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Findings on Color:
A Summary of Literature Search on Color for Computer Interfaces

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Note: Figures to accompany this paper are found in a diskette. They can be viewed using "Studio/8" application on a high resolution color monitor using a Macintosh computer.

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I. Terminology

A. The Dimensions of Color

Everybody, including the experts, uses different terms to describe the properties and characteristics of color. For our research, we are going to use the terminology used by Albert Munsell (1858-1918). Other experts' terminology will be introduced in relation to Munsell's.

1. Hue

Hue is the quality of color by which we distinguish one color from another, as a red from a yellow, a green, a blue, or a purple (Birren, 1969). Each of these is a different hue. While red can become purple through the admixture of blue, it cannot be purple nor blue. An object that exhibits a specific hue, such as red or green, has a *chromatic color.*

Hue is the first dimension of color in Munsell's three dimensional color system. The hues are placed in an equatorial band with the sequence as follows:

> red, red-purple, purple, purple-blue, blue, blue-green, green, green-yellow, yellow, yellow-red, red (this is the same point as the starting point)

(Figure 1)

While wavelength is a physical variable, hue is a psychological one (Murch, 1987).

A hue's appearance is strongly influenced by its surroundings. This aspect of color will be described in detail in Chapter II.

2. Value

Value is defined as "the quality by which we distinguish a light color from a dark one" (Birren, 1969). It is the second dimension in Munsell's color system. It is the perceived (as opposed to measured) lightness or darkness of a color (Marcus, 198..). For example "pink" is a light red and "maroon" is a dark red.

The value of a color corresponds to the gray scale value. This gray scale value is placed as the pole of this color dimension. The north pole is pure white representing pure light. The south pole is pure black representing total absence of light. (Figure 2)

The lightness of a color depends upon the amount of white, black or gray mixed in the color. When white is mixed with the color, the color becomes *desaturated* and lighter. When black is mixed with the color, the color becomes *desaturated* and darker. (Figure 3)

3. Chroma

Chroma is the third dimension of Munsell's color system. The equatorial band of hues of this color system is placed around the pole of value. "... if we imagine any one of these hues on the circumference of the band to grow inward toward the gray pole in the center, growing grayer or weaker in color strength until it reaches this center pole and loses its color entirely, we have grasped the idea of the dimension known as chroma" (Birren, 1969). (Figure 4)

In other words, chroma is the strength or weakness of color, depending on the amount of gray in the color. For example the emerald and certain grapes are light green, but they differ in their chroma. The emerald is strong in color and therefore has a high chroma and grape is weak in color or grayer and therefore has a low chroma.

Other experts use different terms for chroma, such as *saturation, purity,* and *intensity.* From the point of view of physics, saturation is closely related to the breadth of wavelengths contributing to a color sensation: the narrower the band of wavelengths the more highly saturated the resulting color sensation (Murch, 1987). The hues that are refracted from a white light by a prism are of maximum saturation.

Gray, black and white are called *achromatic color* and stand out from their background on the basis of value (Murch, 1987). Black, grays and white are fully unsaturated colors.

B. Color Mixtures

There are two different kinds of color mixture: subtractive color mixture and additive color mixture.

1. Subtractive Color Mixture

The adding of two different pigments will produce a color different from the original pigments. The bands of wavelengths are subtracted or cancelled by the combination of the light absorbing materials (Murch, 1987). The more different hues combined the more wavelengths get cancelled. If all wavelengths are absorbed or subtracted, the result is black. The minimal number of pigments required to produce black is three. They are often referred to as *primary colors of subtractive color mixture* (Murch, 1987). The colors are **yellow, magenta** and **cyan.**

Subtractive Combination	Color
Yellow + Magenta	Red
Cyan + Yellow	Green
Magenta + Cyan	Blue
Yellow + Cyan + Magenta	Black

The principle of subtractive color mixture is used by painters, printers, etc.

2. Additive Color Mixture

Additive color mixture occurs when bands of wavelengths are added to one another directly. The bands of wavelengths are added by the combination of the projected lights. The *primary colors of additive color mixture* are red (long wavelength light), green (middle wavelength light) and blue (short wavelength light). When all of these primary colors are added, the result is white. With combining two or more of these colors one will be able to produce most hues as well as the achromatic colors.

This method is used for color display on a screen (the light is reflected by phosphor compounds on the screen), computer color displays, televisions, etc.

II. Basic Principles of Color Interactions

A. The Relativity of Color

Josef Albers, in his book *Interaction of Colors*, wrote "In order to use color effectively, it is necessary to recognize that color deceives continually." This means that color always changes depending upon the environment--one color evokes innumerable readings.
A certain red would look different when it is put on a certain blue background than when it is put on a certain yellow.

