conducting of the experiments. Appropriate procedures will be established to conduct the experiments, test subjects will be selected and statistical analysis done on the results.

As the user attempts to accomplish specified goals, both physiological data about the user and data about the running of the application will be collected. Data collection will be synchronized and taken at a minimum steady rate controlled by the observation workstation. Data collection will also be triggered by the observation workstation based on the status of the readings, the state of the application, or a user interaction. All data will be time-stamped to make correlation possible. Some real-time monitoring and control will be done at the observation workstation in order to insure that the data is being collected properly and that the sample rates are appropriate. After the data is collected, researchers will use image processing and multivariate analysis to seek correlations, and determine significant interactions..

Possible metrics are:

- 1) Time to train (six times required to understand program operation)
- 2) Amount of eye motion
- 3) Amount of hand motion
- 4) Pupil changes over time
- 5) Face temperature changes over time
- 6) Pupil and/or face temperature changes related to specific application interaction
- 7) Amount of eye motion preceding hand actions
- 8) % utilization of display space
- 9) Tracking of eyes on the display
- 10) Time to respond to program prompt

- 11) User interest level over time (derived from pupil size and temperature time profiles) and correlated with verbal reports
- 12) User satisfaction (derived from ratio of positive to negative interview remarks and Likert scaled test items) and
- 13) Amount of work completed over a fixed period of time
- 14) Detection time and errors
- 15) Recognition time and errors
- 16) Discriminability accuracy (in percent) over time and under different work loads

The initial components of the observation system are:

- 1) An observation workstation to act as a host computer to control and receive data from the other components
- 2) Analysis programs and image processing tools for the observation workstation
- 3) A low resolution infrared camera to obtain digital data on the amount and variation of temperature changes over time of the user's face
- 4) A low resolution color camera to watch the users hand motion
- 5) Video recording of user workstation full screen display
- 6) An eye-gaze system which determines where a user is looking and pupil size by following the gaze point without special headgear
- 7) The user workstation
- 8) The user application, and
- 9) The shell or driver interface to the application to collect user keystroke and mouse moves, and an application monitor to identify these

Recently technological advances have made it practical to put together this system. The eye-gaze system has been commercially available only for the last 18 months, and a headtracker is currently under development. In general, the costs of the other components have been going down and the choices in the marketplace have been increasing. Figure 1 is an overview of the relationships between the components of the observation system.

The need for such a high-tech, flexible configuration is justified by the difficulties in finding the most useful and easily measured metrics, and deriving conclusions as to application usability. At this point, we don't know what metrics are important, how easy they are measured, or how they are

correlated. The opportunity to study what goes on while the user is working with an application without touching or interfering with the user is only possible with cameras and systems such as they eye-gaze system.

Figure 5.5 shows a side view of the camera configuration. The eye-gaze camera system is mounted beneath the user's workstation monitor, and the IR camera observing the face is in-line with the eye-gaze camera but set back farther. The eye-gaze camera has a narrow field of view of about 6 degrees, while the other has a wider angle of view to include the user's face. The user's keyboard and mouse are located at the front of the table and are in view of the low resolution color camera. The dedicated PC, which is part of the eye-gaze system, is not shown. Neither are the rest of the user's workstation, nor the video connection to the workstation display shown. It would be best if the observation workstation be located nearby, but not in the same room with the user.

Figure 5.5 Camera Configuration

With the system in place in the user's environment or similar environment, the actual testing session would proceed from an experiment plan. The plan could originate from productivity requirements desired by the management of a project or organization sympathetic to this research. The designation of user subjects would be determined by the plan and by the requirements for a statistically meaningful sample. The experiment plan would include the metrics for which data would be taken and the usability attributes for which information was desired. The user would be informed of specific tasks to be performed and the time limit.

The session would begin with the eye-gaze subsystem being calibrated to the eye of a new user subject. The user would start up the application. Either modified I/O drivers or an application shell would capture all subsequent user keyboard and mouse interactions. The user would try to complete the tasks outlined in the test plan. From the observation computer, the collected user inputs, video and thermographic data would be monitored, and some real-time analysis done to verify that the data collection was working properly and that the rates of data collection were set appropriately. Eye tracking applications written using eye-gaze software tools would display real-time data on the eye-gaze subsystem monitor. At the conclusion of the session, the user would be interviewed. Subsequent analysis, and the comparison of the results of many different user sessions with the same task assignment would reveal information about the quality of the application's user interface and the productivity of the users.

