CONSIDERATIONS IN USING COLOR-CODED DISPLAYS AT INSTRUCTOR STATIONS OF SIMULATORS

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ABSTRACT

The state-of-the-art of using color-coded video displays in modern day simulators necessitates looking at the human factors elements and the efficacy of whether the use of color is necessary at the instructor operator station. This paper covers some fundamental aspects of the physiology of color vision and the human factors considerations that need to be addressed in the design of video displays. Experiences encountered by Sperry in its design of CRT displays have led to a preliminary color convention. Finally, a list of recommendations and suggestions are provided as a guide in the design of color-coded displays.

INTRODUCTION

The rapid advance of technology and development of microcomputers has led to an accelerated rate of man-machine interface situations in the area of CRT displays, especially colored video displays. Many human factor issues such as luminence and the size of symbols have been well documented. However, many areas are still not well understood. For example, is the use of color as a coding tool an efficient means to reduce data and does it facilitate in the reduction and integration of this data? This paper will review some aspects of the physiology of color vision and provide some fundamental human factor guidelines to help the engineer in the design of colored visual display systems.

We will draw from our experiences in the design of color CRT displays for aircraft simulators. The question of whether or not to use color displays at the instructor console is presently being explored with some vigor.

PHYSIOLOGY OF COLOR VISION

Within the entire range of frequencies of electromagnetic radiation (70 octaves) only one octave of frequencies is effective in stimulating the eye (see Figure 1). The range of wavelengths is approximately 370 to 740 nanometers (nm).

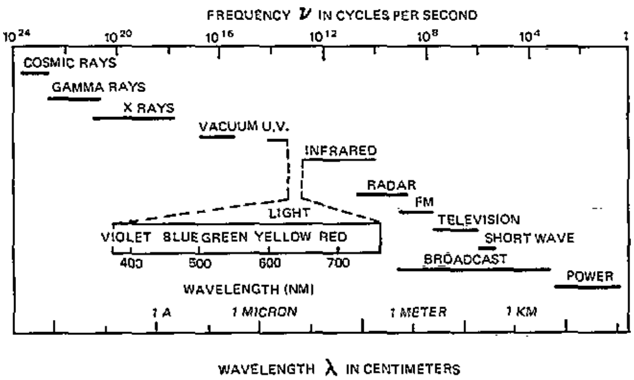

Figure 1. The Visible Spectrum[1].

Prior to reaching the photosensitive layer of the retina, light which stimulates the eye must first pass through several anatomical structures. These structures are the cornea, the anterior chamber, the vitreous humor, and a number of nonsensitive retinal layers (Figure 2). Since the distance from the corneal surface to the retina is very short (about 24mm), the optical elements of the eye must provide a fairly high optical power in order to bend and focus the parallel light rays upon the retina. The power of the eye's lens is nearly 60 diopters.

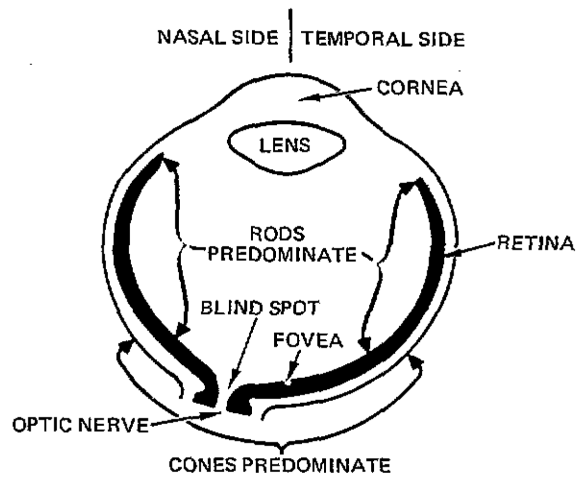

Figure 2. Horizontal Cross Section of the Eye.

Unlike a photographic film, the resolving power of the retina is not uniform over its entire surface. A condition of optimum clarity is achieved for images which fall on or in the neighborhood of the visual center of the eye, the fovea (see Figure 3). The fovea refers to a shallow depression in the retina. It is about 0.5-1.5 mm in diameter, subtending a visual angle of about 4.5-5.5 degrees, and contains a preponderance of cone-type cells concentrated toward the center. Two types of cells are found in the retina, cone-type cells and rod-type cells. The cone-type cells or cones, are involved with color vision and the rod-type cells or rods, are sensitive only to monochromatic light and can only "see" in black and white. It is the fovea and the immediate surrounding areas that the greatest acuity of vision and color discrimination occurs.

Figure 4 illustrates how the geographical location of the rods and cones in relation to the fovea plays a role in color vision[2].

