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NAVAL POSTGRADUATE SCHOOL

Monterey, California

APPLICATION OF COLOR CODING

IN TACTICAL DISPLAY S-3A

by

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April 1980

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The present effort was designed to examine the literature on color coding in terms of the incorporation of color in tactical displays aboard the S-3A. Available literature could be conveniently separated into work concentrating on (1) visual functioning, (2) display/environmental factors, (3) task/performance variables. Overall the results do not strongly support the inclusion of color in S-3A tactical displays. In the event color is incorporated, its usage should be at the control of the operator.

EXECUTIVE SUMMARY

The present effort was designed to examine the literature on color coding in terms of the incorporation of color in tactical displays aboard the S-3A. Available literature could be conveniently separated into work concentrating on (1) visual functioning, (2) display/environmental factors, and (3) task/performance variables.

In terms of available information, it would appear that the categories of visual function and display/environmental factors are sufficient to allow for the design of color displays which take into consideration human capabilities and limitations. This is not to imply that every aspect of human color vision or color display design is well understood. However, sufficient information exists to allow for color electronic display design which will not significantly violate known color vision capabilities.

The major problem involved with color tactical displays involves the significant impact situational variables have on performance. Performance involving color electronic displays is highly dependent upon task demands and environmental variables. Any decision to incorporate color in the S-3A tactical display systems should be based on a comprehensive task analysis. More than adequate task <u>descriptions</u> are currently in existence. This existing work should be complemented with research designed to specify behavior and skills required to perform the various tasks. Once accomplished, recommendations of how and where color could be best employed would be possible.

In the event color displays are to be used prior to the analysis of skills and behavior, it would probably be most advantageous if under

the control of the operator. In this configuration, the operator would designate items to be color coded. Such a color option possesses the potential for improving display management and information transfer efficiency by aiding the operator in "keeping track" of critical information.

Introduction

The present effort examined various parameters related to the application of color as a coding modality in CRT display design, particularly tactical display design in the S-3A aircraft. Literature reviewed suggested that research findings could be conveniently separated into (a) vision dependent factors, (b) display/environment dependent factors and (c) task/performance dependent factors. Admittedly, there is considerable overlap between categories and in most instances distinctions are more apparent than real. However, such a classification scheme did provide a workable method for reviewing literature pertinent to specific problems of tactical display design. Therefore, the present effort will begin with a brief review of applicable literature on the subject of the use of color as a coding modality for electronic displays.

Vision dependent factors

The receptor mechanism sensitive to photic energy is the visual subsystem. The eye represents the peripheral organ necessary for the visual function. The structure of the eye is such as to enable the focusing of light emitted from external objects to light sensitive areas within the structure. The visible spectrum of electromagnetic radiation is roughly limited to wavelengths ranging between 380 and 800 millimicrons with a frequency range of approximately 7×10^{4} to 4×10^{4} Hz (Grossman 1967). The human eye, except in terms of injury, does not respond to energy greater or less than these values (Heimstra and Ellingstad, 1972).

Visual perception has been conveniently separated into spatial, temporal and color aspects. Obviously, there is considerable interaction between these fundamental aspects in the visual process, with separation being impossible in any applied situation. Concentration here will be in differential response to wavelength (color), but will include consideration of fundamental characteristics of spatial and temporal as they influence color perception.

The actual process of color vision is not well understood, in that relationships between wavelength and neural response are extremely complex (Thompson, 1967; Morgan & Stellar, 1950; Butter, 1968). It has been established that color perception involves the sensory characteristics of hue, saturation, and brightness (Roth and Finkelstein, 1968). These are psychological classifications and are characteristics or dimensions of experience and normal functioning of the visual system and not properties of electromagnetic energy (Corso, 1967). They are, however, basic to the application of color as a coding modality in electronic displays.

Hue

Hue refers to that quality we normally think of as "color" (e.g. red, blue, green, etc) (Cornsweet, 1970). It is that sensory characteristic which is most nearly related to the physical property wavelength (Corso, 1967). The number of hues or colors that an observer can distinguish is largely dependent upon a number of situational, task and measurement conditions. Therefore, the range that has been suggested is astonishing. For example Forgus (1966) has indicated that 350,000 just noticeable differences can be distinguished. Corso (1967) has indicated 180 segments of the spectrum that differ in hue can be discriminated by the "normal" observer. Hanes and Rhoades (1959) suggested that extensively trained subjects could identify as high as 50 colors. Realistically in the operational environment an operator is capable of efficiently working with a much more modest number of colors or hues. Baker and Grether (1954) suggest a 9 color set which they indicated are least confusing for normal observers and those observers which are color defective. Cook (1974) suggested a six color set which he considers suitable for color coding.

The wide range of suggestions places the designer in a difficult position when attempting to select the number of hues or colors to be used as coding dimensions in display design. As suggested earlier, a number of considerations must enter into the decision process (e.g. nature of task, display technology, ambient environment, operator workload, etc.). However, there does appear to be general agreement among numerous researchers that the number of colors used as coding dimensions should not exceed four or five at the most (Krebs, et al., 1978; Wagner, 1977; Teichner, et al., 1977).

Given that four or possibly five coding dimensions represent the upper limit in terms of number, the next question consists of determining which colors to employ. Krebs, et al. (1978) have suggested the considerations presented in Table I as basic criteria for color set selection. In terms of hue, the important criterion is wavelength separation. In terms of symbol color coding the research findings of Meister and Sullivan (1969) and Rizy (1965) would indicate red, white and yellow preferable with blue and green being somewhat more limited in their application. These recommendations must be qualified with any final decision being dependent upon numerous other factors. Krebs et al. (1978) have suggested the recommendations presented in Table II.

Therefore, while the human eye is undoubtedly capable of distinguishing hundreds, perhaps thousands, of hues or "colors" it would appear that the application of color as a coding modality should be limited to four or five. Further, a major factor in the selection of

TABLE I

COLOR SET SELECTION CRITERION

1) Maximize wavelength separation
2) High color contrast
3) High visibility in specific application
4) Compatibility of use with conventional meaning
5) Legibility of and ease of coding
6) High saturation

(From Krebs, et al., 1978)

TABLE II

COLOR RECOMMENDATION

1) Use no more than four colors
2) Use red, green and yellow for alphanumeric
3) Use blue for large symbols when symbol identification is not a problem
4) Use white for peripheral signals

(Adapted from Krebs, et al., 1978)

the colors to be used is wavelength separation, and the fact that certain colors (i.e. red, yellow, green) through extensive use have taken on rather specific meaning and tend to encourage an expectancy on the part of observers. This latter fact is highly significant and must be considered in display design situations involving color use.

Saturation

Saturation refers to the purity of hue. Light which consists of a single wavelength is considered homogeneous or spectrally pure (Corso, 1967). White light (e.g. sunlight) contains energy which is randomly distributed over all wavelengths and therefore has a purity of zero, i.e. maximally heterogeneous. Saturation is that aspect that is most strongly influenced by the addition of white light. For example, a 100% saturated red (spectrum red) becomes more "pink" with the addition of white light. However, in terms of hue it is still red, only a red of decreased saturation.

