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LEVEL

COLOR DISPLAY DESIGN GUIDE

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The objective was to develop a design guide for the use of color in advanced avionics displays. Study results are presented in two parts. Part I presents principles for use of color, plus supporting data where such data exist. Principles of Part I are general and can be applied in virtually any application involving color coding of display information. Part II represents the application of these principles to real-world cockpit displays. Recommended color codes are developed for application to electronic displays in fighter/attack aircraft. Examples of representative display formats

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20. Abstract (continued)

incorporating the recommended coding are provided.

PREFACE

This color display design guide was written for use by a human factors engineer. However, an attempt has been made to express the concepts and principles in language understandable by the general reader interested in the effective application of color to a display.

It is assumed that the reader is either considering the use of color in a particular display or has been tasked with determining how an existing color capability might be used effectively in some specified application. As a consequence of this orientation, this document does not specifically address the relative merits of color versus various other codes. Rather, it is assumed that a decision to use color on a given display has been made and that it will be used in conjunction with other codes (e.g., alphanumerics, shapes, position, orientation, etc.).

The most difficult and perhaps least understood aspect of color use is the application of color as a coding tool when applied to a particular display format. Other issues such as symbol size and luminance are better documented. The data and recommendations are based on information available in published articles and research reports. An attempt has been made to use the available data as much as possible in the development of guidelines.

The document is divided into two major parts. Part I presents principles for color use plus supporting data where such data exist. The principles of Part I are general and can be applied to virtually any color display.

Part II applies the principles in Part I to real-world cockpit displays based on analysis of pilot's display usage in several selected high workload missions. The design principles are then used to generate recommendations for color coding these displays. Examples of display formats incorporating the recommended color coding are also provided.

Part I was written by Marjorie Krebs. Part II was written by James Wolf and John Sandvig.

The contents of this document are based on information currently available. No experimental validation of conclusions is made. In some cases inferences are made about trends and relationships that have not been completely validated experimentally. It is hoped that as more information becomes available this design guide will be revised and improved to make it more relevant, sound, and useful to the color display designer.

Acknowledgement is made of the advice and support of a number of Navy personnel who reviewed the many versions of the design guide and made numerous helpful suggestions for revision. Those who reviewed the documents or helped in other ways include: Cmdr. Donald Hanson, technical monitor, and Dr. John O'Hare, both of the Office of Naval Research; Ron Erickson and Dan Wagner of the Naval Weapons Center, China Lake, California; Lloyd Hitchcock and Bill Mulley of the Naval Air Development Center, Warminster, Pennsylvania; and Cmdr. Paul Chattelier of NAVAIR.

Finally, we would like to acknowledge the technical help and guidance provided by the late Dr. Warren H. Teichner of New Mexico State University. Dr. Teichner also studied color coding under ONR sponsorship and provided substantial guidance through his published reports and personal communication over the past several years.

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PART I

PRINCIPLES AND GUIDELINES FOR COLOR CODING DISPLAYS

Prepared by

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SECTION I

PART I INTRODUCTION AND OVERVIEW

The question of whether or not to use color in various display applications is currently one involving some controversy. Data that can support either side of the issue can be selected from the literature. A careful review and analysis of the color literature reveals that the issue of color utility is not a simple one. The value of color as a coding method is entirely dependent on its effective use in a specific application. That is, it can be beneficial, neutral, or distracting. Which of these outcomes will occur is a function of how, where, and when it is used. The operator task, the environment, the display medium, and the specific way in which color coding is applied are all important.

When this project was first begun, it was expected that specific display formats using specific color codes could be provided in this document, allowing the user to select that particular format closest to one of concern. Unfortunately, this has proved to be much more complicated than was initially assumed. The "ideal" color display is dependent upon so many situation-specific factors that a good color display in one application may, in fact, be a poor one in another. Thus the objective of Part I of the Color Display Design Guide is to provide the user with data and principles that will be helpful in making color format decisions. After carefully analyzing the application in question, these principles should provide the basis for making correct color coding decisions.

In Part I, a set of guidelines or principles are provided for color use. Supporting data from the literature are provided in conjunction with these statements. For the general reader who may not be familiar with certain concepts and terms in the human vision, display, and color areas, selected terms and concepts have been defined. These definitions are provided in Appendix A. This information has been placed in the appendix to provide easy access to specific terms while not interfering with the continuity of Section III.

SECTION II

STEPS IN DESIGNING AN ELECTRONIC COLOR DISPLAY FORMAT

The effective use of color in any given situation requires an analysis of the specific environment, the displayed information, and the operator's task-related information requirements. The following steps are provided as a guide for the display designer in performing this analysis. The order in which issues are raised in this section follows to some extent the order of topic areas and principles presented in Section III.

1. Determine the colors available with the display system hardware.

2. Determine the maximum luminance achievable with each color.

3. Consider the ambient illumination in which the display will be used:

   a) Dark

   b) Average room luminance

   c) Variable--dark to bright sunlight

4. Calculate the luminance contrast achievable for each color under the worst possible operating conditions (i.e., high ambient light, such as bright sunlight shining on the display surface).

Any color that will not provide adequate contrast under "worst case" conditions should not be used as a primary (nonredundant) information source. It should be used elsewhere with caution.

5. Of the remaining colors available, select up to five (maximum). The particular colors chosen should be widely spaced in wavelength from one another.

6. Determine where the display will most likely be located relative to the operator's normal viewing position.

   a) If the display is to be peripheral to the line of sight, any signal drawing attention to it should be white if the signal is also peripheral. If colored, the signal should be placed in the line of sight.

   b) If the display is within the operator's normal scan pattern, it can be considered foveal. Caution should be taken to determine if this is a correct assumption.

7. The following size constraints should be observed:

   a) On the display itself all colored alphanumerics and symbols should be at least 21 minutes of arc high. Lines should be about three to four minutes of arc wide for any graphics.

   b) Avoid the use of blue in the coding of alphanumerics or any small symbols.

8. Consider the use of color on the display:

   a) When symbols are difficult to see, as when they are superimposed on imagery, use color as a redundant dimension to improve symbol visibility.

   b) As a general rule use red, green, and yellow according to the conventional meanings only (i.e., red = danger, yellow = caution, green = safe).

   c) For data displays use red, yellow, or green alphanumerics as a partially redundant code to indicate the present relative status of the numbers presented. For example, a digital representation of altitude might be coded as red if it is too high, yellow if borderline, and green if it is within tolerance.

   d) Use color to group spatially separated but related information (e.g., a series of checkpoints on a map or friendly vs. enemy installations).

   e) Use color to reduce the effective density of items on a cluttered display by separating them into several color categories where the symbols can be assigned to task-related groups.

9. Consider the other displays the operator will be using in conjunction with this display. If any of them are color displays observe the following:

   a) Similar colors should have the same or similar meanings across the display set. They should never have contradictory meanings.

b) Color can be used to visually group information across displays as well as within one display.

10. Consider the operator's workload during display use. The higher the workload, the more important the clarity of the displayed information. Under high workload conditions:

    a) Use fewer than the maximum number of colors. The more complex the color code the more difficult it will be to use.

    b) Use color primarily as a fully redundant or partially redundant dimension (i.e., to enhance symbol visibility or to convey relative information quickly).

    c) Avoid the use of irrelevant color (i.e., a multicolored display where color has no specific, necessary, or useful task-related meaning).

11. In all situations except those of very low workload avoid the temptation to overuse color. The more colors used in any one display set the less effective each will be.

    a) A colored warning light will lose its attention-getting power in a panel full of multicolored lights.

    b) The most effective color display is one in which color is used sparingly, only when needed, and where it uniquely conveys information that other codes cannot or do not provide.

c) Remember that each color added to the display not only adds to the potential difficulty of display use, but also increases the demands on the hardware for precise color production.

12. Consider the possibility of display failure. Is the backup display a color display? If not, all critical information should be fully redundant with an achromatic code such as alphanumerics or symbol shape.

13. After reviewing the above points, consider the information to be presented on the display.

    a) What other codes are being used in addition to color?

    b) Is the display cluttered?

    c) How can color serve to quickly convey information to the user?

    d) How can color uniquely provide information that other codes cannot convey?

    e) If color were not available, what are some of the major potential problems in display use?

    f) How can color solve any or all of these problems?

    g) What potential drawbacks can you see in using color in certain ways (e.g., increased symbol size)?

14. Consider the range of missions or tasks in which the display will be used.

15. Sketch out at least two alternative color formats.

16. Work through the various changes in format for the display as a function of changes in mission to see if contradictory or confusing uses of color arise. Be careful to consider related displays in this analysis. Consider also the possibility of display failure (Step 12).

17. If both preliminary formats appear equally good, determine the preference of potential users.

18. If there is no other basis for selecting between two or more equally "good" alternatives, choose the one with the fewest color uses as calculated over the entire range of missions in which the display will be operational.

These steps and the data and principles that support them are further explained in Section III. By considering the questions raised here the reader will form the basis for interpreting Section III contents with a particular application in mind.

SECTION III

PRINCIPLES AND GUIDELINES FOR THE EFFECTIVE USE OF COLOR AS A CODE

In this section principles and guidelines are provided for the use of color as a display code. For each topic area, relevant literature is cited, tables and graphs showing trends and relationships are provided, and where possible, key points are summarized in a box at the beginning or end of each subsection.

First the physical specifications for color symbols (size, contrast, luminance, resolution) are given and the effects of ambient illumination are shown. After this, guidelines for the use of color as a code are provided. Principles are stressed that are considered important in the effective use of color to convey information.

PHYSICAL SPECIFCATIONS FOR COLOR SYMBOLS

Symbol Size and Resolution Requirements

An important distinction must be kept in mind when specifying symbol sizes for color displays. The difference between seeing a symbol and perceiving its color leads to different requirements. That is, a symbol may be seen and even identified, but not be large enough for its color to be recognized. In the following paragraphs size requirements are given for color perception unless otherwise specified. Requirements will also vary with symbol luminance and contrast and will be affected by the range of expected variations in ambient illumination.

SUMMARY OF COLOR SYMBOL SIZE REQUIREMENTS FOR CRT DISPLAYS
• Alphanumerics: 21 minutes of arc minimum height
• As the number of colors increases from 2 to 6, minimum height increases up to about 45 minutes of arc
• Symbol stroke width: two minutes of arc minimum
• Line width for graphics: four minutes of arc minimum
• Symbol aspect ratio: 5:7 or 2:3 width/height

Symbol Size--As shown in Figure 1, minimum symbol size required for adequate color perception varies from about 21 to 45 minutes of arc, depending on the number of colors used.[1] If luminance contrast is low or the display is degraded by noise and/or poor resolution, symbol size should be increased beyond the minimum recommended levels.

---

[1] Haeusing, M., "Color Coding of Information on Electronic Displays," Proceedings of the Sixth Congress of the International Ergonomics Association, 1976, pp. 210-217.

The lower size limit is well documented.[1,2] The consequence of using smaller symbols may be either:

1. The symbol appears to be achromatic (white or grey), or
2. Two symbols of similar color may be confused (e.g., yellow and orange).

The latter point is the major reason for increasing symbol size as the number of different colors is increased.