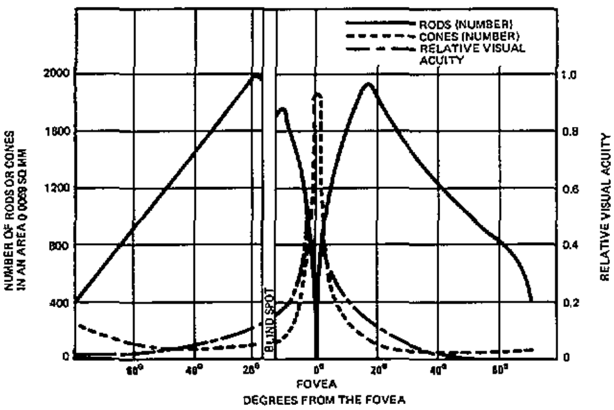

Figure 3. Relationship of Visual Acuity to the Distribution of Rods and Cones[1].

The initial transformation of radiant energy in the eye which results ultimately into vision involves the absorption of light by molecules of photosensitive substance. The photosensitive substance in the rod cells of the retina is rodopsin and the photochemistry of bleaching and regeneration of rhodopsin in the visual process has been worked out in detail by Wald and his colleagues[3].

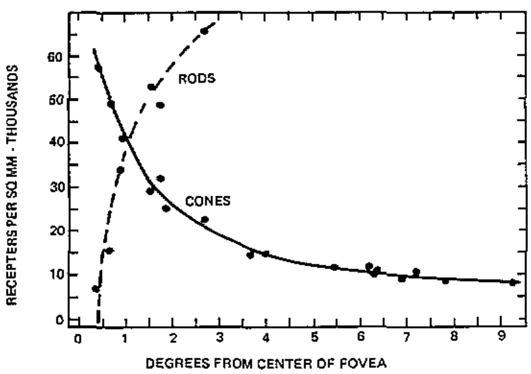

Figure 4. Distribution of Cones and Rods in the Retina[2].

Visual pigments for cone cells which are involved in color vision are not understood nearly so well. Only recently has there been direct evidence as to the existence of three different classes of pigment which probably reside in each of three different classes of cone receptors; each responding to a different spectra or wavelength of light.

The eye is not nearly as good a discriminator of the wavelength or frequency of light as is the ear of the frequency of sound stimulation. Within certain limits, any color sensation may be matched by the mixture of just three primary colors if these colors are appropriately selected spectral lights. For practical reasons in the matching of colors associated with extreme wavelengths and having relatively high luminance, primaries are usually selected to include a red, a green, and a blue or violet element. If any monochromatic light is represented in one-half of a bipartite field, it may be matched by the addition of three primary wavelength colors in the other half of the bipartite field. Figure 5 shows that below about 551 nm in the visual spectrum, a negative amount of one of the three primaries is necessary in order to achieve a match. Since negative values of a primary are not achievable in real life, they really represent the necessity to add one of the primaries to the wavelength of the monochromatic light in order to achieve the perfect match. It is accepted as a convention that when a given amount of a primary is added to the field to be matched, it is treated as a negative value in the overall addition process.

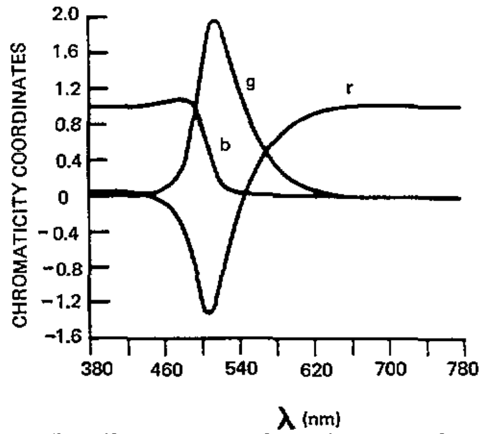

Figure 5. Chromaticity Co-ordinates of Spectrum Colors for the Standard Observer[1].

The fact that just three variables need be taken into account for color matching gave rise many years ago to the speculation that the visual mechanism must involve three selective discrimination channels in color vision[4].

There are certain aspects of the function of the color vision process however, that belie the theory of a simple mechanism of cone cells in the fovea which selectively possess a particular sensitivity to one of the three primary colors. When a red light is mixed with a bluish-green light- the combination tends to be achromatic. Simiarly, addition of a yellow light and a blue light may yield an achromatic product. Also, if the eye is exposed for a period of 5 or 10 seconds to a bright red light and this is followed by a white field, the latter will appear greenish in hue. Such successive color contrast effects can also be seen dramatically following exposure to a green light which induces a red hue in a white field, or a yellow light which induces blue, or a blue light which induces yellow.