In terms of the human visual system the question of thresholds for saturation discrimination are not well understood. Therefore, it would appear that the suggestion of Krebs, et al., (1978) is valid and that only highly saturated colors be used, particularly in situations where the maximum number of colors (i.e. four or five) is being used as a coding mechanism. It is not felt that use of saturation in and of itself as a coding system be seriously considered at this time.

Brightness

Brightness can be considered to consist of two types depending upon the source (Crumley, et al., 1961). Intrinsic brightness originates within the display itself, and reflected brightness originates externally.

Brightness itself is related to the intensity or amount of luminous flux that reaches the eye from the stimulus environment. In terms of visual response, brightness is generally thought of in terms of the physical stimuli and the intensity functions of the visual system. Intensity functions of primary interest here are: (a) absolute threshold, (b) difference thresholds and perhaps (c) critical flicker fusion frequency (Ruch, 1966). As the name implies, absolute thresholds refer to the least intensity that can be detected or "seen." Difference threshold refers to the least discriminable difference between two intensities that can be detected. The ability of the human eye to make such discrimination is of obvious importance to display design, particularly if brightness is under consideration in terms of a coding dimension.

Critical flicker fusion frequency refers to the tendency of flashes of light to appear steady. This tendency is in part dependent upon intensity or brightness in that at low frequency, flashes may be apparent, but that for specific intensities a certain frequency of intermittancy will produce a steady state sensation. As such, knowledge of this phenomena may be of critical importance in certain display applications. Figure 1 indicates the relationship between intensity and critical flicker fusion.

Brightness sensitivity, as suggested above, is largely dependent upon radiant energy, and the wavelength of that energy. Sensitivity of the eye, however, is largely dependent upon the receptor mechanism involved, i.e., the rods or cones. In general, rods require far less energy for vision than do cones (Wulfeck and Zeitlen, 1962). Rods, however, are achromatic and therefore insensitive to color. Figure 2 presents a visual curve indicating spectral sensitivity of rods and cones, indicating relative energy required for response.

Thresholds, however, are not a single absolute value, but rather a range of values (Grossman, 1967). Grossman (1967) has suggested that the human will detect a stimulus of 10° apparent diameter if the energy is in the area of 9×10^{-16} watt. This sensitivity will be influenced by numerous factors including the following:

(a) Dark adaptation
(b) Position of retinal image
(c) Size of retinal image
(d) Length of exposure
(e) Stimulus composition

Dark adaptation

Absolute threshold varies as a function of the degree of dark adaptation. For example, an observer entering an environment of low illumination from one of bright illumination will initially be blind. As such, his absolute threshold will approach infinity. With time the observer's threshold will decrease until he can distinguish aspects of the surrounding enviornment.

Grossman (1967) has suggested that dark adaptation is biphasic with separable functions for rods and cones. Photopic adaptation reaches an asymptotic level in roughly 5 to 8 minutes of exposure. Scotopic requires roughly 60 minutes of exposure to darkened conditions. Grossman has suggested that overall absolute threshold change will involve a 10,000 fold increase in sensitivity.

Obviously illumination or brightness conditions can play a significant part in observer absolute threshold. The nature of adaptation function can be significantly modified by preadaptation to a bright surface of uniform luminance. Further, effects of dark adaptation do not suddenly disappear when the environment is lightened in terms of illumination. Grossman (1967) suggests that at moderate levels of brightness the effects of dark adaptation are slowly reversed and as such absolute threshold is impaired for roughly an hour under most low-luminous conditions.

In terms of color, Grossman (1967) indicated that stimuli in red end (650 mμ) result in photopic phase of dark adaptation. Stimuli below 460 mμ result in scotopic, and the middle of the visible spectrum (yellow-green) result in biphasic adaptation similar to that observed with white light.

Retinal image position

In the light adapted eye the central or foveal region has the lowest threshold. This region contains only cones and therefore demonstrates only the photic phase of dark adaptation. As such, foveal vision does not possess an advantage in the dark adapted eye. In fact, Grossman (1967) suggested that under dark adapted conditions the foveal region may be essentially "blind" to stimuli easily detectable to peripheral receptors. In the periphery, however, sensitivity is not uniform. In the dark adapted eye, the absolute threshold is lowest at 10 to 20 degrees from the foveal region. As the periphery is approached the threshold increases until conditions similar to the fovea exist.

Size of retinal image

Due to the sensitivity differences which exist within the eye it is not surprising that size and position/location of stimuli interact in terms of sensitivity. In the "normal" eye 1 min of arc is usually suggested as the minimum visual angle that can be discriminated. Figure 3 suggests a relationship between detection performance and visual angle. It is obvious that probability of detection is related to visual angle, i.e., as visual angle increases so does probability of detection.

Length of exposure

In situations in which brief exposure times are present, thresholds becomes a function of the product of time and intensity. According to Bloch's Law, the detection threshold with very brief flashes of light is inversely proportional to flash duration (Overington, 1976). For longer presentation times the threshold tends to become constant. Between the two extremes (0.01 second to a few seconds) there exists an uncertain region in which threshold characteristics are not well understood.

Spectral composition

Absolute threshold is also affected by the composition or wavelength of the stimulus. This obviously involves the intrusion of color to sensitivity and therefore involves rod and cone vision differences. Figure 4 illustrates spectral sensitivity curves for rods and cones. In terms of sensitivity the eye appears to be more sensitive to yellow and blue/green illumination. This visual characteristic is presented in Figure 5. It can be seen that in the blue/green and yellow portions of the spectrum the difference threshold is approximately one millimicron.

It is imperative that designers of displays appreciate the distinction between absolute thresholds and recognition or difference thresholds. By definition absolute thresholds are restricted to the detection of presence of a stimulus. Such detection rarely includes the extraction of information from the stimulus object. In most applied situations a display requirement is the transference of information from the environment to the operator. Therefore, data gathered on absolute thresholds is frequently inadequate as a basis for decisions in display design.

Color discrimination/recognition threshold is dependent upon hue, saturation and brightness, and requires the operator to recognize the stimulus as a particular type or class and not merely specify presence or absence. Therefore, it is dependent upon (1) light source intensity, (2) ambient illumination, (3) colors employed and (4) observer's situation (Fogel, 1963).

Analysis and specifications of recognition requirments must therefore consider visual function relevant to absolute detection threshold, plus the added requirement of the classification type task. Some general statements relative to the visual function and recognition thresholds are possible (Roth and Finkelstein, 1968; Overington, 1976; Haber and Hershenson, 1973; etc). However, from the practical point of view it is necessary that conditions other than purely visual capabilities be considered in making design recommendations.