The goal for the first year is to build a minimal system and explore its potential. Components will be brought on-line and checked out one at a time. A sample experiment will be designed and used to check-out the integration of the observation components and the instrumentation of the application. Analysis procedures will be written to calculate the metrics. Experimental data will have to be stored and retrievable. It is desirable that the observation workstation be able to display the data and various usability analysis results simultaneously using windows.

A follow-up proposal is planned for next year, assuming this proposal is approved and the work is favorably received. Next year's proposal will focus on collecting additional data on the user and the tasks being performed, further development of analysis and reporting of results, and wider testing. Additional effort is expected to be needed to solve problems encountered this year, add on a headtracker subsystem, integrate visible video of the user, and study the effects of replacing certain application hand cursor controls with eye cursor controls.

III. Technical Plan

This system will be prototyped by Nancy Storch and Bill Banks over the period of one year based on allocations of 220K. Nancy has extensive experience in user interface design, image processing and real time systems. She will co-lead the project, design the system, develop software, and do experimental system testing and debugging. Bill has a national reputation in behavioral psychology and experiment design. He will act as the co-investigator for human factors research and also provide statistical evaluation and interpretation of the data gathered, and insure consistency and quality assurance in the testing of subjects. An additional person with the experience in integrating real-time personal computer based data acquisition and control, and image capture systems will be needed 0.50 FTE. This person will assist in the: design and implementation of the data acquisition and control, and selection of components. He/she will also assemble and check-out the integrated system.

The deliverability will be:

- 1) A detailed research plan and schedule based on a selected application and selected scenario
- 2) A working observation system
- 3) Defined analysis capability
- 4) Observation data bases
- 5) Identification of key metrics
- 6) Results in using the observation system to analyze the user interface of at least one application, and
- 7) Documentation of the observation system hardware & software design

Questions which will be addressed are:

- Which metrics should be used?
- What are the best ways to obtain data for metrics?
- How accurate are the experimental measurements and the metric calculations?
- What relationships, if any, exist between the different metrics?
- What are the correct relationships between the metrics and the usability attributes?

- Does the user move so much that headtracking will be necessary?
- Will the user need to sit in a high back chair to limit head motion?
- Can observation work in the user's environment?
- Does the eye-gaze subsystem give misleading data when the user becomes unfocussed when thinking?
- Do other physiological measurements need to be take (pulse, etc.)?
- How to correlate the user task performance with the physiological feedback?
- How to interpret the IR face data: What can we learn from medical thermography?
- How to compare similar function prototypes or applications?
- How to determine the significance of observation results?
- How to use observation results to influence design of user interfaces?
- How relevant are observation results on the selection or development of the best user interfaces?

The time estimate is based on the following development schedule for FY92

11/91 - 12/91	Detailed research plan and schedule
12/91 - 4/92	Select and acquire hardware/software
2/92 - 8/92	Integrate components in phases:

I. Application instrumentation (capture keyboard & mouse input; periodically record snapshots of user workstation display; be able to replay the snapshots; collect and analyze metrics used to measure productivity)

II. Add the eye-gaze subsystem; collect related metrics; develop more analysis programs; correlate to the application

III. Add the IR subsystem; correlate IR data with the other data; include in the analysis

2/92 - 3/92	Design of appropriate session data base
	Design of appropriate cross-session data base
3/92 - 8/92	Design and write observation data acquisition and control
	Design and write observation analysis
7/92 - 8/92	Experiment testing
8/92 - 9/92	Test and evaluate results

IV Impacts/Benefits

This proposal has potential benefit to many current projects within the Navy. The proposed observation system could be used to scientifically validate proposed displays using human performance measurements as the ultimate acceptance criteria instead of using the developers subjective assessment. In Navy technical efforts which have high visibility, it will be important to show that we can incorporate human factors performance measures to objectively measure the acceptability of a particular format, interface, and task requirements by the end user. For example, NERSC is currently building a super computer network with symbolic graphic displays to inform technicians as to the operational and diagnostic status of the network.

ASW scientists have developed many interface displays which have been developed using criteria such as ease of programming and speed of programming with virtually no scientific validation using objective measures of human performance. The system we propose to build could be used to validate, identify problem areas and suggest changes to enhance the operability of the system as a whole from a human performance perspective.

This approach would certainly lower the probability of human error and provide a performance based set of criteria for the acceptance of a particular interface design and format.

Within the Navy there are a number of systems which have integrated computers and humans which can affect health, safety, and/or security. Usability analyses of these systems under normal conditions and under user stress conditions could help avoid possible dangerous consequences and harm. The use of the proposed observation system would be a valuable addition to the quality assurance process.