If the region of the retina which permits identification of various hues associated with given wavelengths of stimulation is studied carefully, an interesting result is found. Red and green may be identified out to a certain distance from the fovea which is very nearly the same for each of these colors. On the other hand, wavelengths which typically elicit the response "yellow" or "blue" can be presented at a greater distance from the fovea and will evoke the characteristic color naming response. In a word, the color discrimination ability of the retina for yellow and blue extends out further into the periphery than is the case for red and green. These relations are illustrated in Figure 6.

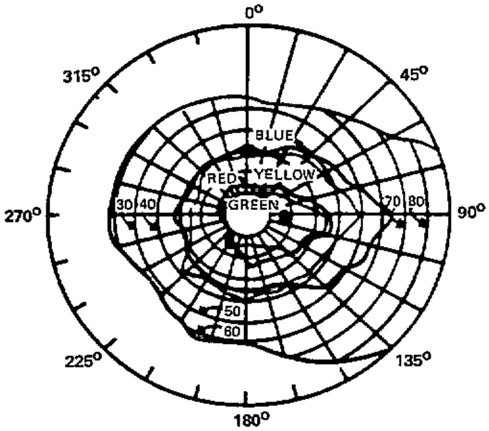

Figure 6. Retinal Receptive Fields for Red, Green, Blue, Yellow, and Achromatic Lights[1].

ENGINEERING AND HUMAN FACTOR ASPECTS

Although the physiological aspects of color vision provides us with some understanding on how the eye processes light, it is in the practical and functional areas of human engineering that designers and engineers must deal. They must understand the use of color as a tool in information processing and how to manage the interface between man and machine. In visual displays, the primary consideration is the use of color for symbols and backgrounds.

Physical specifications for color symbols may be divided into four general areas: size, contrast, luminance, and resolution.

Size. When we talk about symbol size, one has to keep in mind that the perception of a symbol and the discrimination of what color it is are not the same. A symbol may be seen and even identified before one can tell what color it is. M. Haeusing has recommended that the minimum symbol size required for adequate color perception be from 21 to 45 minutes of arc, depending on the *number of colors used*[5]. *Figure 7 illustrates* the effect of the number of colors to symbol height.

Figure 7. Recommended Symbol Size as a Function of Number of Colors Used on the Display.

If the symbol size is too small, then one or both of the following may occur:

a. The symbol(s) appears achromatic.
b. Two symbols of similar color may be confusing.

Luminance. For real-world applications, the major factor influencing display visibility is the ambient illumination. When external lighting can be maintained at a minimal level, achieving adequate visibility is relatively easy. When ambient lighting is variable or becomes very bright problems arise. Colors begin to desaturate or fade and may completely wash out. At a luminance below about 3 candles/sq. meter serious interference can occur on the perception and differentiation of the color itself. If the ambient lighting itself is colored, the symbol colors become more difficult to discriminate and they markedly change in appearance. The following table taken from Semple et. al.6 illustrates how some of these changes occur.

OBJECT COLOR	COLOR OF AMBIENT LIGHT			
	RED	BLUE	GREEN	YELLOW
WHITE	LIGHT PINK	LIGHT BLUE	LIGHT GREEN	LIGHT YELLOW
BLACK	REDDISH BLACK	BLUE BLACK	GREENISH BLACK	ORANGE BLACK
RED	BRIGHT RED	BLUISH RED	YELLOWISH RED	BRIGHT RED
LIGHT BLUE	REDDISH BLUE	BRIGHT BLUE	GREENISH BLUE	REDDISH BLUE
GREEN	OLIVE GREEN	GREEN BLUE	BRILLIANT GREEN	YELLOW GREEN
YELLOW	RED ORANGE	REDDISH BROWN	GREENISH YELLOW	BRILLIANT ORANGE

Table 1. Effect of Colored Light on Symbol Color.

Contrast. Contrast is defined as the measure of the relationship between the luminance of a symbol and its surroundings or background. There are a variety of different methods used to express luminance contrast. Three of these are, contrast (percent); contrast ratio; and contrast efficiency. With colored displays, slightly better visibility can be achieved if the symbols are viewed against a dark background. The reverse is true for black and white displays[5]. Although the most optimum ratio would depend upon other factors such as symbol size and the number of colors used, gen*erally a luminance ratio of about 10:1 works very* well[7].

Resolution. Discrimination of color between two symbols is usually the major reason for increasing the symbol size. As a general rule, the symbol size required for colored symbols is about 50% greater than that for black and white.