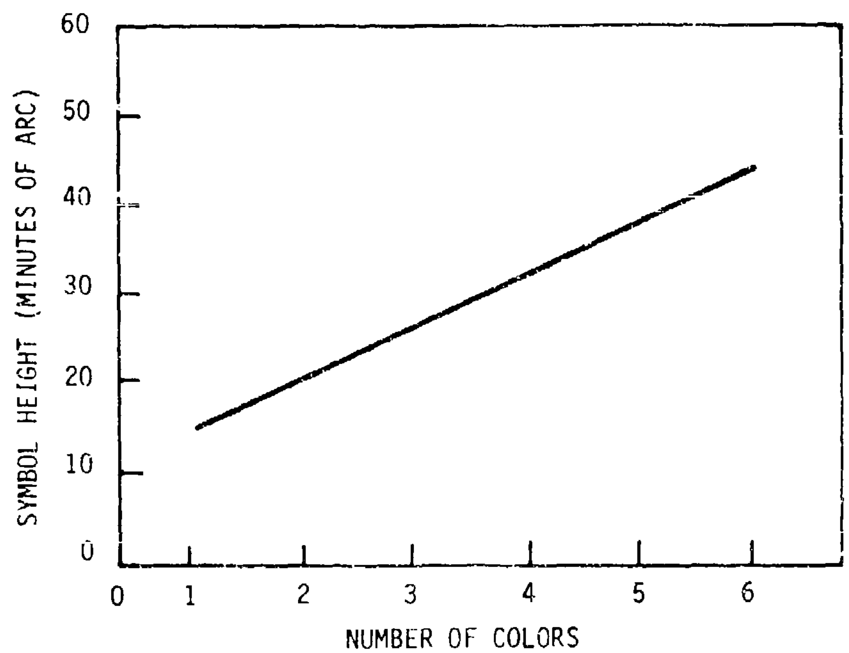

Figure 1. Recommended Symbol Size as a Function of Number of Colors Used on the Display (Below 21 minutes of arc, color perception may be adversely affected.)

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[2] Bishop, H.P. and M.N. Crook, "Absolute Identification of Color for Targets Presented Against White and Colored Backgrounds," Report No. WADD TR 60-611, Wright-Patterson AFB, OH, March 1961.

Size vs. Symbol Luminance vs. Information Type--The particular information being displayed and the symbol luminance will also influence the recommended size of colored symbols. In Table 1,[3] size recommendations are provided for three classes of information at two levels of symbol luminance. Size ranges are expressed as the ratio of symbol size to viewing distance. For a given viewing distance, symbol height can be determined by multiplying this distance by the appropriate table value. Note that as signal luminance is decreased symbol size must be increased. The type and "criticality" of the information also influences symbol size. The data in this table are calculated from achromatic data and have been adjusted to reflect the increased size requirements for color symbols.

TABLE 1. RECOMMENDED MINIMUM ALPHANUMERIC CHARACTER HEIGHT FOR COLORED SYMBOLS ON HIGH AND LOW LUMINANCE DISPLAYS

Type of Information Displayed	High Display Luminance (to 3.4 cd/m^2)	Low Display Luminance (to 0.1 cd/m^2)
Critical Data, Variable Position	0.007 to 0.011	0.011 to 0.017
Critical Data, Fixed Position	0.005 to 0.011	0.008 to 0.017
Noncritical Data	0.003 to 0.011	0.003 to 0.011

(Character height is expressed as a fraction of viewing distance.)

[3] Smith, S. L., "Visual Displays--Large and Small," MITRE Corporation, for USAF Electronic Systems Division, ESD-TDR-62-339, AD 293-826, 1962.

Acuity as a Function of Color--The ability of the observer to discriminate fine detail varies as a function of both symbol color and background color. In Figure 2,[4] reading accuracy is compared for four red and blue target-background combinations. The percentage of correct responses for the various-size openings in a Landolt ring (i.e., target detail) is plotted. The relative performance superiority obtained with red targets is clearly seen in this figure. The observer is more sensitive to fine detail at the red versus the blue end of the spectrum.

RESOLUTION REQUIREMENTS FOR MATRIX DISPLAYS
• Use larger dot format rather than smaller brighter dots[5]
• A 5 x 7 dot matrix will provide marginal performance; larger matrix sizes should be used where possible
RASTER SCAN DISPLAYS
• Fifteen scan lines per symbol height (minimum)

---

[4] Myers, W.S., "Accommodation Effects in Multicolor Displays," Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, OH, AFFDL-TR-67-161, AD 826-134, December 1967.

[5] Ellis, B., G.J. Burrell, J.H. Wharf, and T.D.F. Harokins, "The Format and Color of Small Matrix Displays for Use in High Ambient Illumination," Royal Aircraft Establishment Technical Report 75048, March 1975.

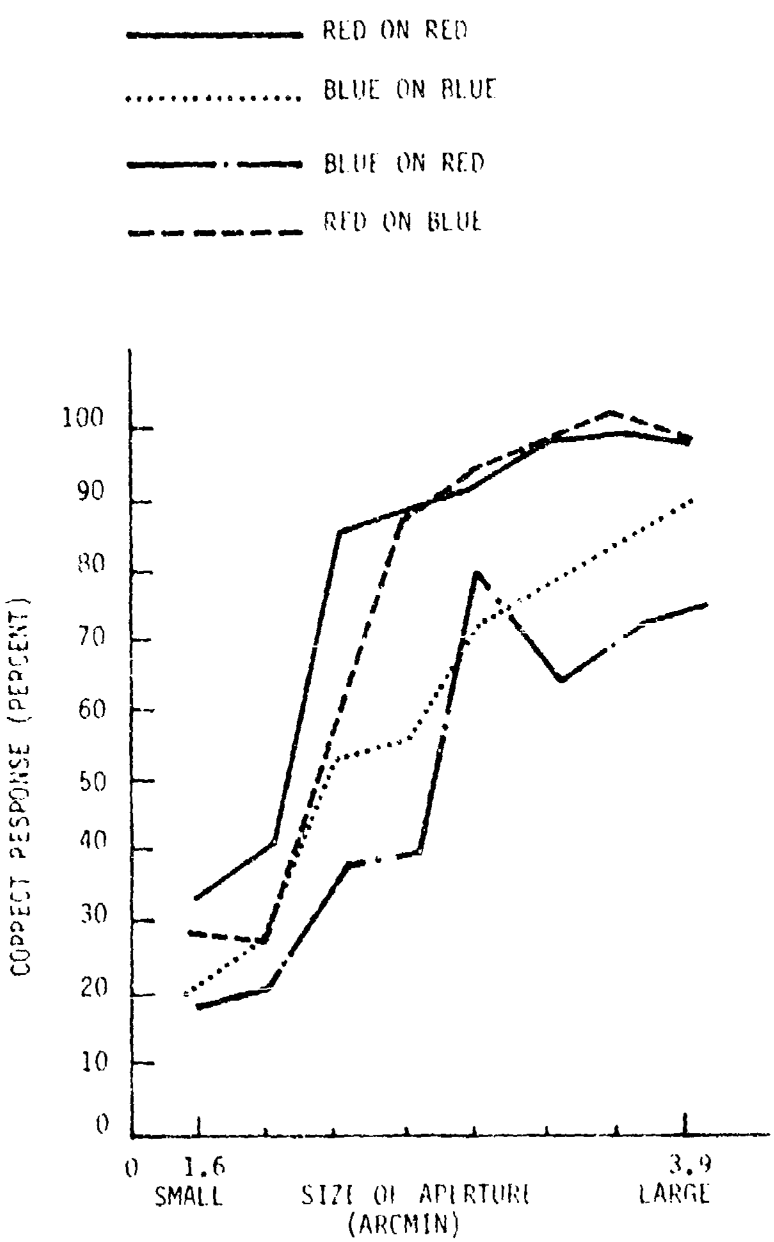

Figure 2. Acuity as a Function of Target and Background Color (The target consisted of an opening in a Landolt ring. Aperture sizes varied from 1.6 to 3.9 minutes of arc.)

Resolution Requirements for Color Symbols--The display requirements for producing color symbols are closely related to color acuity. If the display is a raster scan CRT the resolution is typically defined in lines per symbol height. If it is a matrix or LED display the requirements are defined in terms of number of dots or strokes per character.

For raster displays resolution is expressed as the minimum number of lines per symbol height. A well-established standard for black and white TV systems is ten lines per symbol height for 100 percent accuracy in character recognition.[6,7] Since recommended symbol size for colored symbols is about 50 percent greater than that for black and white symbols, a reasonable standard would be 15 lines per symbol height as a minimum.

Color Display Luminance and Contrast Requirements

The specification of required color symbol luminance depends on a number of factors. The most important of these are background luminance, ambient illumination, and symbol size. At very low symbol luminances or under very high ambient lighting conditions, the color of the symbol is also important. To specify luminances for a particular application, the entire range of ambient lighting conditions in which the display will be used must be specified.

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[6] Ericksen, C.W., "Multidimensional Stimulus Differences and Accuracy of Discrimination," Wright Air Development Center, Wright-Patterson Air Force Base, OH, WADC TR54-165, 1954.

[7] Shurtleff, D.A., "Design Problems in Visual Displays, Part II: Factors in the Legibility of Televised Displays," The MITRE Corporation, Report No. ESD-TR-66-299, AD 640-571, September 1966.

SUMMARY OF LUMINANCE
AND CONTRAST REQUIREMENTS

Symbol luminance:

- Minimum for good color perception: about 3 cd/m^2
- Optimum under moderate lighting conditions: range from 30 to 300 cd/m^2

Background luminance:

- Visibility of color symbols better on dark background

Contrast:

- For CRT displays, symbol-to-background luminance ratios of about 10:1 optimum

Ambient illumination:

- The higher the ambient illumination, the higher the symbol luminance must be to achieve adequate contrast

Contrast--Available data demonstrate that slightly better visibility is achieved on color displays if the symbols are displayed on a dark background. The reverse is true for black and white displays. This relationship is shown in Figure 3[8] for performance on a dial reading task. In Figure 4[8] a performance comparison between color and black and white symbols with equal luminance contrast is shown. In this figure the relative superiority of color symbols (i.e., faster reading time) is attributed to the additional benefits of color contrast. This advantage is only demonstrated for medium luminance contrast values. Analysis of these data indicated that beyond 15 percent contrast, color symbols were not significantly affected. Achromatic symbols were affected at both the lowest and highest values.

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[8] McLean, M.V., "Brightness Contrast, Color Contrast, and Legibility," Human Factors, 7, December 1965, pp. 521-526.

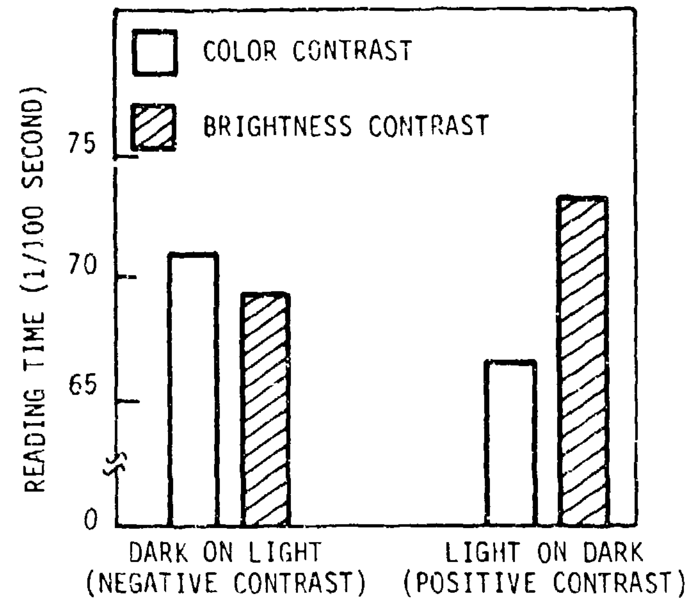

Figure 3. Effects of Interaction Between Color and Brightness Contrast with Direction of Contrast on Reading Time

PERCENT CONTRAST IS COMPUTED AS FOLLOWS:

$$\frac{L_B - L_T}{L_B} \times 100$$

WHERE

L_B = BACKGROUND LUMINANCE

L_T = TARGET LUMINANCE

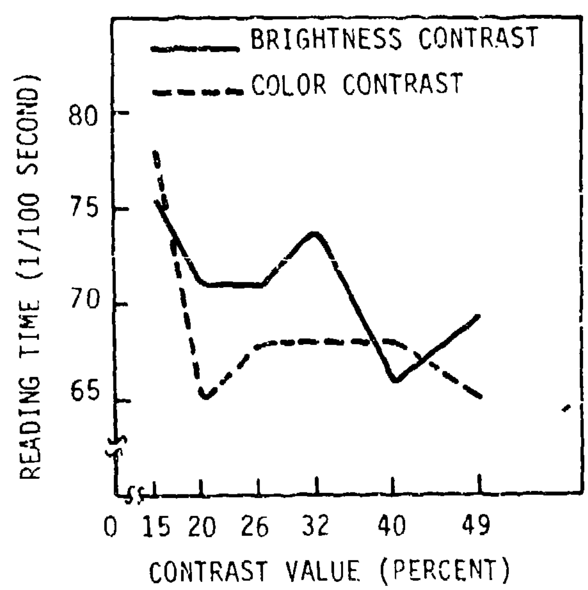

Figure 4. Effects of Target-to-Background Contrast Value on Reading Time

Haeusing[1] recommends luminance ratios (L_1/L_2) of about 10:1 for multicolor CRT displays. Heglin[9] recommends minimum luminance ratios of 5:1 or 8:1. The most relevant ratio would depend on other factors such as symbol size and number of colors used. If one factor is by necessity at a minimum value, values on the other factors should be adjusted to compensate. For example if luminance ratios of 5:1 are likely, then symbol size should be increased well beyond 21 minutes of arc, and/or the number of colors used should be reduced.