Specific Benefits:

- 1) Positions the CNO and US Navy for future military interface assessments
- 2) Employs a multidisciplinary team which will gain experience in this area
- 3) Provides a dog and pony capability for Admirals to show to congress
- 4) Provides an objective, performance based means of measuring a traditionally subjective phenomena (interface acceptability) which could result in a measured decrease in the probability of human error
- 5) Improves QA of computer systems where user actions can affect E S & H

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APPENDIX A

The Use of Color in Complex Information Displays

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The advantages and disadvantages of color coding in information displays are summarized, based on the available experimental data and on the human factors literature. The necessity of analyzing the observer's tasks in making decisions about the application of color to displays is noted. Nevertheless, it is shown that if certain conditions are met as to luminance, subtense, and chromaticity of the light signals, all normal observers and a majority of color-deficient observers can make the necessary identifications to aid performance. Recommendations are made for the effective use of color in complex information displays.

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Running Title: COLOR CODING

Key Words: color coding, color displays

INTRODUCTION

The proper application of color to complex information displays requires a general knowledge of human color vision as well as knowledge of how color has been applied to other displays used in a variety of different applications. Combining these findings with knowledge of the specific displays employed can then result in an initial set of guidelines for the effective use of color. It is the purpose of this paper to suggest preliminary guidelines based on the available experimental data on human vision and on the factors that influence it.

We should first point out that the simple addition of color may offer no necessary advantages over monochrome displays. In fact, color can be detrimental if used incorrectly. Its benefit is achieved only by the appropriate application of specific colors to particular displays and environments. Nevertheless, recent advances in display and computer technology as well as new demands in operator-display performance prompt renewed interest in the use of color in complex information displays.

On an empirical level, a number of investigators have studied color as a coding mechanism in a variety of applications. Some of the investigators have shown that color can improve performance (Wedell and Alden, 1973; Bouwman, 1978; Krebs and Wolf, 1979; Sidorsky, 1979; Kopala, 1979; Witt and Strongman, 1983) while others have shown that, in certain conditions, it may impair performance (Christ and Teichner, 1973; Christ, 1975). Teichner, Christ and Corso (1977), summarizing

the results of 14 experiments, concluded that color has no peculiarities that make it different from achromatic codes (e.g., brightness, position, size, etc.). It is merely another dimension along which to code information; whether or not it should be used depends on how it compares to the achromatic alternatives in any specific situation. The modern consensus however, is that the operator's task, the specific way in which color coding is related to that task, and the environment are all important factors in achieving benefits with color. In short, the key to designing a good color display is to understand the operator's task and how the displayed information will be used. The more complex the task and the more complex the information on the display, the more important this becomes. Nevertheless, there are certain instances in which color can be claimed to be generally advantageous. For example, in almost every visual scene, objects will differ from their background in both color and luminance. The strength or vividness of this perception depends upon how much objects differ from their background in color and in luminance. That either in isolation is a sufficient basis for some degree of pattern perception we know. Data from more realistic conditions in which both luminance and color were varied show very clearly that: (1) although luminance differences are generally more effective in maintaining the visibility of objects, at lower luminance levels color contrast can become more effective (Frome, Buck and Boynton, 1981), (2) borders formed by a combination of color and luminance differences are more visible than borders formed from either color or luminance differences alone (Frome, et al., 1981)

and, (3) when borders combine both chromatic differences and luminance contrasts, the chromatic system makes a greater contribution to the visibility of borders than does the luminance system (Switkes and DeValois, 1983). In short, these results indicate that to enhance the visibility of an object, both an increase in color contrast in addition to an increase in luminance contrast can be useful. In fact, at low luminance levels it may be more effective to increase color contrast. This critical contribution of color should not be surprising. Our visual system operates in a three-dimensional world that is normally illuminated by a strongly directional source, the sun. Because of this, profound luminance contrast is created by shadowing. On a clear, sunny day, the luminance contrast across a shadow border may exceed 90%. Such contours are false, giving misleading information about the presence of objects in the visual world. The color of an object in sun and in shade varies much less because the wavelength distributions of direct and scattered sunlight are not that different. Objects in shadow may appear slightly bluer (as indeed they are), but their apparent color will change much less than their apparent brightness. Thus, it may be to our advantage to segregate objects from their backgrounds on the basis of color differences rather than luminance differences.