The ability to discriminate fine detail varies as a function of both symbol color and background color. More sensitivity to fine detail is found in the red versus the blue end of the spectrum[8].

If symbols are displayed on a dark background, a slightly better visibility is achieved on color displays[5].

Selecting Specific Colors

Two factors must be taken into consideration by the designer when color is to be used as part of a display code. They are:

a. How many colors will be used?
b. What will these colors be?

As the number of color codes is increased in a given display, both the error rate and detection time increase. The general relationship between number of colors and response time is shown in Figure 8. We see that with a greater number of colors used, the more the time is required to respond to any individual color when it appears. Several investigators[6,7] have recommended a three or four color limit for use in operational displays. Much of this is based on high ambient lighting, limited reliability of the display, and the requirement for a fast reaction time from the operator.

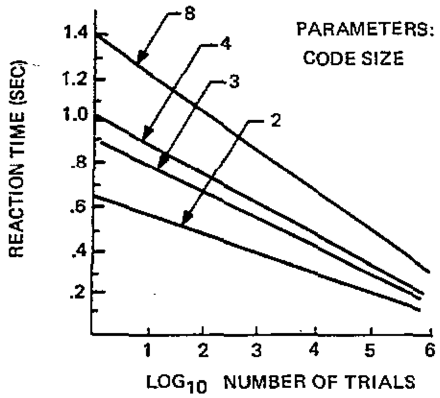

Figure 8. Reaction Time as a Function of Practice for Four Code Sized with Equiprobable Alternatives.

The choice of what color to use should be based upon the attainment of the widest possible spacing in wavelength between the colors chosen. The following table developed by Baker et.al.[8] provides a highly identifiable set of ten colors.

DOMINANT WAVELENGTH (nm)	COLOR NAME
430	violet
476	blue
494	greenish-blue
504	bluish-green
515	green
556	yellow-green
582	yellow
596	orange
610	orange-red
642	red

Table 2. Ten Colors that can be Identified 100% Correctly.

It should be noted that not all colors are equally visible. The documented example of this is the comparison of red, green, and blue in the foveal luminosity curve of Baker et.al.[8]. The approximate ratios R:G:B are, 1.0:1.1:0.03. That is, red and green contribute about equally, and blue only about 1/30th as much. Because of this, blue is not recommended as a color to be used for symbols, unless they are unusually large.

Three colors carry a widely known and accepted color convention. They are red, green, and yellow (danger, safe, and caution) and whenever possible, these conventions should be used.

Redundant Colors, Use and Cautions

Whenever symbols are difficult to discriminate because of clutter, poor contrast, and noise, redundant colors can contribute to improved discriminating ability. In such situations, a totally redundant dimension is recommended. Color and and shape have been found to be the best combination whereas brightness and size were not as effective. Partial redundant codes such as groups of numbers or letters similarly colored or several groups defined in terms of specific colors are useful only in situations where both general and specific status information are meaningful at different times. Then, depending on present information requirements, the redundant code would provide general information at a quick glance. An example is a yellow redundant color to signal a caution condition when certain limits have been exceeded in engine monitoring instruments.

There are times however, when redundancy will not aid performance but rather, will interfere with the effective use of other codes. For example, adding redundant color to displays which are designed to use alphanumeric information may provide no benefit or may even interfere with task performance. This effects was reported in a study by Kanarick et.al.[9].

Irrelevant Color

If the color of a display symbol has no bearing on the operator's task, it can distract the operator in the performance of that task. The color acts as a signal like all color codes and is cognated by the operator and used as an aid in locating a target. Thus this signal from the irrelevant color becomes noise and interferes in the neurological processes of locating and identifying relevant targets. In a multicolored display the irrelevant colors add to the noise and reduce the signal-to-noise ratio of the system.

The phenomenon of irrelevant color contributing to noise in the system becomes exacerbated when the operator's information and tasks vary while the display format remains constant. In a study conducted by Linton[10], the effect of this is dramatically illustrated in Figure 9.

In summary, to minimize the effects of irrelevant coding, a) analyze the ways information might be grouped together for various tasks, b) use color coding as an aid for the most frequently used or the most difficult operator tasks, and c) avoid irrelevant colors.

Color Conventions

Our experiences at Sperry have shown that the use of color in CRT displays at instructor operator stations of simulators can be exploited to enhance the display's appearance, organization, and useability. Color can add to the realism desired in the simulation application, and its use can enhance user acceptance.