Ambient Illumination--For many real-world display 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 the ambient lighting is variable and/or becomes very bright at times (such as is found with cockpit displays in bright sunlight), problems arise. The effect of adding environmental light to a display surface is to decrease the symbol-to-background contrast. Colors begin to desaturate or fade, and under very high ambient lighting they may be completely washed out. Conversely, if outside lighting is very low it may be desirable to keep symbol luminance at a minimum to maintain the operator's adaptation to the dark. If the symbols are colored, reduction of their luminance below about 3 cd/m^2 will seriously interfere with the perception of their color. If either of these situations is likely to occur across the range of expected display uses, color should probably be used as a fully redundant code.

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[9] Heglin, J., NAVSHIPS Display Illumination Design Guide, Section II: Human Factors. Naval Electronics Laboratory Center: San Diego, CA, 1973.

Low Ambient Illumination--Perception of surface colors on maps, charts, etc. requires luminance values of at least 3 cd/m^2. Below this minimum level it becomes difficult to differentiate colors. Comfortable reading and good color perception require from 30 to 300 cd/m^2. At very high luminances (beyond about 3000 cd/m^2), surface colors become increasingly hard to see due to poor luminance contrast.

If the ambient lighting itself is colored, (such as the red night lighting in some aircraft), surface colors become more difficult to discriminate. They may markedly change in appearance. Table 2[10] describes some of these changes.

Both the intensity and the color of the environmental lighting should be considered when choosing specific colors. Particularly for surface colors, the colored ambient lighting may cause color confusion.

When the display is to be used in light-restricted or night time conditions and the background is dark (below about 1 cd/m^2), required symbol luminance is lowest.

In Figure 5,[11] observer response time data are given as a function of signal luminance and wavelength. Below about 0.1 cd/m^2 the symbols are not

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[10] Semple, C.A. Jr., R.J. Heapy, E.J. Conway, Jr., and K.T. Burnette, "Analysis of Human Factors Data for Electronic Flight Display Systems." Technical Report No. AFFDL-TR-70-174, April 1971, 570 pp.

[11] Pollack, J.D., "Reaction Time to Different Wavelengths at Various Luminances," Perception and Psychophysics, 3, 1968, pp. 17-24.

TABLE 2. EFFECT OF SOME VARIETIES OF COLORED LIGHT ON SOME COLORED OBJECTS

OBJECT COLOR	RED LIGHT	BLUE LIGHT	GREEN LIGHT	YELLOW LIGHT
White	Light pink	Very light blue	Very light green	Very light yellow
Black	Reddish black	Blue black	Greenish black	Orange black
Red	Brilliant red	Dark bluish red	Yellowish red	Bright red
Light blue	Reddish blue	Bright blue	Greenish blue	Light reddish blue
Dark blue	Dark reddish purple	Brilliant blue	Dark greenish blue	Light reddish purple
Green	Olive green	Green blue	Brilliant green	Yellow green
Yellow	Red orange	Light reddish brown	Light greenish yellow	Brilliant light orange
Brown	Brown red	Bluish brown	Dark olive brown	Brownish orange

seen as achromatic rather than colored signals. In these conditions, shorter wavelength signals in the blue to green region produce much faster response times than do the longest wavelengths toward the red end of the spectrum.

High Ambient Illumination--In general, the effect of ambient illumination striking the display surface is to reduce the symbol-to-background contrast. Under very high levels of ambient illumination, response time to signals at both the red and blue end of the spectrum are faster than those in the yellow to yellow-orange region. In Figure 6,[12] response time as a function of

[12] Tyte, R., J. Wharf, and B. Ellis, "Visual Response Times in High Ambient Illumination," Society of Information Displays Digest, 1975, pp. 98-99.

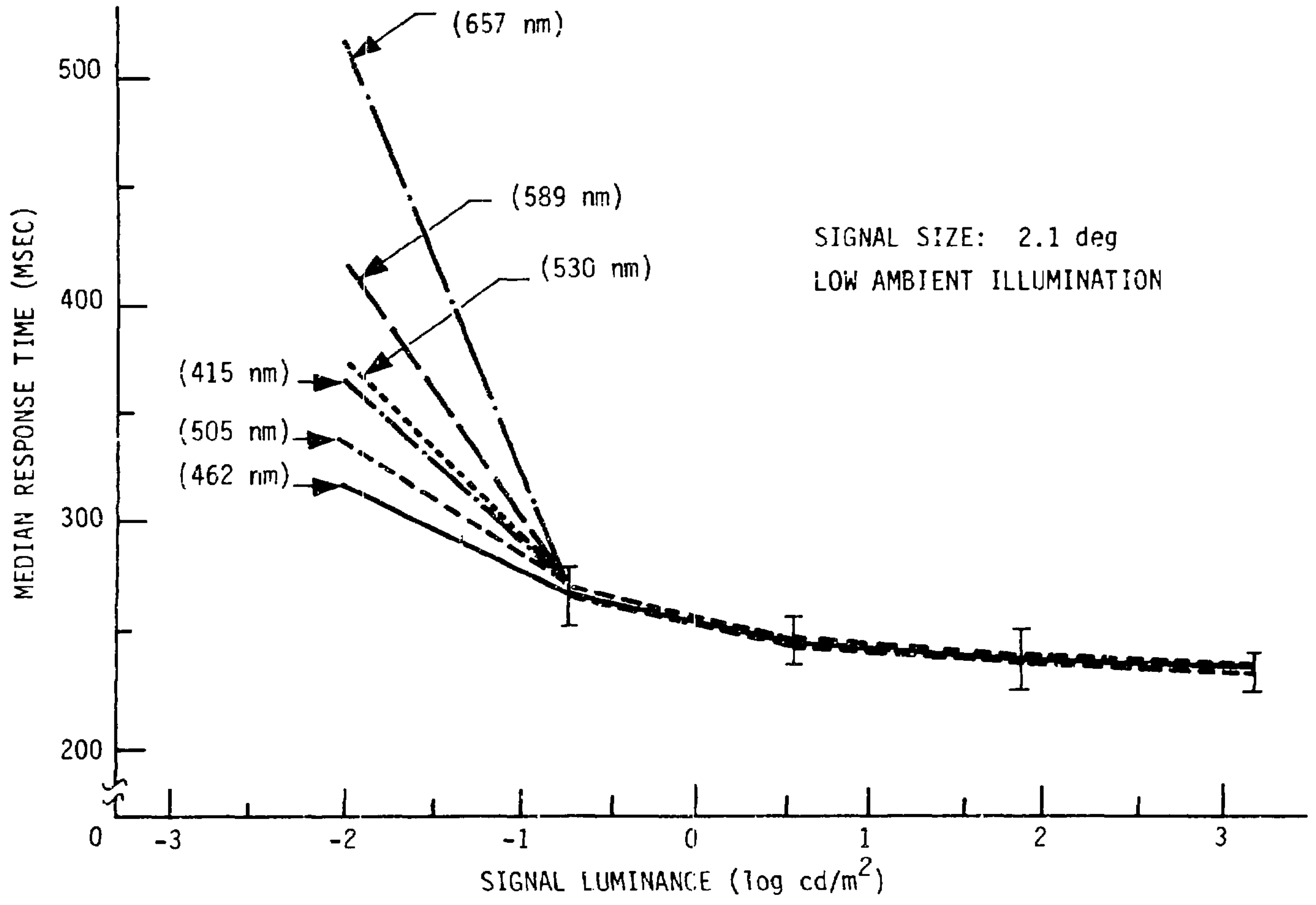
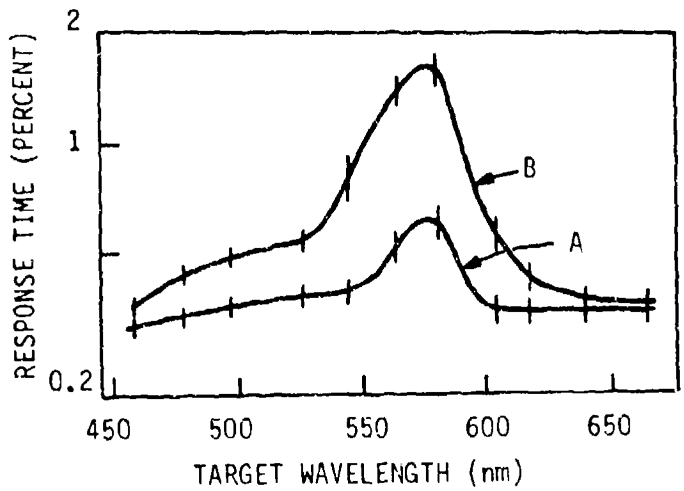


Figure 5. Median Response Time in Milliseconds as a Function of Signal Wavelength for Five Levels of Symbol Luminance (Brackets indicate 0.01 confidence interval.)



LUMINANCES: A = 48 cd/m^2, B = 30 cd/m^2
AMBIENT ILLUMINATION: 10^5 $lumens/m^2$

Figure 6. Response Time as a Function of Wavelength

signal wavelength is shown at two signal luminances under an ambient illumination of 10^5 $lumens/m^2$. The lower signal luminance produced a much greater effect (increased response time) in the yellow region. At 10^5 $lumens/m^2$ red symbols are more visible than green symbols. To be equally visible in high ambient light, green signals should be about three times the luminance of the red.[5]

In Figure 7[12], response time as a function of signal luminance is plotted for red, green, and yellow signals. In this figure the marked superiority of red under high ambient conditions is demonstrated.

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[12]Tyte, R., J. Wharf, and B. F'lis, "Visual Response Times in High Ambient Illumination," Society of Information Displays Digest, 1975, pp. 98-99.

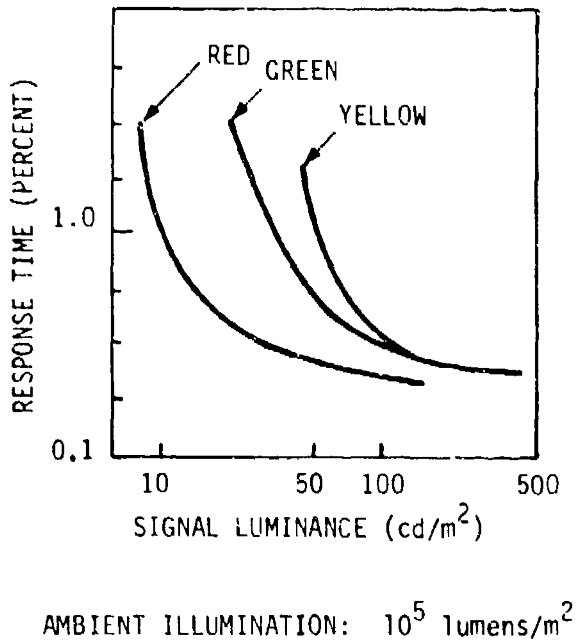

Figure 7. Response Time as a Function of Signal Luminance

Display Location and Peripheral Vision

The eye is most sensitive to color within only a small part of the total field of view. Beyond this area the eye is differentially sensitive to individual colors, both in terms of limits of field of view and in operator response time to different colors. (See Table 3 for a distinction between foveal and peripheral displays.)