Figure 5 is an example of this: the small rectangles in the middle of the two different color backgrounds are the same color but they appear different on two different backgrounds.
Figure 6 is another example: the small rectangles in the middle of the two different color backgrounds are the same color but they look like the colors of the opposite backgrounds.
In Figure 7 the small rectangles have different colors but they appear to be the same on the two different backgrounds.

Color changes are also influenced by the change of:

- quantity
- form
- recurrence
- lighting
- direction and sequence of reading
- materials

B. Color Contrasts

When we see an object, we actually see the difference or contrast between the color and the value of the object and that of the surroundings. Johannes Itten (1888-1967) observed that there are seven different kinds of color contrasts.

1. Contrast of Hue

This is the simplest of the seven. Contrast of hue is a contrast between different hues. Some obvious examples are: yellow/red/blue; red/blue/green; blue/yellow/violet; yellow/green/violet/red; violet/green/blue/orange/black. Yellow/red/blue is the extreme instance of contrast of hue. The intensity of contrast of hue diminishes as the hues employed are removed from the three primaries (Itten, 1961).
(Figure 8)

2. Light-Dark Contrast

The light-dark contrast is a contrast between the value of colors. The extreme example of light-dark contrast is between black and white. This contrast could be of the same hue or different hues as illustrated in Figure 9. It is important to remember that certain hues become dark very easily (blue, violet) and some hues are resistant to becoming dark (yellow).

3. Cold-Warm Contrast

In general we might say that red, yellow and orange are warm colors; and blue, violet and blue-green are cool colors. Like white is the lightest of value and black is the darkest of value, blue-green is always cold and red-orange is always warm. The hues between them in the color circle may be either cold or warm accordingly as they are contrasted with warmer or colder tones. In other words the "temperature" of a color is relative to its surrounding. For example a purple-red is warm compared to dark-blue, but cold compared to red-orange (Figure 10).

4. Complementary Contrast

In terms of subtractive color mixture, two colors are complementary if their pigments, mixed together, yield a neutral gray-black. In terms of additive color mixture, colors are complementary if their mixture yields white.

"Two such colors make a strange pair. They are opposite, they require each other. They incite each other to maximum vividness when adjacent (Figure 11); and they annihilate each other, to gray-black, when mixed (Figure 12)--like fire and water." (Itten, 1961)

In the color circle (Figure 13), complementary colors are diametrically opposite each other. For examples:

yellow, violet
blue, orange
red, green

"In principle, a complementary is a color accompanied by its after image." (Albers, 1963)

5. Simultaneous Contrast

Itten explains that simultaneous contrast results from "the fact that for any given color the eye simultaneously requires the complementary color, and generates it spontaneously if it is not already present." Thus this phenomenon happens in the viewers' eyes, and is not objectively present.

This kind of contrast is illustrated in Figure 14: a small neutral gray square placed in the middle of a pure color square. If we stare at the gray square for a while, it will appear to be tinged by the complementary color of the the pure color.

Simultaneous contrast is also known as after-image. Figures 15 and 16 are also examples of after-image. Figure 15: After staring at the center of the red circle for about half a minute, suddenly shift your focus to the center of the white circle. You will see a green or blue-green circle instead of white.

Figure 16 shows reversed after-image. After staring at the white square with yellow circles for about half a minute, shift focus to the plain white square on the right. You will see diamond shapes (the leftover shapes of the circles) in yellow.

6. Contrast of Saturation

Contrast of saturation is the contrast between pure, intense colors and dull, diluted colors. Figure 17 is an example of this kind of contrast.

7. Contrast of Extension

Contrast of extension is the contrast in the amount of area each color in a space occupies.

Some color theorists developed a theory of the harmonious proportions of colors (from Goethe's light values proportion, Itten developed the proportion of harmonious areas for the primary and secondary colors -- yellow : orange : red : violet : blue : green = 3 : 4 : 6 : 9 : 8 : 6 as illustrated in Figure 18).

Albers went a different direction from many color theorists "..independent of harmony rules, any color "goes" or "works" with any other color, presupposing that their quantities are appropriate." Figure 19 is developed based on Albers' exercise: each panel uses the same four colors but in different sizes, recurrences and placements. The four colors appear to be different from panel to panel and each panel gives a different feeling from the other ones.

There are two different extensions that would influence the appearance of colors:

- the extension in area--the size
- the extension in number--the recurrence

C. Color Harmony

Color harmony is the sense of relatedness among colors. Most color theorists prescribe formulas for color harmony. For our research, only Itten's and Albers' "prescription" will be discussed in this paper.