Lists of the advantages as well as the disadvantages of color coding useful for identifying applications likely to benefit from color and those that would not are shown in Tables 1 and 2. These tables reveal that color coding can offer many advantages when used properly. There is a good deal of experimental literature which shows that color is by far the

most effective form of coding for visual search tasks (Christ, 1975; Carter, 1982). Furthermore, color has also been shown to be an effective way to organize information on various types of displays (Engle, 1980). In view of the substantial amount of search, selection, and global scanning now required by today's observers for locating, identifying, and integrating large amounts of complex visual information into meaningful problem data, the use of color for structuring and emphasizing parts of the display seems justified. However, it should be understood that the disadvantages of color arise from the following conditions: using too many colors (more than six or so), using color in an irrelevant manner, using color in the few situations where it may be more of a hindrance than a help (e.g., coding quantitative information), using color under highly chromatic ambient light sources, and, in some cases, employing color defective individuals.

Insert Table 1 and 2 about here

COLOR CODING FOR CRT APPLICATIONS

There is a growing body of literature on the appearance of color for normal trichromatic observers (Boynton, Shafer, and Neun, 1964; Sternheim and Boynton, 1966; Weitzman and Kinney, 1967; Kaiser, 1968). A number of techniques have been developed, and data from many laboratories have demonstrated the reliability with which these

observers assign given color names to spectral stimuli. The normal trichromat can reliably describe the visible spectrum in terms of four colors with minimal overlap: blue, green, yellow, and red. Blue is used for spectral stimuli between 400 nm and 520 nm, its peak occurring at 450-470 nm. Green is used between 460 nm and 570 nm with a broad maximum at 500-530 nm. Yellow is used above 520 nm with a sharply defined peak between 570 nm and 580 nm. Red is used with increasing frequency above 570 nm. Maximal values occur above 620 nm or 630 nm. Accordingly, wavelengths between 450-460 nm will always look blue regardless of their intensity. Similarly, wavelengths around 500-520 nm will always look green, 575-580 nm looks yellow and wavelengths between 620-630 nm always looks red to the color normal eye. In short, for color normals, there should be minimal confusion for the display of images of blue, green, yellow and red colors.

Previous work has shown that no one size of color codes is best for all possible CRT applications. The optimal number of colors in a display depends on the specific task; that is, it depends on the different types of information which need to be categorized. The color of a piece of information will, along with other nonredundant codes, convey all of the meaning of that information. Therefore, it is advantageous if the observer can not only discriminate the colors when seen side-by-side, but identify each color when it is perceived alone. There is general agreement that where this type of absolute identification of color is desired, only a handful of colors is feasible. However, if comparative identifications are desired, the number of colors can increase to six

or seven which is near the upper limit of the recommended color set size for electronic displays (Conover and Kraft, 1958; Demars, 1975; Silverstein, 1982).

Color Codes for Color Normal Observers

For normal trichromatic observers, up to five possible colors can be recommended for application to information displays: red, yellow, green, blue, and white. This color set of five can actually be considered a set of four plus one. Only red, yellow, green, and white should be used for alphanumeric. Blue should be limited to highlighting and framing data, area filling, and backgrounds; it should not be used for any information that the observer must read. A set of five colors is probably sufficient to categorize the major types of information presented on most displays. Being required to discriminate only five colors and to learn the types of information they represent should pose no problem for an observer, whereas discriminating ten or twelve is difficult without a great deal of practice. Using a small number of colors to code data on an absolute basis also allows for consistency in the use of colors within and across displays; red can have a similar meaning in whatever context the observer perceives it. Finally, limiting the set to five colors/categories also makes it less likely that the major influences of color (grouping and emphasis) will be hampered by the distracting influence of numerous conspicuous color contrasts. The particular colors of red, yellow, green, blue, and white are recommended for color-normal persons for the following reasons. They are the only colors which can be reliably seen without contrast with other colors. They are well spaced

throughout the visible spectrum and so are easier to discriminate than a set of hues grouped in only one or two spectral locations. Four of the colors make up the two opponent-color pairs (red-green and yellow-blue) around which the human color vision system is organized (Hurvich, 1981). These pairs offer maximum color contrast or discriminability. Red, yellow, green, and white are easy to resolve visually. Blue, however, should be avoided as a code for alphanumerics, because it results in poorer visual acuity. This is because at any instant, the retinal image is quantized into an array of discrete samples of light by the mosaic of color-sensitive photoreceptors. Theoretical considerations concerning the design of digital information processing systems suggest that this sampling process is limited in the blue region because of the coarse spacing of the blue-sensitive mechanism in the retina. Many lines of evidence from anatomy (Rushton, 1962), physiology (Marc and Sperling, 1977; Bowmaker, Dartnall, and Mollon, 1979), and psychophysics (Brown and Wald, 1964; Green, 1968; Kelley, 1973; Daw and Enoch, 1973) indicate a correspondence between low acuity under blue light and the low density of blue sensitive photoreceptors in the retinal mosaic. In fact, visual acuity under blue light is correspondingly low, even when the deleterious effects of chromatic aberration (in which images of different colors are focused at different depths) are removed (Stiles, 1949; Brindley, 1954). The only solution to compensate for poor acuity in blue light is to increase luminance level, increase symbol and letter size or desaturate the blue light. Perhaps limiting blue to non-alphanumeric applications such as area coding, framing, axes, and backgrounds is the