In summary, the variables of dark adaptation, retinal image location, size of retinal image, duration of exposure, and spectral composition all interact and can impact significantly on visual performance. In considering colors it is imperative that these factors be well understood in terms of the work environment and task requirements. In real world environment of S-3A an analysis of the operational environment must include examination of the possible range of values or conditions that may exist and apply such information to the possible inclusion of color in the tactical display system.

Color vision deficiency

A visual factor that must be considered in any situation involving possible color use is the question of (1) color blindness and (2) the color defective individual. Color blindness itself is rarely a problem in that a very small percentage (.003%) of the total population suffer from the anomaly and the fact that it is rather easy to detect. The color defective individual presents a greater problem in that a much larger proportion of the population (6 to 8% for males and .05% in females) suffer from the defect, and secondly, methods employed in color vision deficiency detection and analysis are not always accurate (Paulson, 1973).

The conventional classification of color deficiency is as follows:

(1) Trichromats
(2) Dichromats
(3) Monochromats

Labels attached to this classification scheme indicate the number of primary colors necessary in order to match all colors in the visible spectrum. Trichromats require all three primary colors as do normals, however, the color deficient trichromat differs from the "normal" in that he is deficient in one of the three photochemical substances necessary for color sensitivity (Heimstra and Ellingstad, 1972). For example, a green deficient trichromat would require more green in a red-green mixture before he could recognize yellow. Red defectives would require more red before he could recognize yellow, etc.

Dichromatism is characterized as a defect which results from the complete absence of one of the three photosensitive pigments. Individuals suffering from this vision anomaly can match the spectrum with only two primary colors. In terms of wavelength discrimination, dichromats may require a wavelength difference 10+ times greater than normal for detection (Hsia and Graham, 1965).

Monochromats are characterized by a complete absence of at least two of the photosensitive pigments. One-variable monochromats can be considered perceptually in terms of variation along the brightness dimension only (Hurvich, 1973).

It should be obvious that the subject of color vision deficiency is complex and highly variable. Design questions relative to the various forms and characteristics of color deficiency are numerous and solution of one may not necessarily provide a suitable display medium for a subsequent form.

Roth and Finkelstein (1968) have suggested that aviation red, green and blue may be effective in certain situations to mitigate some of the display problems associated with color vision defectives. However, designation of "aviation" can impose significant problems in CRT display design, and may be difficult and/or expensive to accomplish. Oda (1977) has indicated the Penetron system is capable of approximating the aviation designation.

In terms of the visual system itself, potential display designers must be aware of visual functioning and variables that can influence the manner in which the human will respond or function. As a bare minimum, consideration must be given to the following in terms of the specific application:

(1) Relationship of structure and function of visual system (e.g. rods and cones).
(2) Parameters involved in color vision (hue, saturation, brightness).
(3) Limitations and capabilities of visual system with particular reference to color vision.

Obviously there are numerous gaps in our knowledge of the nature of color vision. From an applied point of view, it does appear that sufficient information is available regarding the function of color vision to enable the incorporation of color into electronic display design. Designers need to be familiar with the variables capable of impacting on visual functions and consider them in their design efforts. Appropriate application will depend upon consideration of visual functioning in terms of display/environment interaction with the visual system.

Display system/environmental variables

The fundamental purpose of a display system is to take information not directly observable in the real world and present that information to an observer. The total system is therefore designed to supplement the sensory abilities of the observer. The display system consists of a combination of a translator and a receiver; the receiver consisting of an operator whose function is to receive information displayed and act upon it in the performance of system functioning.

In display design there is no "perfect" display for all situations. A display which is appropriate in one situation may be quite inappropriate in a different situation. This condition is compounded with the introduction of color. Obviously, displays should be designed with consideration being given to visual capabilities of potential observers. Further, in most display design situations merely making the display visible is frequently not sufficient for the transfer of information (Grether and Baker, 1972).

Display parameters

Resolution. Resolution can be viewed as a measure of discrimination of fine detail. As such, resolution is dependent upon visual system acuity (resolution) and display system resolution (Anon, 1968). Visual acuity is dependent upon many of the functions suggested earlier (e.g. luminance, contrast, retinal location, duration of exposure, nature of target, color(s) used, etc.) (Kuehn, 1968). Display resolution depends, in part, upon the image creating element, positioning image diffusion, etc. The task of display design must consider the resolving power of eye as the upper bound from an operational point of view. That is, once the maximum resolving capability of the eye is attained, further display resolution capability will not enhance operational performance.

In the present application the important question involves the impact of color on display resolution requirements. Krebs, et al. (1978) have suggested that symbol size for colored symbols should be roughly 50 percent greater than for black and white. They have also suggested the following electronic/CRT display requirements:

(1) 21 minutes of arc at a minimum.
(2) With increased number of colors increase minutes of arc to 45.
(3) Stroke width — 2 minutes of arc at a minimum.
(4) Line width for graphs -- 4 minutes of arc at a minimum.
(5) Symbol aspect ratio -- 5:7 or 2:3.

Resolution requirements would appear to be well within the scope of present technology (Hassberg, 1979; Oda, 1977). Oda (1977), has suggested that the penetration control color tube is capable of achieving the desired resolution; and further, is "rugged" enough to survive the operational environment. This particular type of system functions by controlling the depth of penetration into phospor layers (Asher and Martin, 1968). Oda (1977) has indicated that the Penetron can match, in terms of resolution, the monochromatic display presently used in the S-3A and is capable of 1000 to 1500 resolution TV lines by Raster height. Krebs et al (1978) have suggested that a reasonable standard in terms of color symbols would be 15 lines per symbol height as a minimum.

Brightness/contrast

As suggested earlier brightness is the measure of light intensity. Contrast refers to relative brightness of a signal over that of its background. In most tactical display systems the operator is required to make some judgment on the basis of brightness or contrast.

In terms of color displays consideration of contrast in terms of luminance (brightness) and color contrast is required. Numerous authors (Roth and Finkelstein, 1968; Wulfeck and Zeitlen, 1962; Grether and Baker, 1972; etc.) have suggested that color contrast is not as effective as brightness contrast in terms of increasing visual acuity. That is, making the target and background two different colors does not necessarily increase acuity given a high level of brightness contrast. At high brightness levels, color influence on visual threshold is dependent on several factors present in the viewing situation (Overington, 1976). First, if symbol and background are of the same color, but non neutral, there can be a slight impact on threshold as a result of a shift in spectral balance. In situations in which target and background are of a different hue there will be a threshold associated with a particular hue when brightness is equal. Maximum sensitivity under these conditions appears to be in the yellow/orange and blue/green region with somewhat reduced sensitivity with green and poor sensitivity at extreme red or blue. In situations in which both color and intensity contrast vary, color contrast can aid sensitivity. In such situations, overall contrast can be defined as the root mean square of intensity and color contrast. That is:

$$C = \sqrt{C_1^2 + C_c^2}$$

where

C = contrast

C_1 = luminosity contrast

C_c = color contrast.