Peripheral Sensitivity to Color--Of the various colors the field of view is widest for yellow and narrowest for red and green (see Figures 12 and 13). Within the total field of view, response time to different colored signals also varies. Reaction times (RT) obtained for red, green, blue, yellow,

TABLE 3. CRITERIA FOR DETERMINING IF A DISPLAY IS FOVEAL OR PERIPHERAL

Display *can* be *considered* FOVEAL if:	Display must be *considered* PERIPHERAL if:
1) It is the only display the operator must use and 2) It is *either* very small--three or *four degrees* of visual angle or 3) It is *actively* and *frequently* scanned by *operator* or 4) It is one of several displays actively and frequently scanned by operator or 5) It is *located* in the operator's normal line of *sight*	1) It is one of many displays and 2) It is outside of normal scan pattern or 3) It is larger than *three* or *four degrees* of visual *angle* and *portions of it* are *seldom* scanned

and white were mapped over the visual field in one study.[13] These RTs fell into bands. When plotted as in Figures 8 through 12, these bands of similar response time ("iso-RT" zones) show some distinct color differences. In these figures, zones are plotted and the related RT within each zone is indicated. These data are summarized in Figure 13, which indicates that white has both the widest field of view and the shortest response times over the entire field, while red has both the narrowest field and the longest response times.

Blue, green, and yellow are roughly similar to each other and fall between the red and white plots. In Figure 14, the iso-RT plot for red is superimposed over a cockpit instrument panel. From these results it can be concluded that a signal light should be placed as close as possible to the direct line of sight. White is the best choice for a signal light and red is the poorest, as indicated by reaction times. The further into the periphery the light is moved, the greater the discrepancy.

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[13] Haines, R.M., L.M. Dawson, T. Galvan, and L.M. Reid, "Response Time to Colored Stimuli in the Full Visual Field," Report No. NASA TN D-7927, NASA Ames Research Center, Moffett Field, CA, March, 1975, pp. 27.

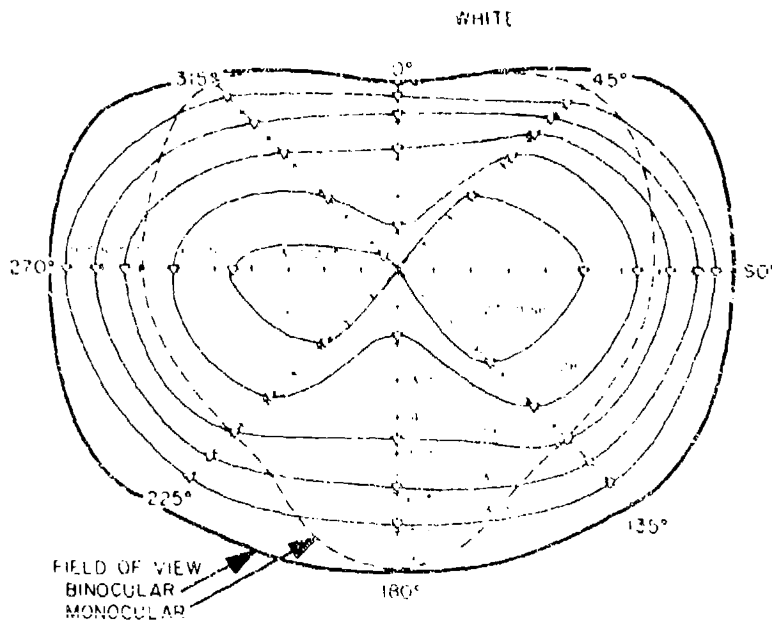


Figure 8. Retinal Iso-RT Zones for White

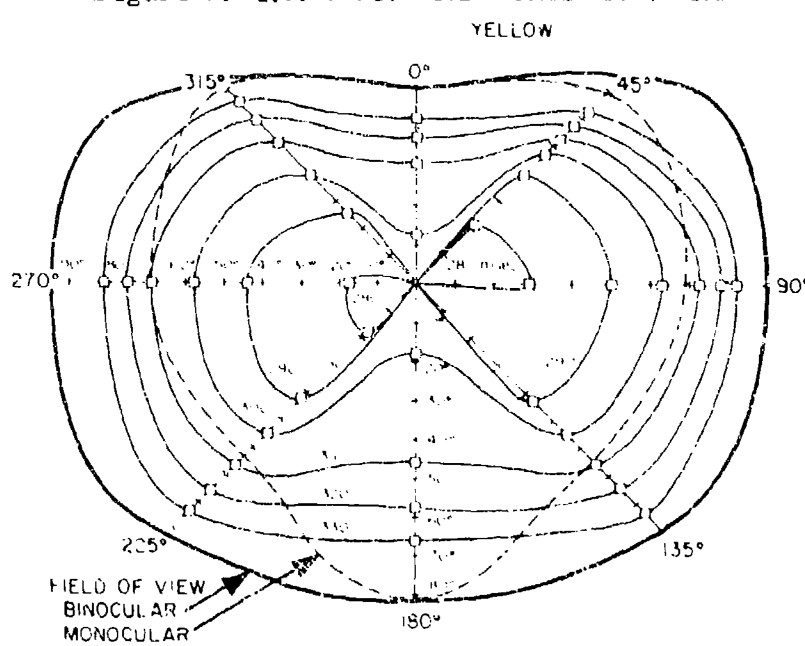


Figure 9. Retinal Iso-RT Zones for Yellow

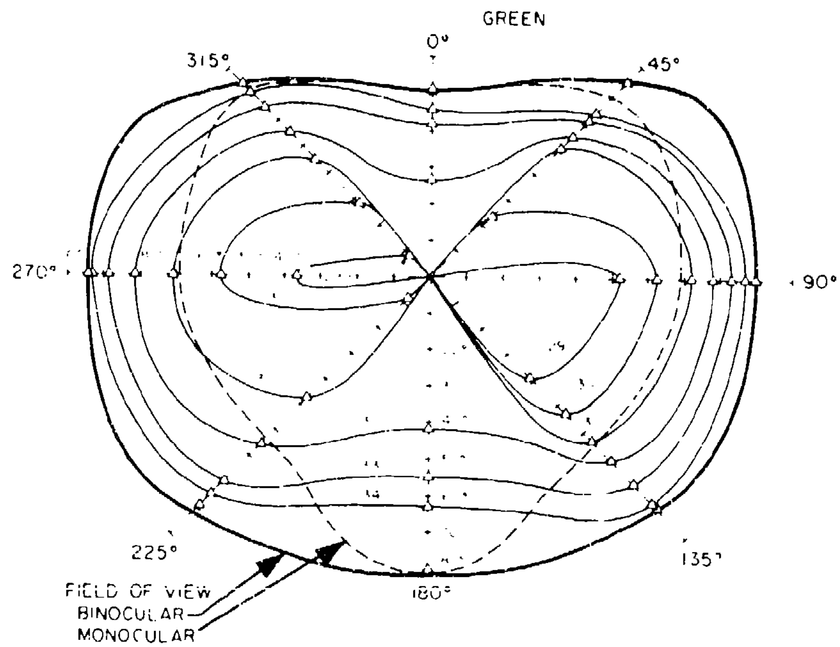


Figure 10. Retinal Iso-RT Zones for Green

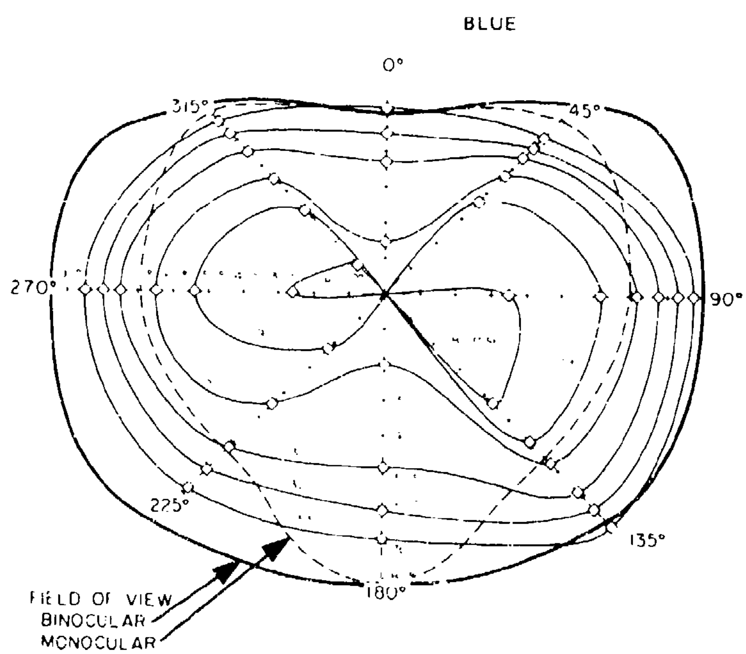


Figure 11. Retinal Iso-RT Zones for Blue

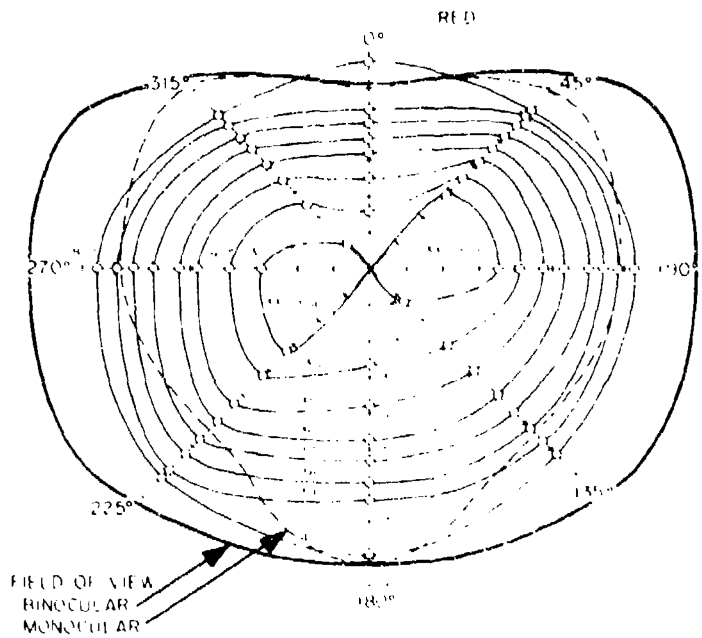


Figure 12. Retinal Iso-RT Zones for Red

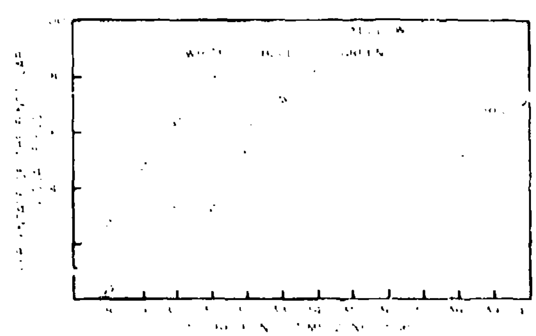


Figure 13. Percentage of the Binocular Visual Field Represented by the Iso-RT Zones Presented in Figures 8-12 for Each Color