easier solution. In summary, it is possible to recommend a set of up to five colors that insures maximum probability of recognition of color and code by all normal observers. This recommendation also takes into account the limitations imposed by manufacturing technology and color measurement.

It is important to note that in implementing these five possible colors, it may be desirable to use different relative intensities in order to further increase discriminability. Saturation should also be substantial without being spectrally extreme in most cases since saturated colors are perceived as brighter than desaturated colors when the two are equated in luminance. Preliminary specifications for these five colors can easily be determined for any standard phosphor color monitor. Some adjustments to these specifications may be required for a specific monitor used in an information display system. However, a summary of the general principles for the use of color that are applicable to all CRT displays is presented in Table 3.

Insert Table 3 about here

Color Codes for Color Defective Observers

For many years it has been considered necessary to exclude from certain occupations individuals with deficient color perception. Numerous studies have therefore been devoted to the development of tests for identification of those who should be disqualified. Recently, attention has also been given to the possibility of modifying the

characteristics of the color codes in such a way that some or all of the color-deficient group can make the required discriminations. The question here is, can we provide specifications for certain colors that are identifiable for color defectives as well as for color normals. In order to understand the basic assumptions involved in the following suggestions, it is necessary to understand that color defective individuals are generally classified as monochromats, dichromats, and anomalous trichromats.

Monochromats are individuals who cannot discriminate color at all.

Cases of total color blindness are extremely rare. For the great majority of dichromats (red-green dichromats), who make up about 2.5% of the population, the colors perceived are blue, yellow, and the achromatic series, white, gray, black (Judd, 1943). They have then, only two colors remaining in their spectrum--yellow and blue separated by a neutral zone at or about 495-500 nm that is perceived as white--and hence they are called dichromats. From zero at the neutral zone the saturations of the spectral colors increase toward both the long and short-wave ends of the spectrum. Another type of dichromia (blue-yellow dichromia) also sees the spectrum in but two colors, red and green, but this occurs much less frequently (approximately .01% of the population). Anomalous trichromats, unlike dichromats, show no absolute absence of red or green sensitivity; their color loss is merely a relative one, and hence higher intensities are needed to permit more normal color recognition. Nearly 5.5% of the population are anomalous trichromats.

Dichromats are surprisingly good at naming color fields correctly in the everyday world. Color terms are used with skill by many color defectives although these skills are less apparent in the laboratory. Laboratory tests use small fields and spectrally pure colors, putting color defectives at a disadvantage in comparison with their experiences in daily life, where they may make few errors. Of course, two stimuli, although of the same color for a dichromat, can be differentiated if they arouse different sensations of brightness or lightness. Many congenital dichromats reach maturity without realizing that there is anything abnormal about their color vision.

Attempts to describe fully the color perceptions of red-green dichromats indicate that the dichromat, like the normal trichromat, will use the response categories blue, green, yellow, and red to describe the spectrum (Weitzman and Kinney, 1967; Luria, 1967; Boynton and Scheibner, 1967; Scheibner and Boynton, 1968). However, it should not be inferred that dichromats have four unique sensory percepts corresponding to these names. Blue light, if of adequate subtense and luminance, is reported as blue by both normals and color defectives. The response green (or white) shows a peak between 490 and 510 nm, the neutral zone. Above 510 nm, the use of response categories green, yellow, and red depends on luminance: with a dark surround and low luminance stimuli, dichromats are likely to call spectral stimuli above 510 nm red; at high luminance, they may call such stimuli yellow. Although typically the response category red is not well differentiated

from the categories green and yellow for wavelengths above 510 nm, some dichromats reliably differentiate these response categories even when luminance is controlled (Scheibner and Boynton, 1968). In addition, the ability of dichromats to give correct color responses to spectral stimuli also depends upon the category of colors to be differentiated. For example, dichromats who perceive red light as yellow will, nevertheless, call it red if they know that the display includes only red, blue, and green (below 510 nm). Conversely, dichromats who also perceive the greens as yellows will call them green if the display includes only blue, green, and white. Finally, colors in a limited range varying from blue-green to yellow-green (for normals) will, to the dichromat, vary from a slightly bluish-white to a slightly yellowish-white. Because of their lower saturation, they can be distinguished by dichromats from blue and red lights. Moreover, a green light on the blue side of the green region will not be mistaken for white if white is not included in the display.