Therefore, while color contrast by itself may not be as effective as brightness contrast, it can provide additional benefits. It may be of particular value in situations in which brightness contrast is less than optimum.

The importance of maximizing contrast is dependent upom numerous factors, including the following:

(1) Target size
(2) Ambient illumination
(3) Target/background
(4) Shape
(5) Information displayed
(6) Etc.

Krebs, et.al. (1978) suggest the following design principles:

<u>Symbol luminance</u>
(1) For good color perception -- 3 cd/m^2
(2) Optimum under moderate lighting conditions 30 to 300 cd/m^2

<u>Background luminance</u>
(1) Background color -- dark

<u>Contrast</u>
(1) Luminance ratio of 10:1

<u>Target size</u>
(1) 21' to 45' arc

<u>Ambient illumination</u>
(1) Higher ambient illumination the higher the symbol luminance.

Registration

In some color display systems image registration (i.e. accuracy with which colors bound each other) can present a display situation with the potential for performance degredation (Vlahas, 1968). Modern display technology minimizes, in many situations, the question of misregistration. Where color fringing is felt to be a potential problem, it can be reduced through limiting to four the number of colors used.

Format

Format refers to the physical arrangement of information to be displayed (Debons, 1968). Applicability of a particular format depends upon information presented and the use to be made of that information. In color displays, the formatting function will determine color used and the nature or manner of use.

Format can be fixed (e.g. specified scales, intervals, etc.), random (e.g. essentially unformatted) or variable (e.g. a combination of fixed and random). In variable format displays, certain stimuli are fixed (e.g. terrain or geographical features) with target or transient stimuli essentially random.

In terms of color use, Krebs, et al. (1978) have suggested color may be most helpful in unformatted displays. However, it may be that maximum benefit could be obtained by allowing the user to define new "formats." That is, display request language may be monochromatic with a provision for a set up language which will allow the observer to introduce the parameter of color for essentially a new "format."

Screen size

In regard to screen size Loewe (1968) has suggested two major elements:

(1) Audience configuration
(2) Information density

In the case of tactical display in the S-3A the displays are of the console type with one or possibly two operators viewing the display. Information density is highly variable in that the range is from a dearth of data to overload.

Loewe (1968) also suggested the following relationships as useful in display design:

$$\tan\frac{(n\sigma)}{2} = \frac{S}{2d}$$

where

n = number of alphanumeric characters
σ = includes visual angle of character and space
S = screen dimension
d = furthest distance of observer from screen

Obviously the question of screen size is going to be dictated by the following:

(1) Amount of information presented
(2) Operator task/workload
(3) Space available
(4) Format used
(5) Resolution of display on a visual system
(6) Etc.

However, research needs to be conducted in an attempt to optimize the size-task relationship. The lack of data emphasizing this relationship represents a major deficiency.

Display location

Sensitivity to color is not uniformly distributed across the total field of view. In fact, a very small part of the eye is most sensitive with areas beyond this limited segment differentially sensitive to specific colors. For example, the field of view is widest for white and narrowest for green. Figures 6 and 7 indicate the various sensitivity zones. The suggestion in the figure is that white followed by yellow and blue are greatest in terms of angular color limits. However, DeMars (1975) has indicated that the eye lacks blue sensitivity when a field size of a given brightness subtends a visual angle of 15 minutes of arc or less. This limitation could be significant in terms of image size and display location.

Therefore, due to selective color sensitivity and the fact the periphery of the retina consists of primarily non color sensitive rods, position of the display and screen size can impact substantially on performance in color displays. Careful attention must be paid to the location to insure the display does not fall outside the range of color sensitivity for the colors used.

Environmental influence

Numerous environmental considerations can influence operator performance in general and color vision specifically (e.g. noise and vibration, temperature and humidity, atmospheric fluctuations, etc.). Of specific interest in the present effort is the question of ambient illumination. Crumley et al. (1968) have suggested that ambient illumination should be adjusted on the basis of the following criteria:

(1) Maximize brightness of task elements.
(2) Keep glare potential at a minimum.
(3) Minimize contrast between display and environment (surround contrast).

In situations in which ambient illumination is high, a reduction in background contrast can be anticipated. In terms of specific colors, red and blue appear to be somewhat more resistant to negative effects than yellow/orange in high ambient illumination environments. Ellis, et al. (1975) have suggested the use of red most suitable for high surround illumination environments. However, all color codes are degraded and not suitable for use in very high illumination environments.

In addition, high ambient illumination situations possess the potential for "glare." Glare interferes with visual performance generally and color vision specifically. It reduces contrast thereby reducing visibility and/or readability. Regardless of its nature or origin (reflected or specular) glare can produce operator discomfort which can induce subjective fatigue, producing perceptual narrowing and performance degradation.

On the other hand, low ambient illumination can also influence operator performance. For example, low ambient illumination environments may require that target luminance be reduced to maintain dark adaptation, thereby inhibiting color discrimination.

The above parameters are but a few of the considerations that a display designer must be aware of when considering a display for a particular purpose. Therefore, at a minimum, designers must be aware of the potential of the following for influencing system performance:

(1) Display resolution
(2) Brightness/contrast
(3) Registration
(4) Format
(5) Screen size
(6) Symbol size
(7) Display location
(8) Ambient environment
(9) Etc.,

In terms of display design parameters and environmental influence it would appear sufficient information is availabe to guide the designer in the appliction and use of color in electronic CRT displays. This is not to suggest that there are no problems areas when considering color displays for the S-3A. However, the state of the art in display technology appears adequate to provide color tactical displays.

Task/performance

The nature of the task involved appears to exercise considerable influence on the success or failure of color coding in electronic displays. Operator function involving CRT type displays have been variously characterized as detection, recognition, classification, search/locate, etc. The literature suggests that color coding may be of advantage in search/locate type tasks but inferior, in terms of performance, to other coding techniques in tasks classified as identification etc. (Hitt, et al., 1960; Krebs, et al., 1978; etc.). Therefore, the evidence would suggest the possibility that benefits are limited to the use of color in specific types of task.

The problem is that few functions involve a single type task to the exclusion of all others. That is, most functions in modern systems, including the S-3A, are multidimensional in that they have elements of several tasks embedded in each function. Therefore, while color may possess certain advantages to a limited aspect of the total function, it may possess a degrading influence in terms of overall performance.

The issue of task performance and color is a major contributor to the controversy that surrounds color coding and its effect on operator performance. Some efforts suggest that color coding may be superior to other coding methods (e.g. alphanumerics, shapes, etc.). Still other reports indicate color is actually inferior to commonly used coding modalities, while still other research efforts indicate little or no advantage or disadvantage.