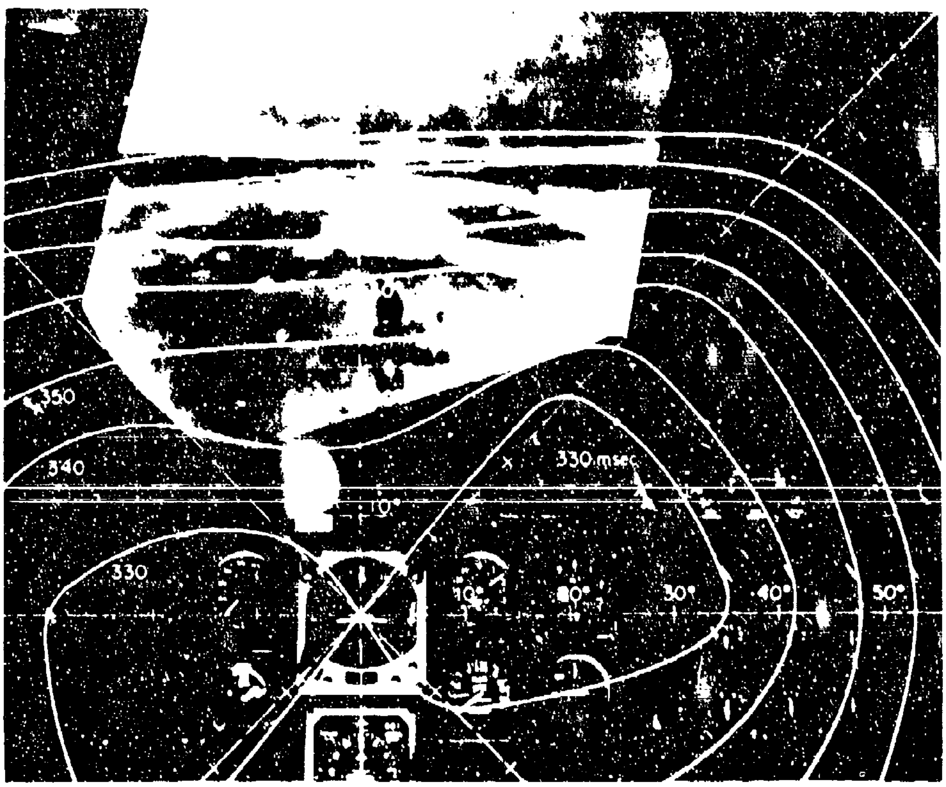


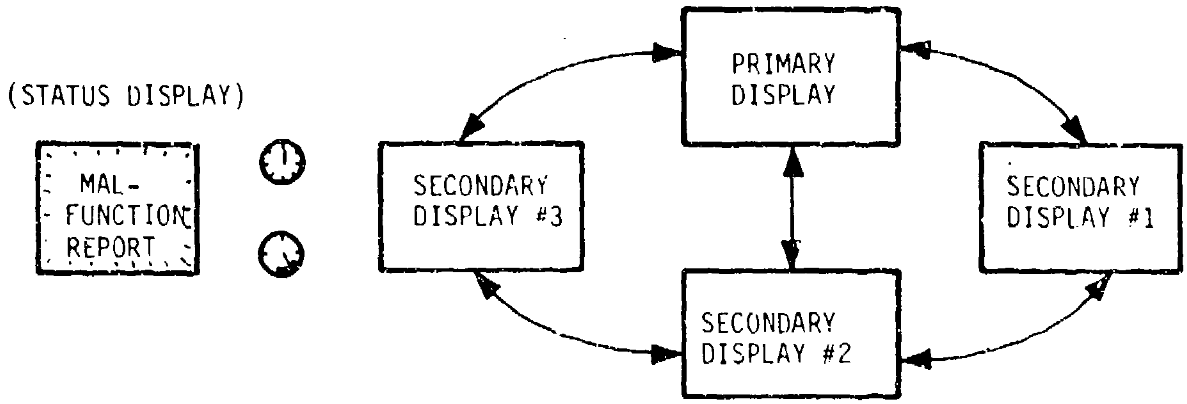
Figure 14. Superposition of Iso RT Zones for Red upon Simulator Cockpit Instrument Panel and Runway Scene

Peripheral Displays--If many displays are being used by the operator, some must by necessity be located peripheral to the line of sight. If these displays are routinely scanned the problem may not be significant. However, for those outside the normal scan pattern, special precautions should be taken. For example, a given display may be located outside the normal scan pattern. It may contain system status information, which is usually in tolerance. The information on the display only becomes critical when a tolerance limit is exceeded. If the display were centrally located, red could be used to alert the operator. However, red is poor when used as a peripheral cue. What should be done? Several color coding possibilities exist. The most straightforward one would be to use a central master warning light as shown in Figure 15. Another solution would be to display the warning light or abbreviated message directly on the primary display.

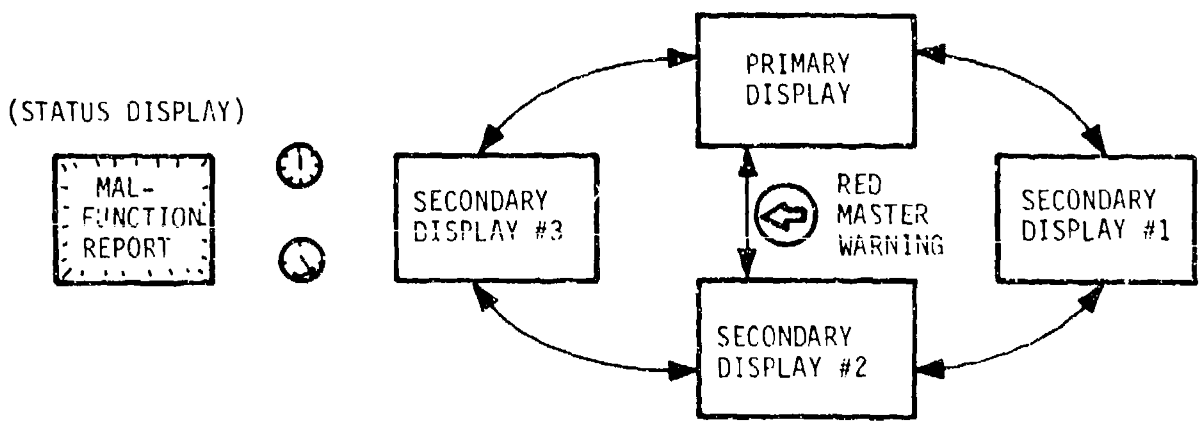
Selecting Specific Colors

Where color is to be used as part of a display code the designer must determine 1) how many different colors will be used, and 2) what these colors will be.

How Many Colors Should Be Used?--The decision to use a given number of colors must be made after considering the limitations of the display medium, the ambient lighting, and perceptual limitations of the observer or display operator. All of these factors are important in arriving at a proper decision.



a) Arrows indicate normal scan of operator among major displays. Status display is outside of this pattern. Message printed in red would not help in initially alerting operator.



b) Addition of master warning light in center of scan area provides effective alerting signal. Directional arrow would further reduce operator response time. Warning light could be colored red.

Figure 15. Illustration of Peripheral Color Display Problem and a Proposed Solution

FACTORS INFLUENCING NUMBER OF COLORS
• Surface colors vs. self-luminous displays • Ambient illumination • Operator workload • Color code relation to operator task
GENERAL RECOMMENDATION FOR COCKPIT CRT DISPLAYS
• No more than four colors on any one display

Display Medium--Self-luminous displays such as CRTs may or may not have a limit on the number of different colors possible. The important point to remember is that the greater the number of colors used, the greater the demands on the system for precise reproduction of each color. The more similar two colors are, the more critical it is that each be precisely defined and reproduced on the display. The probability of operator error will increase if color control is not fairly rigid, due to confusion as to which color is being displayed. In Table 4,[14] an example of some common color confusions is presented. Note that these confusions occur only for adjacent colors in the table.

---

[14] Connolly, D.W., G. Spanier and F. Champion, "Color Display Evaluation for Air Traffic Control," Report No. FAA-RD-75-39, Federal Aviation Administration, Washington, D.C., May 1975, 41 pp.

TABLE 4. ERRORS OF COLOR IDENTIFICATION

Shown	Called					
	Red	Orange	Yellow	Green	Total	Percent
Red	X	21	0	0	21	2.9
Orange	9	X	10	0	19	2.6
Yellow	0	6	X	15	21	2.9
Green	0	0	6	X	6	0.8
				Grand Total =	67	2.3

Human Perceptual Limits--With very extensive practice and under ideal conditions, human observers can individually identify up to 50 colors.[15] This number, however, far exceeds any reasonable number for operational conditions outside of the laboratory. With less practice but still under laboratory conditions, it has been found that as the number of colors increased the number of identification errors also increased:

Number of Colors	Percent of Incorrect (Error) Responses
10	2.5
12	4.5
15	5.2
17	28.6

[15] Hanes, R.M. and M.V. Rhoades, "Color Identification as a Function of Extended Practice," Journal of the Optical Society of America, 49, 1959, pp. 1060-1064.

If the operator task requires absolute identification of a color, ten colors appears to be maximum for good accuracy. If absolute identification is not required more colors can be used. Up to 23 colors can be profitably used in coding of surface color maps where color served as an aid to search, according to the results of one study.[16]

Number of Colors vs. Performance--As the number of colors is increased in a situation where symbol color is assigned a particular meaning, both error rate and detection time increase. The general relationship between code size (e.g., number of colors) and response time is shown in Figure 16.[17] The greatest effect occurs early in training and diminishes with extended practice. This figure clearly shows, however, that the greater the number of colors used the more time required to respond to any individual color when it appears.

Similar relationships have been reported by Hitt,[18] who averaged the number of responses per minute over a variety of tasks involving multiple targets. This is shown in Figure 17. Stated more positively, when fewer colors are used the response time will be faster for each one when it appears.

---

[16] Shontz, W.D., G.A. Trumm, and L.G. Williams, "Color Coding for Information Location," Human Factors, 13, 1971, pp. 237-246.

[17] Teichner, W.T. and Krebs, M.J., "Laws of Visual Choice Reaction Time," Psychological Review, 81, 1, 1974, pp. 75-98.

[18] Hitt, W.D., "An Evaluation of Five Different Abstract Coding Methods," Human Factors, 3, 1961, pp. 120-130.