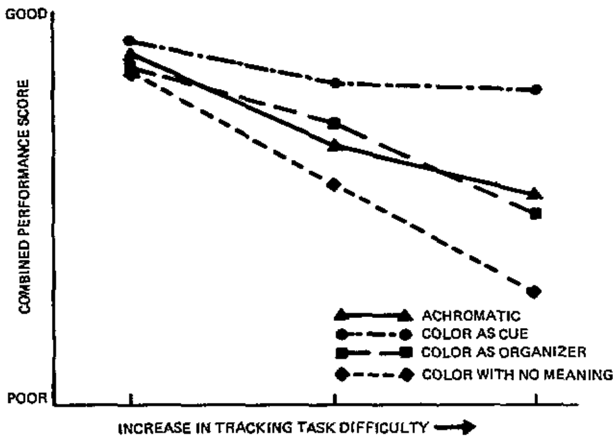

Figure 9. Relative Effects of Task Difficulty on Performance of Simulated Piloting Tasks as a Function of Different Methods of Color Coding.

The establishment of color conventions or standards applicable to every display is particularly desireable. The color conventions used in simulation must agree 100 percent with the conventions that have been established for the actual device being simulated. This is essential in order to maximize positive transfer of training, and *to eliminate negative transfer of training.*

The numbers of colors to be used in a simulation application, and the use of existing universally exercised color conventions (red infers danger; yellow exhorts caution, etc.) must be considered. Experience has shown that a small number of colors can be more effective than a color rich display. Excessive use of color can overwhelm a necessarily busy display whereas discrete and consistent use of color - a single red message on a neutral background - conveys meaning (danger) even before the precise message (generator overheat) is read and understood.

In this regard, the following color conventions have been used successfully in a complex multiplace simulator and are offered as a starting point for consideration in color assignments in color-graphic CRT design:

Color	Use
GREEN, dark	Fixed text; (SPEED, HEADING).
light	Dynbamic text associated with fixed text. (360 deg. associated with (HEADING).
	Dynamic text which occurs automatically as in an alert message prior to automatic activation of a preselected malfunction event.
	Borders outlining and dividing the basic display.
RED and YELLOW	Danger and warning, and military classification code (Secret/confidential).
WHITE	Target symbology and ownership symbol, and for symbols used to record the history of ownship movement (trail dots).
	Dynamic entries by the instructor as they appear on an edit line.
BLUE, light	Used to locate and box in the address of a data field (address locator box) which can be changed by the instructor through keyboard/keypad entry, or activated by touch screen/light stick technology. Note: light blue color is used to indicate the data field is <u>inactive</u>, *as well as to <u>locate</u> changeable* data fields.
MAGENTA	Magenta is associated with the use of light blue to indicate activity in a data field. Whenever an instructor exercises a data field which can be changed, the light blue address locator box will change to magenta. When the change has been completed and entered, the magenta box will be replaced by a light blue box.

GUIDE FOR DESIGN OF ELECTRONIC COLOR DISPLAYS

To use color effectively requires a careful analysis of the display information, tasks, and environment. To assist the design engineer and others in the decision-making process, the following steps are provided as a guide.

<u>Color</u>

1. Determine what colors are available in the system hardware that is being used.

2. *What is the maximum luminence allowable for* each color?

3. Calculate the luminance contrast achievable for each color. Use worst case i.e. highest ambient light.

4. Do any of the colors available fail to provide adequate contrast?

5. Select a maximum of 4 colors with their wavelengths widely spaced.

6 Avoid use of blue for coding symbols.

7 Consider using color as a redundant dimension or to improve symbol visibility.

8 Remember: green = safe; yellow = caution; red = danger.

9 Use color to group related information.

10 Avoid irrelevant color or overuse of color.

<u>Symbol Size</u>

1. Are all colored alphanumerics at least 21 *minutes of arc in height?*

2. Are lines over 3 minutes of arc wide?

Miscellaneous

1. Is the backup display a colored display?

2. Are other codes being used?

3. Is the display cluttered?

4. Will color uniquely provide information that other codes cannot convey?

5. Sketch at least 2 alternative color formats.

6. Work through various changes in format versus changes in mission. Are there any confusing or contradictory uses of color?

Anecdotes

1. As the number of colors used increases, the minimum symbol size goes up too.

2. The higher the ambient lumination, the higher the symbol luminance must be to achieve adequate contrast. Optimum contrast is 10:1.

3. Color coding is helpful if:

a) Display is unformatted
b) Symbol density is high
c) Operator must search for relavent information
d) Color code is logically related to operator's task

4. "Resolution is probably the most important parameter of a visual system"[11].

5. "Color is superior to size, brightness, and shape as a unidimensional target feature - but inferior to alphanumeric symbols."[12].

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