For example, Markoff (1972) examined resolution, target size, ambient illumination and chroma in a recognition type task. he concluded that color coded targets were recognized faster and with fewer errors than with monochromatic displays. Hitt (1961) suggested color coding had advantages over numbers and symbols in a task of locating targets in noise. Christner and Ray (1961) observed similar findings. Burdick, et al. (1965) reviewed the literature and concluded color was probably cost effective with certain types of tasks (search and locate). Kopala (1979) examined the effectiveness of redundant color coding and observed a significant reduction in response time and error rate under high workload conditions. Wagner (1977) conducted a series of experiments designed to explore color coding in aircraft display systems. Color and black and white display systems were compared in terms of effectivenss as malfunction indicators for engine management display. Color coding resulted in faster reaction time in terms of target detection.

Oda (1977) in a study of particular interest to the present effort has concluded that color coding in a simulated ASW tactical display situation resulted in improved performance in terms of a reduction in reaction time and errors. That is, data interpretation accuracy and response time were significantly improved with color. It was his conclusion that computer aided color coding would result in the following:

(1) Improve the ability of tactical coordinator to stay ahead of tactical problem
(2) Decrease significance of normal work station distraction.
(3) Improve functional effectives of low experience level operators.
(4) Improve mission effectiveness.

On the other hand, however, a body of the color coding literature suggests the addition of color may be of little, no, or even a decrement in terms of performance. Teichner, et al. (1977) in a review of research and as a result of a series of experiments concluded color was of little decrement or benefit to performance. Loeb, et al. (1967) examined the effect of onset-offset, relative position of the target (i.e. top vs. bottom of display) and color on response time in a watch keeping task. They concluded color had no significant effect on performance. Fowler and Jones (1972) investigated target acquisition with color and black and white CRT displays. Their observations suggested no benefit of color on detection or range recognition. Christ and Corso (1975) in a series of experiments compared color codes, letters, shapes and digits. Their findings did not indicate color possessed advantages in the tasks examined. Beyer, et al. (1971) in a series of experiments investigated the readability and interpre-ability of CRT displays involving color. Their findings indicated color may have resulted in some reduction in variance and reaction time. However, color did not manifest the advantages they had expected.

Krebs, et al. (1978) have suggested that redundancy involving color as one of the redundant codes may exert a positive influence on performance. Situations may be either totally redundant (i.e. two coding techniques involved, only once of which is necessary for identification) or partially redundant (i.e. a coding technique identifies a characteristic of a group).

Shontz et al. (1971) used color as a partially redundant code for coding information location. Color seemed to aid in terms of reducing time required to locate checkpoints. They attribute their findings to the possibility of color aiding in structuring search patterns. However, they also suggest the benefits were greatest where number of objects per category were kept relatively small (i.e. at or below 11). Cahill and Carter (1976) likewise found a relationship between display density and color coding. Their results suggested a linear relationship between density and color, with time to search increasing with increased density and a curvilinear relation to number of colors employed.

Kanarich and Petersen (1971), however, examined colors or numbers versus redundant presentation and found no benefit to performance with redundant presentation. Further, Saenz and Riche (1974) examined four shapes, four colors, and four redundant color/shape codes in a search/detection type task. Color and color/shape redundant code were superior to shape, however redundancy did not improve nor degrade performance.

Review of the performance literature has revealed a very ambiguous state of the art in terms of color and performance. This is particularly true of anyone attempting to apply what is known as a result of traditional experimental methodology to the real world of work as experienced by the crew of an S-3A. Methodologies employed, while being faithful to established experimental design principles, generally make extrapolation to operational systems impossible. The findings suggest that rather subtle changes in any of a multitude of variables can have rather dramtic effects on results. In few instances has the research even attempted to deal with experimental tasks that approximate the environment and task complexity experienced by the operator in the real world. Evidence derived from experimentation wherein most variables have been neutralized for the purpose of purity do not agree, let alone lend themselves to the cluttered operational world of the S-3A. The statement by Chiles (1971) that, ". . . laboratory research has let us down again," is nowhere more true than in color coding and performance research.

It must be recognized, of course, that the sheer number of variables present in (1) visual functioning, (2) display/environment parameters, and (3) task/performance make experimentation difficult. However, decisions relative to the application of color in "real world" environments require an attempt be made to incorporate multiples of the variables involved in a specific application. In this case the tactical display system of the S-3A.

Application of color coding information to tactical display design and use in the S-3A

Review of the literature suggested that a great deal is known about the way in which the visual system functions relative to color perception. Further, a great deal of effort has been devoted to the study of display parameters in terms of color coding. Krebs, et al. (1978); Smith (1978); Christ (1974,1975); Teichner, et al. (1977); etc. have all addressed the subject of display design involving color use. As has been suggested earlier much of the available information is not directly transferable to the S-3A tactical display situation. That is, it is difficult if not impossible to specify conditions and applications on the basis of what is known. The primary problem being that very subtle changes in environmental, task, and performance requirements impact significantly on design considerations.

In view of the above, an attempt was made to suggest those areas in which more or specific information is required in order to make suggestions relative to S-3A tactical display design. In general, it can be concluded that the primary area in need of additional information involves specific information relative to the tasks and skills demanded for completion of the missions of the S-3A aircraft.

S-3A mission

The first step in an attempt to fully appreciate the nature of the tasks involved must include an examination of the mission assigned to the S-3A system. Kovalcik and Becker (1975) have suggested that the primary mission(s) assigned the S-3A include:

(1) Task force and convoy screening attack
(2) Antisubmarine barrier surveillance and attack
(3) Contact investigation and attack
(4) Antisubmarine search and attack
(5) Ocean surveillance

These primary mission statements suggest a rather wide range of non-specific operational areas in which the S-3A can be expected to function. Furthermore, each mission is going to place emphasis on different aspects of crew functioning. As such, crew member requirements are likely to change as a result of the particular mission being considered at any given time. Further, primary mission statements do not suggest the multiplicity of secondary missions the aircraft and its crew may be expected to perform. This complexity poses significant problems in the analysis of information transfer and/or display management. Based on what is known about color, what may be beneficial for one mission or aspect thereof may in fact tend to degrade performance on a second mission requirement. Therefore, it is necessary that a comprehensive mission analysis be completed to assess commonality and difference and apply what is known in an attempt to determine where color may be of benefit and where a detriment.

Task requirements

The crew, as presently configured, consists of a pilot, co-pilot, sensor operator (SENSO) and tactical coordinator (TACCO). Responsibilities of the various crewmembers are as follows:

(1) Pilot -- overall command, safety of flight
(2) Co-pilot -- relief pilot, navigator, communication and non-acoustic operator
(3) Tactical coordinator (TACCO) -- tactical mission commander
(4) Sensor operator (SENSO) -- acoustic sensor operator

Figure 7 suggests the degree of the interaction between various crewmembers. Based on this interaction it is imperative that a comprehensive appreciation of individual "jobs," "tasks," and "skills" be determined along with the actual nature of interaction between postions. Efforts have been devoted to the study and analysis, particularly the TACCO's function.

For example, Helms (1975) in an exhaustive effort studied crew responsibilities in the S-3A. The method employed in this effort was the Functional Description Inventory (FDI). This technique purports to analyze operational functions. The approach includes a classification of activities as to roles, duties and tasks. In this scheme each classification represents a somewhat more restricted analysis (i.e. from broad categories to more specific activities). The result of this effort was a very comprehensive listing of activities at the various work stations.