Itten's definition for color harmony is "..the craft of developing themes from systematic color relationships capable of serving as a basis for composition." He describes color relationships for harmony as color chords. The chords may be formed of two, three, four or more tones and they are called dyads, triads, tetrads, etc.

1. Dyads

A harmonious dyad is the two colors diametrically opposed in the color wheel. They are complementary colors, for example: yellow/violet and red/green.

2. Triads

A harmonious triad is the three colors in the color wheel which connections form an equilateral triangle, for example: yellow/blue/red. Isosceles triangles also form harmonious triads, such as yellow/blue-violet /red-violet.

3. Tetrads

A harmonious tetrad is the four colors in the color wheel which connections form a square, such as yellow/blue-green/violet/red-orange. A rectangle also form harmonious tetrads, for example: yellow-green/blue-violet/red-violet/yellow-orange.

Albers on the other hand, as mentioned above, sees color harmony differently. In practice, we use color for different irregular shapes and proportions. It is hard to measure the correct proportions to achieve the prescribed harmony. He suggests that practically any color can work together with any other color presupposing that their quantities are appropriate. The appropriateness is determined by one's perception and one develops this sense by doing color exercises.

III. The Semantics of Color

Most people see the world in color, it is very difficult to get away from. Because of this, people develop some basic cultural and universal associations between certain colors and certain aspects of emotion and cognition. For example, red is associated with danger and heat, maybe because red is the color of blood and fire.

A more extensive study should be done concerning the denotations and connotations of different colors in different cultures, since products are now more internationally distributed.

Common Western denotations of color (Marcus, 1986; Apple Computer, Inc., 1986)

Color	Denotations
Red	Stop, Danger, Hot, Fire, Failure, Error
Yellow	Caution, Slow, Test, Delay, Warning
Green	Go, OK, Clear, Ready, Power On
Warm Colors	Action, Response Required, Spatial Closeness
Cool Colors	Status, Background Information, Spatial Remoteness
Grays, White, Blue	Neutrality

IV. Color and Form

Some experts did studies of the associations between color and form. This is a very subjective aspect of color. The importance of this is in the use of certain colors for certain shapes of icons. The relationship between color and form experts have proposed is not to be viewed as restrictive. The color should enhance the meaning of the icon. Gestner (1986) quoted Kandinsky who once said: "It is easy to see that there are many colors whose value is underlined by many forms and dulled by others. At all events sharp colors have a more suitable sound in sharp forms (for example, yellow in the triangle)." (Figure 20)

Gestner in his book *The Forms of Color* studied extensively the relationship between color and form. For example, the association of dark blue and a circle corresponds to the characteristic of dark blue which is as static and passive as a color as the circle is as a form. Gestner stated that colors and forms have a character of their own, independently of what they represent. These characters have quite definite interactions upon each other, including agreements like that between yellow and the triangle (Gestner, 1986).

V. Color for Computer Displays

As color monitors have become more widely available, many studies have been done regarding the use of color for computer displays. This chapter will discuss recommendations by experts in the use of color as well as recent research findings.

A. Advantages and Words of Caution

Experts seem to agree that there are advantages in using color for computer displays. They also seem to agree that despite the advantages of color, there is a danger that the misuse of color can lead to low task performance due to confusion and fatigue.

1. Advantages

The following are the advantages of using color for computer displays as presented by some experts (Christ, 1978; Hoadley, 1990; Schneiderman, 1987; Silverstein, 1987).

a. Aesthetic

Silverstein (1987) found that while color did not necessarily increase performance, users exhibited a general preference for color over monochromatic presentation. Color can be pleasing to the eye and adds accents to an uninteresting display. Color can also evoke more emotional reactions.

b. Information Coding

- Attention-getting

  Particularly in a crowded display. Color can increase the attention-getting of a particular signal. For example, color can be useful for alerting an operator of a change in status. However, this property of color is often due to its novelty effect (Christ, 1978).

- Organization

  Color can help to identify categorical information, but only if there are a limited number of alternative values or categories. Color can be used to discriminate between different areas, and also to show relationships among objects.

c. Retention of Information

Color can aid in the retention of information.

2. Words of Caution

Because color displays have become widely available and are more fun to use than monochromatic displays, people have the tendency to use color excessively. Also because of its complexity, color is a very difficult medium to deal with.