As a consequence of the pattern of color confusions exhibited by the great majority of color defectives (red-green dichromats), not only all normal observers but those with deficient color vision can distinguish up to five different colors of panel lights, if certain specifications are met as to their angular subtense (about 1°), and the luminance (about 2.23 cd/m^2 and greater) of these indicator lights; these colors include red or yellow, yellow-green, green (between 490 and 510 nm), blue-green, and blue. However, under conditions requiring rapid recognition of colored signals, it may be advisable to restrict the color

set to red, blue, and a green on the blue side of the green region (or white) if color is to be usable by most color deficient observers as well as by all color normal observers. Also, as previously noted, noncolor coding will further reduce the possible color confusions by dichromats.

VISUAL ACCOMMODATION TO MULTICOLOR DISPLAYS

The lens of the eye functions similarly to a prism in that they both refract light. In both the lens and the prism, shorter wavelength light (blue) is bent to a greater extent than longer wavelength light (red). This bending is called refraction, and the degree of refraction is inversely proportional to wavelength. Therefore, only one wavelength can be focused on the retina of the eye at one time. This effect is referred to as chromatic aberration (Duke-Elder, 1949).

Recently, concern has been expressed that chromatic aberration of the eye would require continual re-accommodation (or refocusing) in order to bring images of varying color into simultaneous focus (and by implication, cause visual fatigue and eye strain) due to the different focal lengths at which colors are imaged (Ostberg, 1980; Kruger, 1980; Murch, 1983). In addition, if the retina is in the plane of any one colored image, the rest of the colored images will be out of focus in that plane and will produce blur. In theory, visual acuity should also be impaired because the retinal image is blurred; that is, the image is subject to wavelength-dependent chromatic aberration. In fact, the lowered visual acuity for short-wavelength (blue) stimuli is often attributed, albeit incorrectly, to a condition of temporary "near-sightedness" induced by

chromatic aberration. Nevertheless, for reasons that are not presently understood, measurements of visual acuity are scarcely affected when chromatic aberration is eliminated (Luria and Schwartz, 1960). More interestingly, reading performance in normal daylight vision appears to be independent of wavelength effects (Legge and Rubin, 1983; Legge, Pelli, and Rubin, 1985).

It appears that, for monochromatic (narrow-band) colors, the effects of chromatic aberration upon accommodative and convergence responses are as expected. Red is focused behind the retina, requiring a reduction in accommodative response in order to bring the image to focus on the retina, while green and blue require an increase in accommodative response so that proper focusing can occur. Although the effects on accommodation have been confirmed they are found to be present only under very restricted laboratory conditions when observers view targets monocularly (Campbell, 1975). Thus, important visual cues for depth, such as convergence, apparent size of familiar objects, and stereopsis (which produces stereoscopic images or perceptions), which all aid accurate accommodation in everyday life, were not available in these experiments. In fact, there is no evidence that multicolor displays upset or disable the accommodation system under normal binocular viewing conditions. Only a presbyopic (far-sighted) individual who has lost all powers of focusing his lens may notice that when red text is seen sharply the blue is slightly blurred, or vice versa. However, if this individual is wearing a spectacle power matched to the middle of the spectrum (green) he/she should see no difference in clarity for the different colors,

owing to depth-of-focus. It is well but not widely known that there is substantial tolerance to small errors of refraction due to the depth-of-focus of the eye (Donohoo and Snyder, 1985). An observer with active accommodation will not experience any difficulty in accommodating the respective colors. Depth-of-focus plus trivial changes in accommodation can easily overcome the necessity to continually refocus between the different colors provided the accommodation system is active or correct spectacles are being worn (Oyama and Yamamura, 1960).

Further problems have been thought to arise when trying to bring differently colored characters into focus at the same time. Presumably, this would cause a continual refocusing of accommodation between the colors and thereby stress (or fatigue) the accommodation system. However, there is no evidence of an increase or indeed decrease in the fluctuations of accommodation when viewing multicolored displays (Campbell, 1959). The fluctuations that do occur are naturally occurring fluctuations that are not produced by neural excitation resulting from viewing different colors, but are similar to the normal residual tremor produced in any muscle system, e.g., in the fingers of the extended hand, or in the ciliary muscle which controls the movement of the lens of the eye. It would seem that a basic problem in presuming a connection between frequent re-accommodation and visual fatigue lies in the fact that the accommodated lens is always in motion--the lens may oscillate over a quarter of a diopter range at a rate of about three to four times a second when viewing a steady state target. Hence, even under steady

viewing conditions, the lens of the eye is very active (Campbell and Whiteside, 1950). Considering this normal activity of the accommodation response, it should not be surprising that researchers have not been able to find a link between the frequency of changing accommodation and visual fatigue.