Doll (1973) analyzed the operational function of Naval Flight Officers (NFO) activities in various aircraft types. The effort was geared to search for commonalities between aircraft. The method used was again the Functional Description Inventory. As was true of the work of Helm (1975) the effort revealed considerable information of a discriptive nature relative to the NFO position in the aircraft types studied.

Clisham (1973) conducted a very similiar effort on the search for commonalities between the TACCO position in the P-3C and the S-3A. Clisham's approach was similar to the studies mentioned above in method and was very successful in describing tasks and drawing comparisons between aircraft.

All of the above efforts were directed at the question of training. As such, each represents a significant and most useful effort. However, the question to be addressed here involves developing display design criteria as opposed to the development of training programs. The completed efforts consist mainly of a description of jobs and attendant tasks. The concentration is on what an operator does in the conduct of the job and as such is a compilation of the objective events that occur in the performance sequence.

The descriptive aspect of job and task performance is the required first step in the process of analysis. Identification and job/task description provide an understanding of job/task structure. This, however, must be followed by an analysis of equipment requirements and behavioral elements involved in performance (Meister, 1971; Salvendy and Seymour, 1973). This latter analysis involves a categorization of the various task aspects in terms of behavioral classification (how) as they relate to operator output (what). The behavioral classification should involve a comprehensive understanding of the total skill and knowledge requirements for the gross tasks and subtasks. Each aspect should be analyzed in terms of specific stimuli, stimuli criticality, decision making requirements, feedback, sensory modality, output requiremnts, etc. (Jones and Fairman, 1960).

Munger (1960) has suggested the following general classification of behavior:

(1) Sensing and filtering
(2) Collection and processing
(3) Decision making
(4) Signal transformation/interpretation
(5) Controlling, correcting and monitoring equipment
(6) Information transfer/management

The analysis of S-3A tasks should include examination of requirements in terms of the above or similar classification schemes.

Therefore, the identification and description of job and tasks involved in tactical aspects of the S-3A weapon system are for the most part currently available. Information relative to overall jobs, duties, roles and to some extent gross tasks and subtasks in a descriptive sense have been considered. What is needed if the use of color, or for that matter any operational or equipment modification in the system are anticipated, is specification and analysis of skills or task elements demanded by system requirements. Such an effort must address the interaction between skill requirements, equipment(s) and personnel in terms of task/job performance. Statements such as "read longitude and latitude of arbitrary point" or "extend MAD boom" are inadequate in terms of appreciation of abilities, skill, and information required in order for an operator to efficiently perform his "task."

As suggested above, the literature is replete with information relative to the capability of the visual system in terms of color vision. Further, the state of the art regarding the design of color displays is quite advanced. The technology required for incorporating color, given the user is willing to pay the price (estimated to be 20% to 30% over cost of black and white) and prepared to accept possible maintainability and reliability limitations attendant to color displays, suggest the feasibility of color tactical displays.

What is needed prior to any consideration, however, is a detailed and comprehensive analysis of the tasks and required skills involved in various performance functions aboard the S-3A aircraft. Given the complexity and diversity of tasks involved, a procedure similar to that used by Helms (1975) and Conners (1979) should be employed in task assessment for the S-3A. Conners, due to the complexity of the total task, selected a specific scenario and described requirements beginning with mission planning and concluding with tactical mission analysis. His approach included an attempt to reconstruct the activities of specific operational classifications and then step through a functional description of the task. What is needed is for Conner's type effort to be expanded to include all major scenarios, and an added expansion in terms of the skills/behavior involved in performance and the nature of information necessary for completion of task. If accomplished, it would then be possible to make specific recommendations as to where color might serve as a factor in performance enhancement, and where it may actually degrade system performance.

In addition, completion of an operational task analysis may be applicable to digital computer simulation for impact assessment. Strieb, et al. (1978) have described the Human Operations Simulator (HOS) and suggested its potential as an analysis and evaluation instrument. Such a simulation system may have the potential for assessing various configurations and parameters in terms of system effectiveness and cost benefit.

Conclusions and recommendations

The results of all research done on color does not allow one to make definite statements relative to its applicability in the tactical display system. It is possible to indicate the type of task (search and locate) where color appears to hold advantage over other coding techniques, and to specify certain other general design principles (e.g. location, number of colors used, population stereotypes, etc.). The greatest need in terms of the present problem is detailed information relative to tasks and subtasks involved in system performance. Based on what is available one can suggest that color could be beneficial in the tactical display system if it was under specific operator control. That is, due to the nature of the tasks involved, color could be called up, thereby allowing the operator to introduce the parameter of color. If color is not at the operator's option, there are many operational configurations in which color may serve to impair performance. For example, while tactical operators aboard the S-3A are definitely involved in search functions, it is highly questionable as to whether the nature of the operational search task is equivalent to that typically used in the experimental setting. Experimental environments generally involve forcing an observer to monitor a display searching for a specific and unique stimulus. The task is uniquely search and locate. In the S-3A operational environment, operators do not usually perform a search task of that nature. Rather, observers are provided with advance information relative to target location and therefore are simultaneously involved in an identification/recognition/classification task as well as a modified search environment. In the case of some aspect of the total task (e.g. identification) color may serve to degrade performance. However, color may aid in the "relocation" of already identified and classified information. In such a situation, the operator would designate which target or stimuli to assign color coding. Color may aid the operator in keeping track of critical information, based on the individual operator's interpretation of data presented.

Obviously, color by demand poses significant design problems in terms of software, display design parameters, etc. However, given the present body of knowledge it does not appear prudent to suggest that color be added for color's sake. It does not appear that wholesale application of color would result in improvement in information transfer and/or display management. It may be that with additional information relative to task requirements and improved task design, aspects of the total function could use color to advantage. However, given the present structure it does not appear color displays would provide additional benefits in terms of performance.

In addition, the present crew configuration of pilot, copilot, SENSO, TACCO is presently under evaluation and in many operational units undergoing modification. This modification involves replacing the position currently occupied by the co-pilot with a Naval Flight Officer. Such a position change possesses the potential for impacting on the possible inclusion of color in the tactical display system.

For example, in present configurations the co-pilot is responsible for non-acoustic sensor operation and as a result has tactical display equipment available (e.g. Multipurpose Display). The workstation, however, does not appear optimally designed if the occupant is charged with overall tactical responsibility. The fact is that dimensions of the Multipurpose Display (MPD) system, illumination levels at the workstation, display location, etc., are not optimally designed for the duties of the TACCO. These variables are also important in that they may impact on the effectiveness of color as a coding modality. Therefore, if such a workstation change is inevitable, further consideration of the merits of color are desirable.