There are important words of caution to think about before designing a color display:

a. Limited benefits:
Hopkin (1983), in his paper *"Use and Abuse of Colour"*, wrote that on the whole the benefits of color are more apparent than real; users prefer color displays over monochromatic ones because they are more aesthetically satisfying. He found that the benefits are task dependent, and are quite small. He further wrote: "Typically, colour-coded information is used by different viewers in different ways for different purposes. If the task was always the same it would be possible to specify an optimum: because tasks differ, any colour coding convention is likely to aid some tasks and hinder others, by requiring within-colour collation of data in some instances and across-colour collation in others." However, Hopkin wrote that color can, if used properly, cut search time, provided that the color of the sought information is known. Marcus (1986) also stated that people do not learn more from a color display, but color is more enjoyable and color information is easier to remember.

b. Color is generally not useful if: (Christ, 1978)
- a detailed set of more than six values is required
- it will serve as a distractor or is sometimes irrelevant
- the area of the color symbol is very small
- the target is in the periphery of vision
- illumination or signal intensity is very low

c. Color deficiency should be considered:
Christ (1978) wrote that color is generally not useful if the operators are selected from the general population without regard to their color vision capabilities. Approximately 8% of male population and 0.5% of female population some kind of color deficiency.

d. Consider the lighting condition of the environment:

Since color is a relative medium and it changes according to the surroundings, it looks different under different lighting conditions. Wigert-Johnston (1987) suggested that to achieve the best conditions for using color displays we should:

- eliminate the reflection of light and glare,
- use indirect ambient lighting with a user-controlled dimmer switch,
- use incandescent track lighting, positioned to control glare, instead of the fixed fluorescent type,
- use a room without windows or with windows that could be completely covered to block out sunlight.

B. General Principles of Using Color for Displays

1. Begin the Design in Black-and-White

Experts suggested that when we design color displays we should start by using black and white (Apple Computer, Inc, 1986; AT&T, 1988; Schneiderman, 1987). When the design works well, then add colors appropriately. Marcus (1986) suggested that color should be used to enhance black-and-white information. There are several reasons for this:

a. Lighting Conditions

We do not know what kind of lighting conditions the display is going to be used under. As shown in **II. Basic Principles of Color Interactions**, color is very sensitive to changes: it changes according to the environment (e.g., the lighting condition) under which the color is observed. Because of this, we want the design to work not just based on the hue and saturation differences, but mostly based on value and even shape or texture differences, so when the color changes the contrast is still perceived.

b. The Monitor

The color we saw on the screen one hour ago may not be exactly the same as what we see now. Color appearance on the monitor is not stable. Sometimes there will be problems in which the color does not show at all. When this happens, the design should still work.

c. Color Deficiency

Experts found that 8% of male and 0.5% of female population have some degree of color deficiency. The most common is the reduction in the discrimination of red and greens (Hunt, 1987). Also color vision varies to some extent as a function of the age of the observer. Rapid improvement has been reported for color discrimination up to approximately 25 years of age, followed by a gradual decline which becomes more pronounced around age 65 (Burnham et al., 1963).

d. People do not learn more from a color display, but the crucial factor is that color is more enjoyable and color information is easier to remember (Marcus, 1988).

2. Colors Used

a. Number of Colors

Experts seem to agree that the number of colors used should be limited to between four and seven distinct colors, especially when the meaning of color must be recalled (Marcus, 1986; Schneiderman, 1987; Silverstein, 1987; Smith, 1988; Wigert-Johnston, 1987)

d. Palette

A palette is a set of colors that harmonize well, and this should be used. Harmony relates closely to the contrasts of colors. Marcus (1986) suggested that color harmony can be achieved by:

- using a monochromatic palette: different values of one hue
- using "split complementary": one color is selected along with colors on either side of its complement (in a color wheel)
- selecting colors in three equidistant points around the color circle

e. Contrasts

- Hue Contrast

The use of spectrally extreme colors simultaneously should be avoided. Marcus (1988) suggested that to ensure distinctive coding, we should use only five colors:

- red
- yellow
- green
- blue
- brown

- Value or Light-Dark Contrast

Marcus (1986) suggested that between two and five values of each hue used should be developed. It is important that the value difference should be easily perceived. He also suggested that harsh contrast (like using pure white on dark background) should be avoided.

- Cold-Warm Contrast

  Marcus (1986) suggested that foreground colors should be warmer than background colors.
- Complementary Contrast

  We should avoid strong complementary colors. Their edges vibrate making them difficult to look at and focus on. As a result, they tire the eyes quickly.
- Simultaneous Contrast or After Image

  To avoid after images, especially for continuous reading tasks, do not use spectrally extreme colors (like red and blue) or saturated colors. Instead, use desaturated and spectrally close colors (cyan, green, yellow).
- Contrast of Extension

  As previously mentioned, there are two different kinds of extensions that will influence the appearance of color: the extension in size and the extension in number. Smith (1988) in *"Standardizing Colors for Computer Screens"* wrote that most color images should subtend at least 16 minutes of arc. Blue and yellow should subtend at least 20 minutes of arc in order to be correctly identified.