The spectral characteristics of a phosphor set used in most commercial display systems are far from monochromatic since each phosphor generally emits over a substantial part of the visible spectrum (half bandwidths of up to 50 nm are common). It is well known that broadband or desaturated colors are less influenced by chromatic aberration (Charman and Tucker, 1978). Similar results have been reported for colors produced by multiple phosphor excitations such as cyan (blue-green), magenta (red-purple), yellow, and white and by filters in which an increase in bandwidth was accompanied by a reduction in color-dependent refocusing requirements. These results occur because broad-banded peaks of spectral power are so ill-defined that they are undetectable by a person with normal or anomalous color vision and so will have no effect upon the accommodation system. Given the presumed link between frequent refocusing and the visual fatigue arising from intensive viewing of multicolored displays, these findings suggest that broadband or desaturated colors would reduce refocus requirements and the attendant fatigue. In addition, desaturating the blue will also offset the lowered visual acuity for short-wavelength stimuli since this will lessen the contribution of the blue sensitive mechanism relative to the other photoreceptors in resolving visual detail.

A few users of multicolored displays have noticed that characters in red are seen to be nearer than those in green and that green is nearer than blue, thus giving the impression that the characters are located at different distances. This phenomenon, called chromostereopsis, can be fairly easily explained. Because of lateral chromatic aberration, the different colors fall on slightly disparate parts of the retina; this retinal disparity is detected by our normal stereoscopic depth-detecting mechanism, thus producing an illusion of depth. It is not therefore a physiological problem, although the effect can be annoying and distracting initially to some people, but usually becomes less noticeable with time. It can be minimized by desaturating the colors in the display so that color contrast is reduced or by brightening the background.

An additional factor is introduced when a color for a display background can be selected. Although this is not normally available for alphanumeric computer displays it is being used for television information services such as teletext or weather reporting. However, there is no evidence that when a colored symbol or character lies on a differently colored background, refocusing or fluctuation of accommodation occurs between the two.

AMBIENT ILLUMINATION

A variety of ambient lighting conditions are obviously available in areas where CRTs would be used. Visual displays are often located in areas that have traditionally been illuminated by low-level white light

(of unspecified bandwidth and color temperature) to facilitate brightness contrast on the CRTs. To the extent that color is used in a display, the question naturally arises as to which ambient lighting condition is best when looking at color coded displays. The chromaticity of display colors changes as a function of ambient illumination (Silverstein, 1982), and the phosphors of a CRT are capable of being excited by room light. For these reasons the use of any bright ambient light is to be avoided. Given a "low-level" of ambient illumination (less than 21.53 lx) there remain three possibilities: no light, color or white. The problem, of course, with no ambient light is that there are keys, buttons, and printed material that still must be read; this requires some illumination. The problem with spectral illumination is that it may affect the appearance of the display colors. Strongly chromatic light has the potential for decreasing the range of colors seen and interacting with the display colors to produce new shades. These color interactions are not always predictable and are certainly undesirable. Consequently, colored illuminations should be avoided.

The best choice is therefore a "low-level" broadband, white light, for the following reasons. First, by producing comparable amounts of energy throughout the visible spectrum, there is less likelihood of unwanted interactions with display colors; color rendition would remain close to what it was designed to be. Second, there is some evidence that performance on actual CRT detection tasks is best under white light (Luria and Kobus, 1982). Third, there is some evidence that far-sighted individuals show more evidence of visual fatigue under spectral

illumination than under white, because of the difficulty in accommodation (Kinney, Neri, Mercado, and Ryan, 1983). Therefore, because problems of color appearance and visual fatigue are avoided, and because visual performance may be enhanced, it is recommended that "low-level" white light be used in those spaces where color CRTs are used.