In summary, it is not possible to make a definite statement relative to the incorporation of color in the tactical display system aboard the S-3A. The literature indicates that color coding is situation specific, and the situation will in large part determine whether the impact of color coding is positive, neutral, or negative. In the present problem information relative to situation specifics is frequently inadequate for making decision on the use of color. The complexity of the task and its dynamic nature suggests that certain scenarios may be able to benefit from the addition of color while still other stiuations may suffer from the addition of color as a coding modality.

Therefore, it might be suggested that color be selectable in that it is employed in those scenarious where it is positive and perhaps neutral, and avoided where it may degrade overall system functioning. This obviously requires that situations where it is to be used or avoided be identified. This requires that an analysis of the tasks based on the behavior involved in task performance be completed. Such an analysis would enable decision makers to determine where, or for that matter, if, color possesses the potential for enhancing performance or perhaps degrading operator performance.

If forced to make a recommendation on the basis of currently available information it does not appear that a very strong case can be made for the addition of color in the tactical display system of the S-3A. The performance literature, the additional cost, reliability/maintainability requirements, nature of operator tasks, etc. do not suggest that color would result in sufficient system performance enhancement to make its inclusion cost/effective.

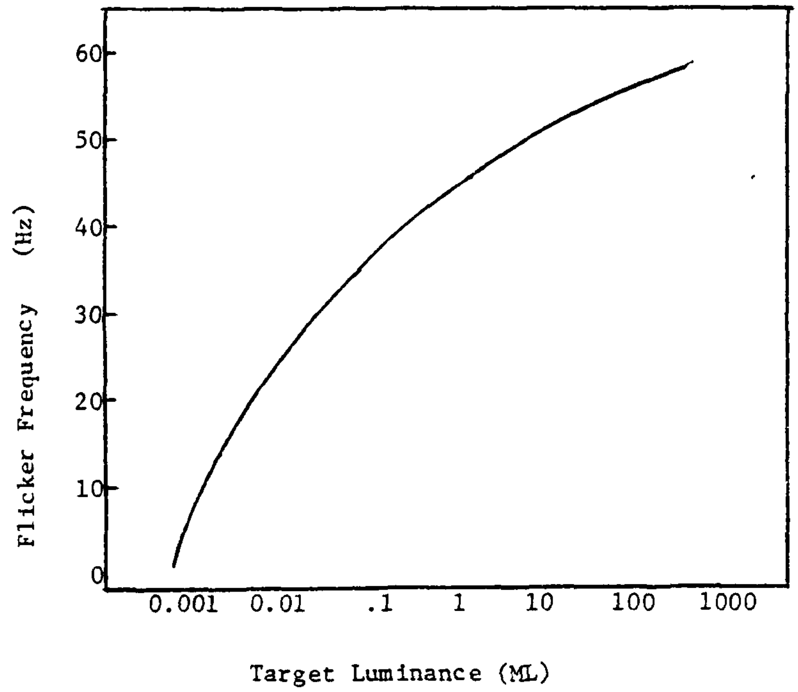

Figure 1

Relationship Between Intensity and Critical Flicker Fusion Frequency
(From Roth and Finkelstein, 1968).

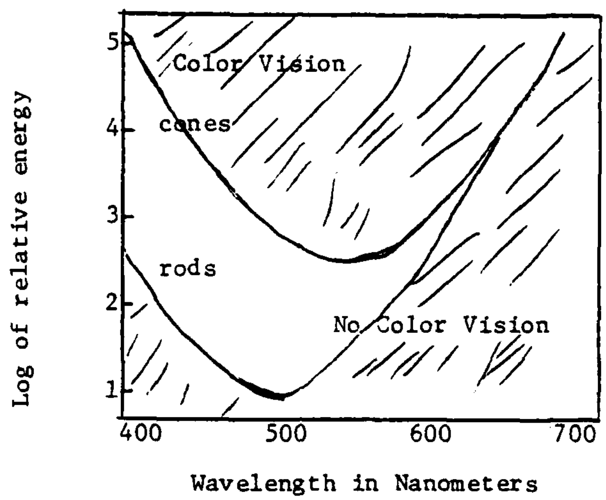

Figure 2

Spectral Sensitivity of the Eye as a Function of Wavelength (From Oda, 1977).

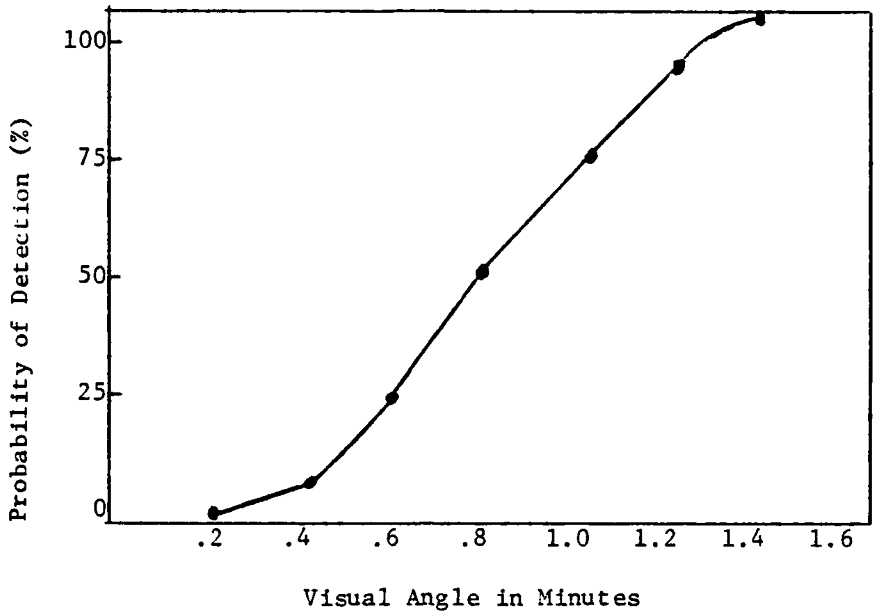

Figure 3

Relationship Between Detection Performance and Visual Angle

(After Roth and Finkelstein, 1968)

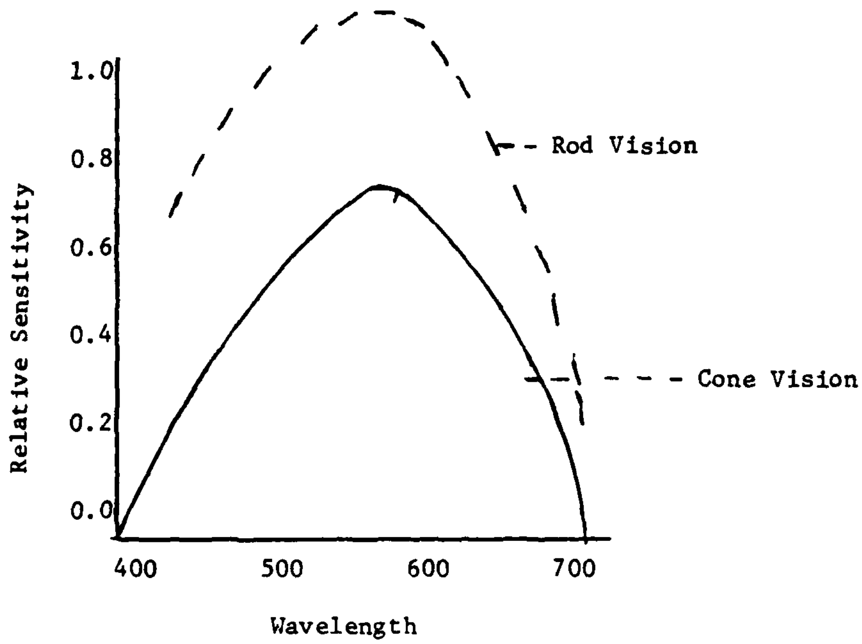

Figure 4

Spectral Sensitivity Curve

(After Wulfech and Zeitlen, 1962).