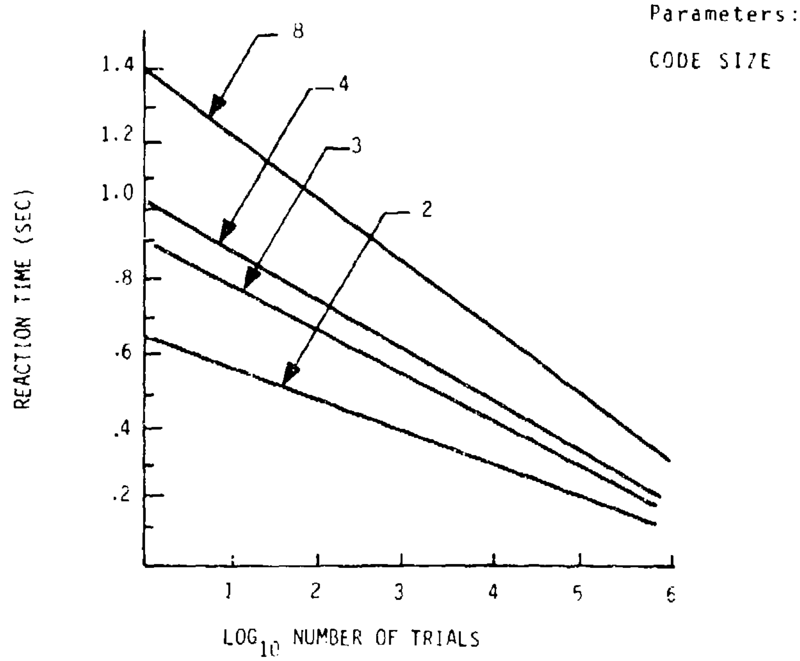


Figure 16. Reaction Time as a Function of Practice for Four Code Sizes with Equiprobable Alternatives

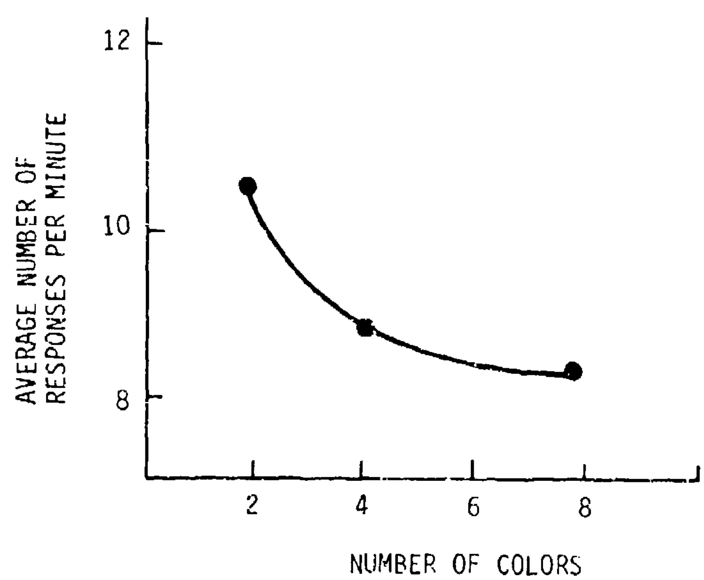


Figure 17. Effect of Number of Code Levels on Operator Performance

The importance of increased response time (or increased errors) must be related to the operator's task. If the workload is expected to be high or fast reaction time critical, then the number of colors used should be kept as low as possible.

<u>General Recommendations</u>--Although no specific data appear to exist from real-world displays, several investigators[1,10] have recommended that a three-to-four-color limit be used for operational displays. The smaller code size for operational situations is based on the expectation that ambient lighting may at times be high, that display reliability may be limited, and that fast reaction time of the operator may often be critical.

<u>Which Colors Should Be Used?</u>--The best general criterion to use in selecting a set of colors of specified size is to pick colors as widely spaced in wavelength as possible along the visible spectrum. Under good viewing conditions the ten colors indicated in Table 5[19] provide a highly identifiable set.

CRITERIA FOR SELECTING SPECIFIC COLOR SET

- Maximum wavelength separation
- High color contrast
- High visibility in specific application
- Compatibility of use with conventional meanings
- Legibility and ease of reading
- High saturation

[19] Baker, C.A. and W.F. Grether, "Visual Presentation of Information," Wright Air Development Center, WADC-TR-54160, AD 43-064, 1954.

TABLE 5. TEN COLORS THAT CAN BE IDENTIFIED CORRECTLY NEARLY 100 PERCENT OF THE TIME UNDER GOOD VIEWING CONDITIONS

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

However, as indicated in the preceding subsection, the limitations of hardware, the effects of ambient illumination, and operator workload may limit this number somewhat.

Table 6 presents a six-color code recommended by Cook.[20] This table also provides several notations helpful in identifying each color.

[20] Cook, T.C., "Color Coding--A Review of the Literature," U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, HEL Tech Note 9-74, November 1974.

TABLE 6. RECOMMENDED COLORS FOR A SIX-COLOR CODE

Color Name	Munsell Notation	Chromaticity Coordinates	Dominant Wavelength (nonometers)	Federal Spec 595 Equivalent (paint chips)
Purple	1.0 RP 4/10	X - .2884 Y - .2213	430	27144
Blue	2.5 PB 4/10	X - .1922 Y - .1673	476	15123
Green	5.0 G 5/8	X - .0389 Y - .8120	515	14260
Yellow	5.0 Y 8/12	X - .5070 Y - .4613	582	13538
Orange	2.5 YR 6/14	X - .6018 Y - .3860	610	12246
Red	5.0 R 4/14	X - .6414 Y - .3151	642	11105

Relative Visibility of Individual Colors--All colors are not equally visible. Even if a specific color can be accurately named when simply presented as a test patch under good viewing conditions, in other conditions or other tasks it may create problems. The best documented example of this is the color blue. The fovea of the human eye, which is sensitive to detail, is essentially blue-blind.[21] As a consequence, small symbols or fine detail are not seen as well in blue. Because of this, blue is not recommended as a color to be used for alphanumerics, lines, etc. unless they are unusually large. Better yet, blue should be reserved for coding large zones or areas on the display.

Relative legibility of six colors (including white) as a function of symbol size is shown in Figure 18. The data[22] show the speed at which alphanumerics can be read as a function of symbol color and size. Under the conditions of this test red, white, and yellow symbols were read at a much higher rate than green or blue symbols. Similar data[23] are shown in Figure 19.

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[21] Wald, G., "Blue Blindness in the Normal Fovea," Journal of the Optical Society of America, 57, 1967, pp. 1289-1303.

[22] Meister, D. and D.J. Sullivan, "Guide to Human Engineering Design for Visual Displays," Office of Naval Research Contract No: N00014-68-C-0278, Office of Naval Research, Engineering Psychology Branch, Washington, DC, AD 693-237, 1969.

[23] Rizy, E.F., "Dichroic Filter Specification for Color Additive Displays. II. Further Exploration of Tolerance Areas and the Influence of Other Display Variables," USAF Rome Air Development Center, RADC-TR-67-513, AD 659-346 September 1967.

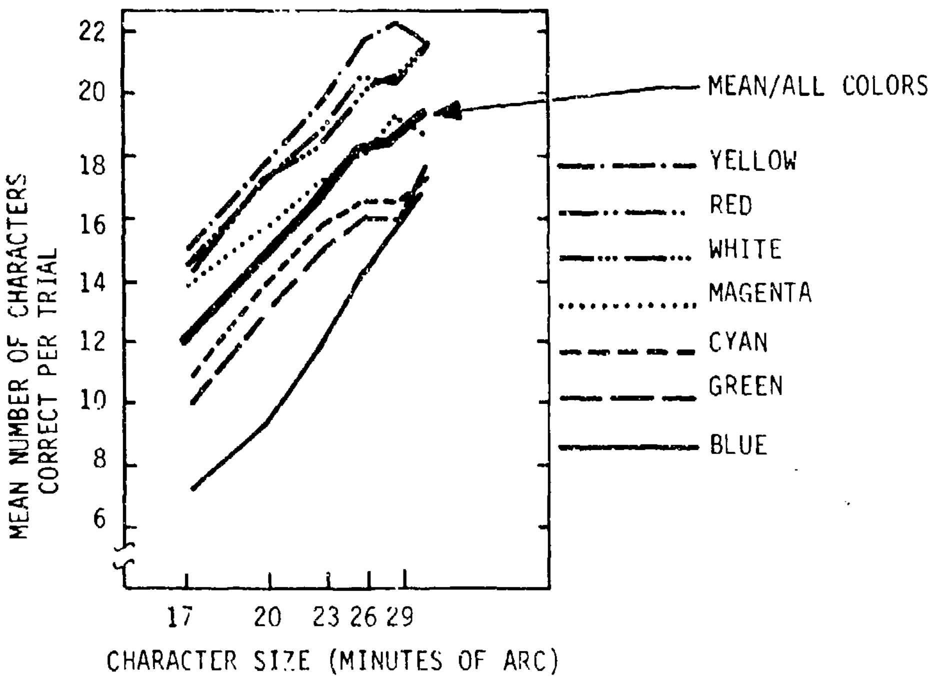

Figure 18. Performance In Reading Color-Coded Alphanumerics as a Function of Size and Color

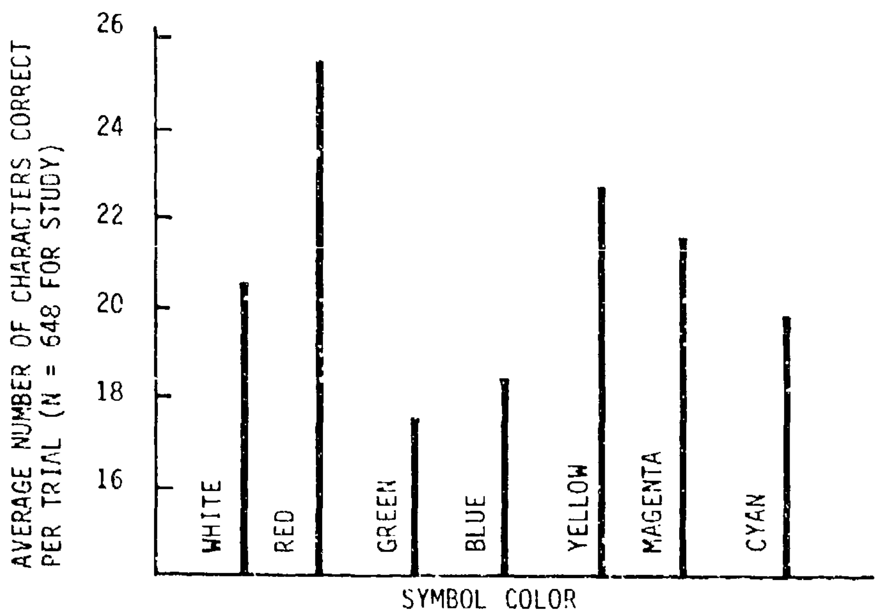

Figure 19. Reading Accuracy as a Function of Symbol Color

Visibility of Colored Signal Lights--Amber, violet, and red are spotted more quickly and named with fewest errors in both laboratory and air-to-ground flight tests of eight different signal lights.[24] Incandescent lights were the worst signals by all measures. It was also found that flashing ground lights were seen no more quickly than steady lights if the intensity of the two were the same. The attention-getting power of a flashing strobe-type light may be due to the relatively greater intensity of each flash.

Conventional R, G, Y Color Code--The three colors, red, green, and yellow, and their associated meanings of warning, safe or advisory, and caution, respectively, are widely known and accepted color conventions. Color display design should adhere to these conventions where appropriate. If the type of information being presented on the display can be readily assigned to these categories, the resulting display format will be easily learned by the operator. Military Standard 411-D[25] lists the use of the colors indicated above.

In Figure 20, chromaticity specifications for red, green, and yellow are given, as well as for several other colors.[26] (See Appendix A for an explanation of the chromaticity diagram.)

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[24] Hilgendorf, R. L., "Colors for Markers and Signals: Inflight Validation," AMRL TR-71-77, Wright-Patterson Air Force Base, OH, AD 737901, 1971.

[25] Military Standard, MIL-STD-411D, 30 June 1979 with Notice-1, Aircrew Station Signals, 30 August 1974, Washington, DC: Department of Defense.

[26] Military Specification, MIL-C-25050A (ASG), 2 December 1963, with Amendment-1, 30 September 1971. Colors, Aeronautical Lights and Lighting Equipment, General Requirements For, Washington DC: U.S. Government Printing Office.