SUMMARY

Although the human eye can differentiate 150-200 variations of color in the spectrum, it is very poor at making absolute discriminations. From color naming we know that only eight colors exist without auxiliary names: blue, green, yellow, brown, red, white, gray, and black, whereas violet, orange, rose, and purple are named after flowers, etc. From these eight colors another three: brown, gray, and black can be seen only by contrast with other colors. Thus, for a precise color coding system up to five colors are suitable: blue, green, yellow, red, and white. From the psychophysical point of view, the opponent colors blue-yellow, red-green, and white-black can be judged the most suitable for color recognition and color coding. These represent a compromise between reliable color recognition for observers with normal color vision and the limitations imposed by manufacturing technology and by the tolerances of color measurement.

A significant number of people--about 8.0% of all males--have some form of defective color vision, and this fact can be taken into account when recommendations are to be made. As a consequence of the pattern of color confusions exhibited by the very great majority of

people with defective color vision (red-green dichromats), blue, green (or white), red, blue-green, and yellow-green should generally be the preferred colors chosen for a color-coding system that is also intended for the use of people with normal color vision. However, for rapid recognition of colored signals, it is recommended that red, green (or white) and blue should be the preferred colors. Further safeguards against possible confusion can be obtained by suitably adjusting display luminance.

The eyes' optics exhibit a fair amount of chromatic aberration which can serve as a stimulus for accommodation. In principle, this might cause problems with the eyes focal adjustment and result in visual fatigue when viewing a multicolored display. However, there is no reason to treat this as a serious problem, in particular if the observer is viewing the display binocularly, has normal or corrected vision, or one refrains from employing deeply saturated colors.

ACKNOWLEDGEMENTS

The views expressed in this article are those of the authors and do not reflect the official policy or positions of the Department of the Navy, Department of Defense, the U. S. Government nor The Mitre Corporation.

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TABLE 1

Advantages of Color Coding**Search/Identification**

Superior for finding a particular item of random location on a display

Superior to size, brightness, and shape coding on identification tasks

Helpful for counting members of a class and locating information

Attention/Recognition/Memory

Focuses attention

Effective for coding low probability or very important events

Useful for alerting an observer to a change in status

Superior for process control and monitoring

Speed of recognition increases for contrasting colors

Increases retention of information

Information

Increases information content; provides an additional dimension to display

Acts as a "chunking" mechanism to organize information; separates categories of information

Need only a small number of color codes in most applications

Learning

Natural association of certain colors with well known physical states

Speed, ease of learning and comprehension; requires little additional training

TABLE 1 (Concluded)

Advantages of Color Coding

Vision

Appearance of color common to all color normals

Enhances contrast

Improves visual acuity through color contrast when low luminance contrast exists

Enhances perceptibility of objects in parafoveal (or noncentral) regions of the visual field where form is indistinct

Coding

Superior for a real coding, as in distinguishing spatial locations on a display

Beneficial as a redundant code

Display Design

Allows for reduced display brightness

Reduces the appearance of display clutter

Practical to implement

Colors effective under a wide range of broad-band ambient lighting conditions

Preference/Aesthetic

Generally preferred as less monotonous

Has known aesthetic properties

TABLE 2

Disadvantages of Color Coding

Search/Identification

Inferior to alphanumeric coding for identification tasks

Attention/Recognition/Memory

May be a distracter when irrelevant or partially redundant

Information

Can result in information overload with too many colors

Learning

Problems arise when using colors that contradict cultural conventions

Vision

Not as effective in the visual periphery when compared to central vision

Can discriminate only a limited number of hues absolutely, less under adverse conditions

Approximately 8% males, 0.4% females are color defective (see page 10)

Anomalous color vision for very small (30' of arc or less) or very brief (100 msec or less) spectral stimuli

Coding

Limited number of categories that can be coded

Generally not suitable for coding quantitative information

TABLE 2 (concluded)

Disadvantages of Color Coding

Coding (concluded)

Color is advantageous relative only to size, brightness, and shape; it may be no better or poorer than other coding forms

Irrelevant color can interfere with achromatic attributes of information

Preference/Aesthetic

People may not always agree on hues (or color names) when other aspects of color (such as saturation) are not controlled

TABLE 3

General Principles for Applying Color to CRT Displays

Keep Colors

Task related

Relevant and conventional (e.g., red = "conflict")

Consistent

To a minimum number

Discriminable

When Appropriate, Color Should Be Used To

Designate particular objects in a dense display

Demarcate a display area or visual event of special importance

Warn the observer of critical situations (most effective when there is a small number of alternatives)

Classify or group data where the number of classifications is small, to reduce display clutter

Enhance pictorial realism when this is considered important

Code qualitative information on a map-like display by using different hues

Remember

All alphanumeric characters should be a minimum of 30' visual angle in size due to both loss of resolution and anomalous color effects

Whenever possible evaluate experimentally the use of color in the specific application

END

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