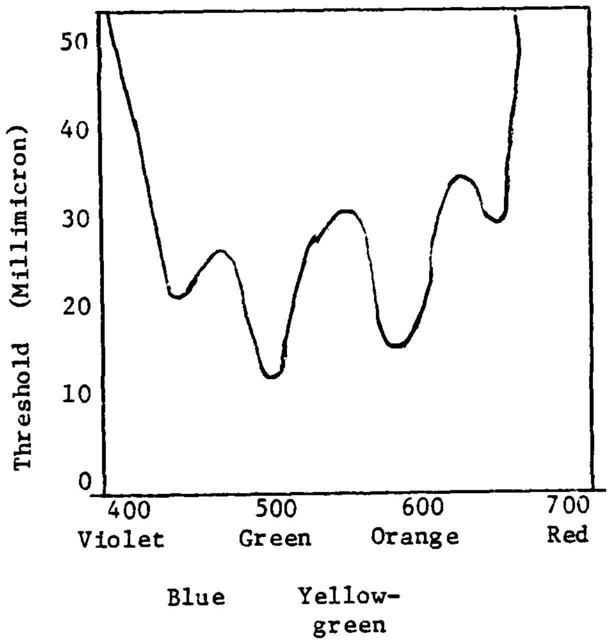

Figure 5

Hue Discrimination

(After Roth and Finkelstein, 1968).

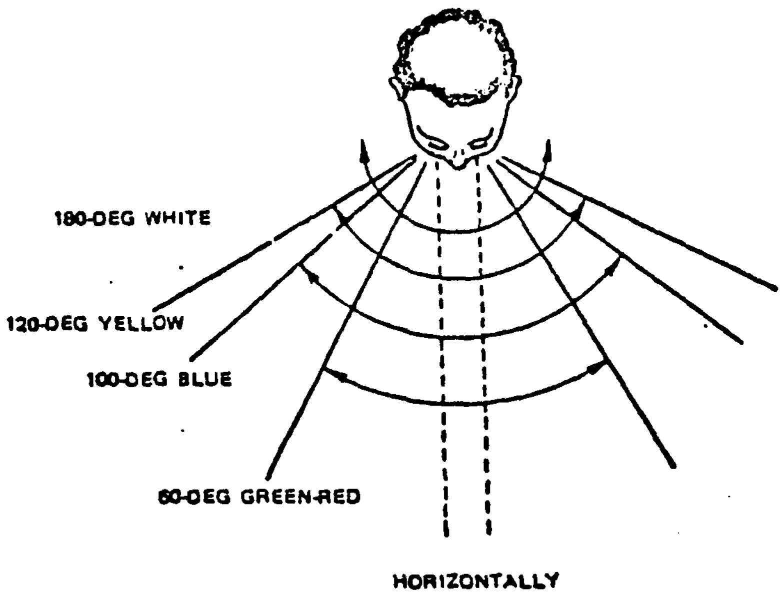

Figure 6

Horizontal Angular Color Limits

(After Krebs, 1977).

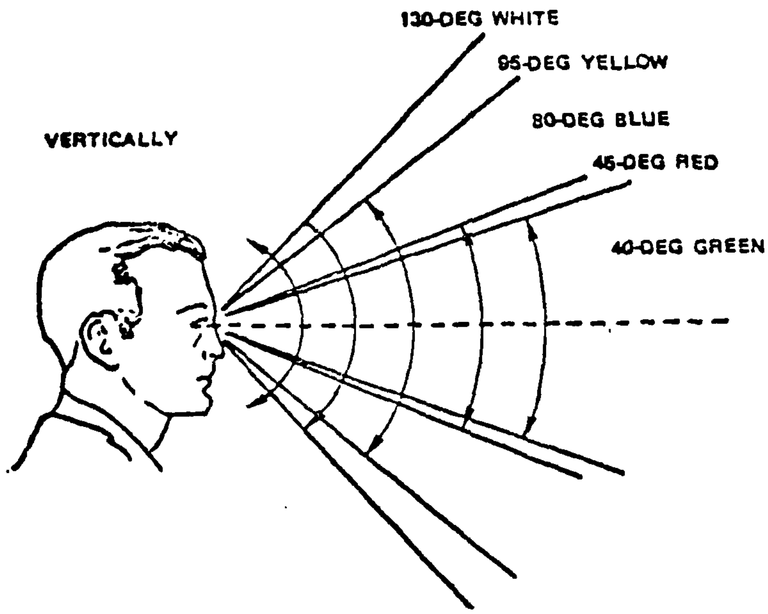

Figure 7

Vertical Angular Color Limits

(After Krebs, 1977).

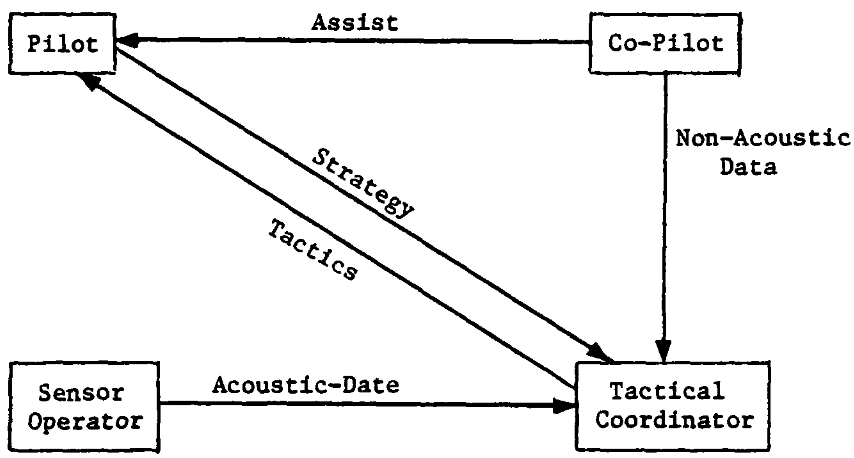

Figure 8

S-3A Crew Interaction

(From Kovalick and Becker, 1972)

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