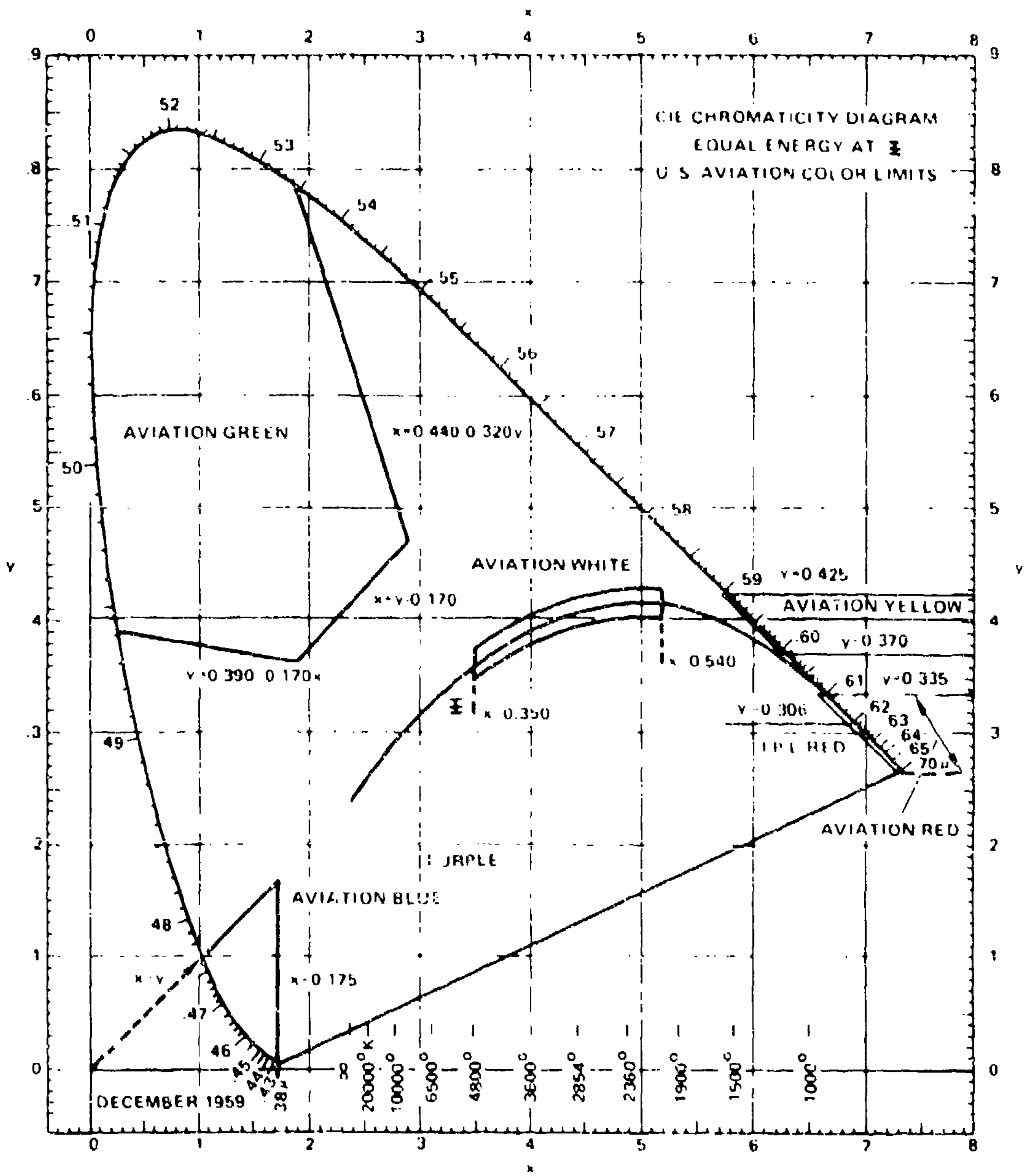

Figure 20. Aviation Colors from MIL-C-25050A

SPECIFIC COLOR RECOMMENDATIONS FOR CRT DISPLAYS

- Use no more than four colors
- Use red, green, and yellow to code alphanumerics
- Use blue for large symbols or where symbol identification is not a problem
- Use conventional color code when appropriate
- Use white for peripheral signals

Use of Saturation Difference in Color Coding--The preceding discussion of which colors to use on a display has been concerned entirely with differences in hue. The general recommendation would be to use highly saturated colors (hues) to maximize the differences between colors. In some situations it may not be possible or desirable to use highly saturated colors alone. One major reason for adding saturation as another color dimension would be to increase the number of color steps achievable with a particular display medium. For example, if the designer had only a two-color display, it might be possible to use saturation differences to produce more than two discriminable steps in the color code. A red-green display could then become a four-color display by producing a high and low saturation version of each color. Thus, red would become red and pink, and green would become light and dark green.

Saturation differences are used to produce the many color variations on maps and other printed (surface) color materials. Hue-saturation combinations can provide a large number of discriminable different values for the color code.

Caution should be taken to ensure that the changes in saturation do not produce colors that are difficult to see under some viewing conditions. High ambient illumination on the surface of the display will, itself, tend to desaturate or wash out the color of a symbol. If the symbol is already desaturated its visibility may be seriously degraded.

If ambient lighting can be controlled in those situations where the display is to be used, saturation level may provide a good method of increasing the color code size. If lighting will vary widely, use saturation level change only with caution. The visibility of desaturated colors under all levels of expected ambient lighting should be tested prior to use.

COLOR CODING PRINCIPLES

Benefits of Color vs. Other Codes

COLOR CODING WILL BE HELPFUL IF

- The display is unformatted
- Symbol density is high
- Operator must search for relevant information
- Symbol legibility is degraded
- Color code is logically related to operator's task

When used appropriately, color coding can provide significant performance improvements compared to other codes. It is clear from the available research literature that the relative effects of color coding are strongly determined by the specific function being served by the code. Results obtained from a number of code comparison studies[27] are shown in Table 7. This table shows that there are situations in which color is clearly superior to other codes. It also shows that in some situations color is significantly inferior as a code. One major factor that determines the relative merits of color coding is the task performed by the operator.

TABLE 7. RANGE OF PERCENT DIFFERENCE SCORES FOR SEVERAL USES OF COLOR CODING

Comparison Achromatic code	Choice Reaction Task (response time)		Search/Locate Task (response time)		Identification Task (response time)		Identification Task (response time)	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Letters	11.8	[illegible]	7.8	+27.3	[illegible]	+27.4	17.0	[illegible]
Digits	16.0	+29.2	6.7	+21.[illegible]	9.7	+1[illegible]	15.0	[illegible]
Shape	6.5	+16.4	2.3	+12.9	0.1	+15.[illegible]	13.1	+1.1

(Positive scores indicate that performance with color coding was superior to the comparison code; negative scores indicate color coding was inferior.)

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[27] Christ, R.E. and G.M. Corso, "Color Research for Visual Displays," Technical Report No. ONR-CR213-102-3, July 1975, 108 pp.

Results of two code comparison studies[18,28] demonstrate that color coding is clearly superior to numbers, shapes, or letters when the task involves locating targets in a cluttered field of nontargets. Numeric coding is superior for identification tasks. Both the numeric and color codes are beneficial in a counting task. The remaining tasks (comparing and verifying) showed no specific advantage for any of the codes.

An investigation of symbol identification time for seven different codes including numbers and colors was reported.[29] Numeric coding was superior to all others and color coding was the worst of the six. These results demonstrate the fact that color coding when used alone is a poor choice for a task requiring identification. To provide performance benefits, color is most effective as an aid in locating target symbols quickly. Its value is attributable to the added discriminability provided by color.

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[28] Christner, C.A. and H.W. Ray, "An Evaluation of the Effect of Selected Combinations of Target and Background Coding on Map Reading Performance--Experiment V," Human Factors, 3, 1961, pp. 131-146.

[29] Alliusi, E.A. and P.F. Muller, Jr., "Verbal and Motor Responses to Seven Symbolic Visual Codes: A study in S-R Compatibility," Journal of Experimental Psychology, 55, 1958, pp. 247-254.

USE COLOR

- To aid operator in locating particular information
- To draw attention to some specific place or symbol

USE ALPHANUMERICS

- To convey specific status information
- To identify specific targets

Color Used in Conjunction With Other Codes

USE MULTIDIMENSIONAL CODING

- To convey specific information that cannot otherwise be conveyed
- To increase the amount of information that can be displayed

On any complex display a number of coding dimensions are typically combined to convey specific information. The most frequently used codes are: alphanumerics, shape, symbol orientation, symbol size, and symbol brightness. Color can be used in combination with any of these codes to provide additional information, or to make existing information easier to see or use.

If the particular color of a symbol is correlated with a value or values on another dimension, then color is a redundant dimension. Full redundancy occurs when this correlation is perfect, such that knowing the value on one dimension completely determines the value on another dimension. If this correlation is not perfect, as is the case when fewer values are used on one of the two or more dimensions, then there is partial redundancy.

An example should help to clarify the meanings of full and partial redundancy. A hypothetical digital readout has nine possible values it can assume. If color were fully redundant with numeric value, then each of the nine digits would be associated with one of nine different colors. Knowing the color of the symbol would provide full knowledge of the numeric value and vice versa.

If, however, several numbers were associated with the same color, such that for example the three lowest values were coded yellow, the three middle values green, and the three highest values red, then the color code would be partially redundant with the numeric code. That is, knowing the symbol color would give only partial information about its numeric value. Knowing that the symbols displayed were green would indicate that the numeric value was one of three intermediate values.

A third form of multiple coding involves use of two or more codes in a situation where each conveys unique information not contained in the other codes. Such coding is nonredundant.

USE FULLY REDUNDANT CODING
• To improve symbol detectability
• To aid in discriminating among symbols
USE PARTIALLY REDUNDANT CODING
• When information can be categorized at more than one level of specificity
USE NON-REDUNDANT MULTIPLE CODING
• To increase the total number of identifiable categories

Nonredundant Use of Multiple Codes--Nonredundant color coding can be used to increase the number of symbols which can be absolutely identified on a display. Several studies[6,30] have reported improved ability to discriminate among objects when size and color or size, color, and brightness were combined in a single display than when any were used alone. (See Table 8.[6])

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[30] Garner, W.R. and C.G. Creelman, "Effect of Redundancy and Duration on Absolute Judgments of Visual Stimuli," Journal of Experimental Psychology, 67, 1964, pp. 168-172.

TABLE 8. DISCRIMINATION ACCURACY FOR THE THREE SINGLE AND THE FOUR MULTIDIMENSIONAL SYMBOL CODES

Symbol Code	Number of Absolutely Discriminable Symbols
Size	7.19
Hue	8.45
Brightness	5.06
Size-Hue	11.90
Size-Brightness	7.89
Hue-Brightness	13.55
Size-Hue-Brightness	17.28

Practical applications of nonredundant coding include, for example, the coding of friendly and enemy "targets" on a map, sensor display, or air traffic controller's display. Targets could be coded by color as either friend or foe. Further distinctions as to target type (aircraft vs. land vehicles) could be coded by shape. Specific targets within a type could be coded alphanumerically. Using such a system, a large number of targets could be uniquely coded in such a way that each is absolutely identifiable.

Use of Totally Redundant Codes--Symbols may be difficult to discriminate because the display is degraded by noise or poor luminance contrast, etc., or they may be difficult to locate because of clutter. In such situations color may be used as a totally redundant dimension to improve symbol discriminability. Targets that can be defined on several dimensions are found more quickly than when either dimension is used alone. Color and shape have been found to be the best combined code. Other dimensions such as brightness and size were not as effective.[31,32]

Use of Partially Redundant Codes--When color is combined with, for example, an alphanumeric code, such that groups of numbers or letters are similarly colored and several groups are defined in terms of specific colors, then color is a partially redundant dimension. Such combined coding is used to provide relative status (using color) and specific status (using alphanumerics). For example, altitude could be coded as high, in-tolerance, or low, using a three-color code such as yellow, green, and red, respectively. Actual, absolute altitude would be given digitally. Depending upon present information requirements, a quick glance at the display would inform the pilot of the relative altitude as compared to plan. Specific information would be available, if required, by the numeric value. Such multiple coding would be useful only in situations where both general and specific status information are meaningful at different times.

Redundancy May Not Always Aid Performance--In some situations, adding a redundant dimension may interfere with the effective use of other codes. If the operator has a strategy for using alphanumeric information, for example, and redundant color is added to the display, the colors may either

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[31] Ericksen, C.W. and H.W. Hake, "Multidimensional Stimulus Differences and Accuracy of Discrimination," Journal of Experimental Psychology, 50, 1955, pp. 153-160.