3 Position

Marcus (1986) suggested that foveal (center) and peripheral colors should be used appropriately. Blue should be used for larger areas. Red and green should be used in the center of the visual field. If they are used at the periphery, some signal to the viewer must be given to capture attention, such as size change or blinking.

4. Background and Foreground

Some recommendations have been made for the use of background and foreground color. Hopkin (1983) suggested that multicolored backgrounds should not be used because they are a common source of fatigue.

There seems to be disagreement as to whether background color should be light or dark. Marcus (1986) suggested that for the background it is best to use cool, dark hues because they recede. However, Apple Computer Inc. (1986) suggested that all backgrounds for interfaces should stay white. Hopkin (1983) wrote that there are issues to be considered in both dark and and light backgrounds. If the background is very dark, bright characters and shapes may have excessive contrast and seem to float in space. If the background is very light, it may be impossible to provide sufficient brightness to satisfy contrast requirements.

Color symbols presented on a light background or surround are perceived as more saturated than the same colors presented on a dark background (Farrell&Booth, 1975; Pitt & Winter, 1974).

Marcus (1986) recommended the following background hues in order of priority: blue, black, gray, brown, red, green, purple.

The choice of foreground colors should permit easy harmony and function on a wide range of background colors. The colors should be as different as possible from background colors. They also should have the same chroma or saturation, except red and orange (Marcus, 1986).

5. Physical Impressions

Smith (1988) in *"Standardizing Colors for Computer Screens"* suggested some guidelines for certain physical impressions:

Color Used	Physical Impression
saturated or bright colors	lager size
desaturated or dark colors	smaller size
equal lightness	similar size
saturated, dark colors	depth or heaviness
desaturated, light colors	height
saturated, bright colors and long wavelengths	closeness
desaturated, dark colors and short wavelengths	distance

6. Color and Coding System

a. Spectral Order

Use spectral order in color coding: red, orange, yellow, green, blue, indigo, violet. Viewers see a spectral order as a natural one, and would select red, green and blue (cyan) as intuitive choices for the front, middle and back layers when viewing a multi-layer circuit board (Marcus, 1986).

Short wavelengths should be assigned to the low end of a continuum and long wavelengths to the high end. To show graduated changes spectral order (e.g., blue, green, cyan, yellow, and red) or lightness order (e.g., darkest to lightest color or vice versa) should be used. Short wavelengths should be used to represent the lowest magnitude of change and long wavelengths to represent the highest magnitude of change (Smith, 1988).

b. The Semantics of Color

It is important to use familiar, consistent color coding with appropriate references. Refer to **III. The Semantics of Color** for the list of the common Western denotations.

c. The Relationship With Other Coding Systems

Silverstein (1987) found that redundant coding methods--where information is available through multiple dimensions or codes (e.g., color and shape) that have zero correlation between them--are beneficial. The benefits include:

- The preservation of information in the event of partial display or color component failure.
- Minimal impact of color shifts as a function of display instabilities and aging.
- Color vision deficiencies in the user population are less of a concern when all displayed information is available through multiple codes.

7. Color and Typography

Some experts believe that light colored text (e.g., white) on dark background is better than dark text on light background. Other experts believe just the opposite. Some believe that colored text is harder to read than black on white (Apple Computers Inc., 1986).

Marcus (1986) suggested that light text, thin lines and small shapes (white, yellow or red) on medium dark and dark backgrounds (blue, green, red or dark gray) should be used for long distance or low ambient-light viewing situations such as slide presentations, workstations, video, etc. Dark text, thin lines and small shapes (blue or black) on light backgrounds (light yellow, magenta, green, blue or white) should be used for light viewing situations such as overhead transparencies, paper, etc. He also suggested that the highest contrast in figure-field relationships should be reserved for text type.

Silverstein (1987) found that color contrast at intermediate values of luminance facilitated reading time.

Smith (1988) suggested that for continuous reading, spectrally extreme colors or saturated colors should be avoided since they may cause defocused images, depth effects and after images.

VI. Conclusion

This has been a very broad examination of the characteristics of colors and their interactions as they may be applied to computer displays. The most important finding is that color is a relative medium, it changes when the environment changes. A certain red will have different appearances when placed on a certain yellow and on a certain blue background. When using more than one color, the contrasts (seven kinds according to Itten) should be considered. These basic principles of color should be the basis for designing computer displays in color.

Caution should be taken when designing color displays, since it is very easy to misuse color, which could result in low task performance.

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