[32] Saenz, N.E. and C.V. Riche, Jr., "Shape and Color as Dimensions of a Visual Redundant Code," Human Factors, 16, 1974, pp. 308-313.

provide no benefit or may interfere with task performance. This effect was reported in a study[33] in which the operator was to keep track of the value on each of a large array of digital readouts. Adding redundant color did not aid performance in any way. Substituting color for digits resulted in poorer performance. When the strategy employed by operators was examined, the reason for such results became clear. Single digital readouts were "chunked" by operators into multidigit numbers. Colors used alone could not be easily chunked. Unless redundant color coding permits the use of a new and more effective strategy for information extraction, it should be avoided or used only if it provides other benefits such as increased symbol legibility.

<u>Color as an Irrelevant Coding Dimension</u>

WHEN COLOR CODE IS IRRELEVANT TO OPERATOR'S TASK

- Symbol color serves to distract operator
- Similarly colored items may be visually grouped in nonmeaningful or distracting ways . . .
- Color can functionally become "noise"

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[33] Kanarick, A.F. and R.C. Petersen, "Redundant Color Coding and Keeping-Track Performance," Human Factors, 13, 1971, pp. 183-188.

When the color of a displayed symbol has no direct bearing on the operator's task, the color code can serve to distract the operator in performing that task. "Signal" can be defined[34] as those aspects of a display that aid the operator in locating a target. "Noise" can be defined as those aspects of a display that detract from locating the target. Any irrelevant code becomes noise. Following this analogy, irrelevant color in a multicolor display adds to the noise and reduces the signal-to-noise ratio. The greater this noise, the poorer the operator performance will be.

If operator information requirements were always the same, the application of a color code would be relatively simple. A more typical problem occurs when the task and the operator information requirements vary while the display format remains constant. The result is that a code relevant for one task may be irrelevant for another. Therefore, it would be advisable to use color coding (or any code) with caution and with a consideration of the entire range of display uses and applications planned for that display. To be maximally effective a given color should be related to the operator task, and its presence should convey specific information.

Example of Relevant vs. Irrelevant Color--An illustration of the distracting effect of irrelevant color is provided by the results of an experimental study conducted under this contract. A simulated set of VFA/VSTOL aircraft

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[34] Green, B.F. and L.K. Anderson, "Color Coding in a Visual Search Task," Journal of Experimental Psychology, 51, (1), 1956, pp. 19-24.

cockpit displays (see Figure 21 for an illustration of achromatic formats[35]) were color coded in several ways and the effects of the different color codes on performance were analyzed. The displays were static (projected slides) and the operator's task was to detect out-of-tolerance conditions in any of the major parameters displayed. Therefore, the displays simulated cockpit displays and the operator's task simulated one important piloting function. A two-dimensional tracking task was added that varied in difficulty from low to high, simulating another aspect of piloting an aircraft.

The displayed symbology was coded in each of the following ways:

1. Achromatic symbology--no color
2. Three-color displays with color used to "group" similar items (i.e., all scales green, all alphanumerics red, other symbols yellow)
3. Three-color display where color served no apparent function (i.e., some scales were green, others yellow; some alphanumerics were green, others red, etc.)
4. Three-color display in which all symbols and scales were green or yellow. Red was used solely to indicate an out-of-tolerance condition. A symbol or indicator would be displayed in red in such cases, rather than in its "normal state" color

[35] Linton, P. M., "VFA-V/STOL Crew Loading Analysis," Report No. NADC-75209-40, Crew Systems Department, Naval Air Development Center, Warminster, PA, 15 May 1975.

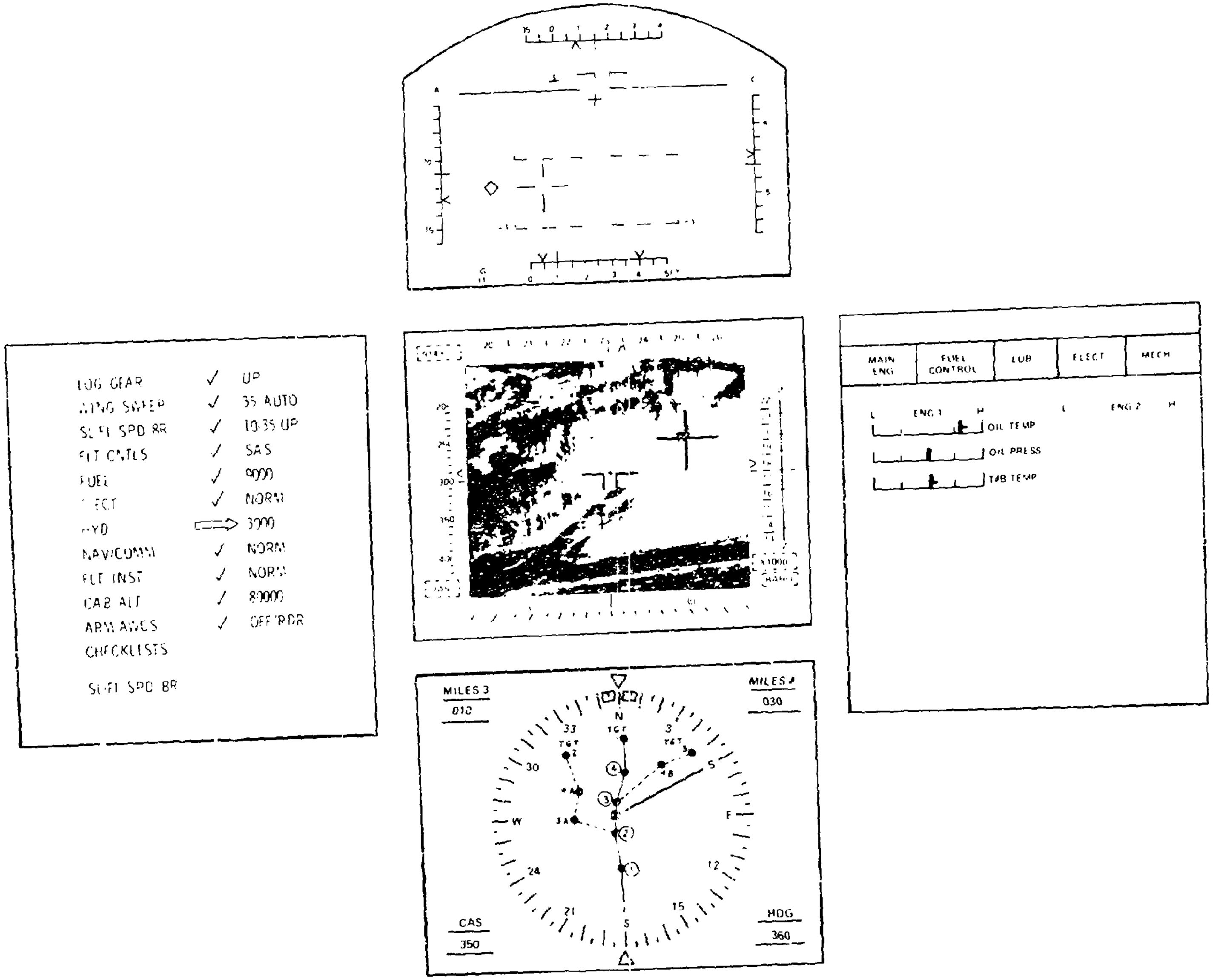

Figure 21. Representative Advanced Integrated Display System (AIDS) Formats

Given the operator's task in this experiment (detect out-of-tolerance parameters), only the fourth coding scheme was task relevant. The second and third color codes were irrelevant. Both the effects of relevant and of irrelevant color were of interest.

The results of this study are shown in Figure 22. A combined score reflecting both tracking accuracy and detection speed are shown for each of the four color codes as a function of tracking task difficulty. As was seen in Figure 21, when the task is easy (low workload), there is very little difference among the codes used. As the task became more difficult, however, the effect of the different codes is quite different. The color-as-cue code is far superior to the others. The color-as-organizer code is no different from the achromatic code. Note that the condition in which color has no task-related function yields the worst performance. In this last case, color served only as a distractor.

This example demonstrates two important principles:

1. If the operator's task is easy and/or the display is uncluttered, color provides no performance benefits.
2. If the task is difficult, color coding must be appropriately related to the operator task to have value. If it is not related, it can degrade performance by serving as a distractor.

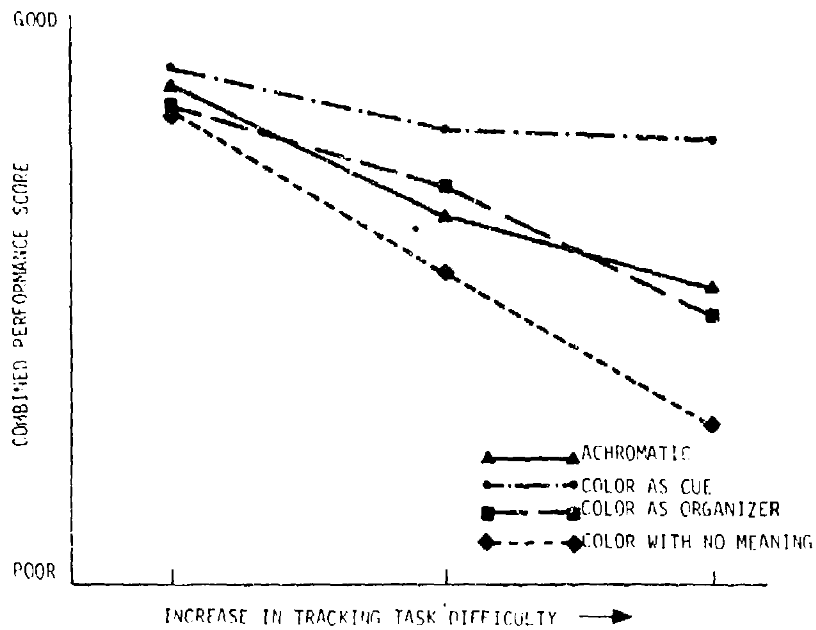

Figure 22. Relative Effects of Task Difficulty on Performance of Simulated Piloting Tasks as a Function of Different Methods of Color Coding

TO MINIMIZE EFFECTS OF IRRELEVANT CODING

- Analyze various ways in which information might be grouped together for various tasks
- If possible use color coding as an aid for:
  1) The most frequently used, or
  2) The most difficult operator task
- Avoid use of color that serves no definable task function

COLOR CODING IN HIGH DENSITY DISPLAYS
• Reduces search time: 1) If target position is unknown, and 2) Target color is known • Increases search time: 1) If target color is unknown

Effects of Displayed Symbol Density

Display density refers to the number of symbols on a display. When the display is unformatted to the extent that target position is unknown, the non-target symbols serve as distractors. If symbols are similar (e.g., all alphanumerics) the operator may have to examine each symbol to determine whether or not it is a target. One study[36] reported search times approximately equal to one fifth of the total number of symbols. When color coding was added, search times were reduced to one fifth of the number of alternatives of the target color.

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[36] Green, B.F., W.J. McGill and H.M. Jenkins, "The Time Required to Search for Numbers on Large Visual Displays," Report No. 36. Lincoln Laboratory, Massachusette Institute of Technology, August 1953, 15 pp.

The relationship between accuracy of locating targets and display density is shown in Figure 23 for three viewing times.[37]

To be effective as a code, the color of the target must be known. Without this knowledge, multicolor displays may only distract from performance. This relationship is shown in Figure 24.[34]

In Figure 25, a comparison between color coding and several shape codes is plotted as a function of symbol density.[38] The fewest counting errors occurred using color coding. The relative superiority of color coding becomes more pronounced as symbol density increases.

USE COLOR CODING TO REDUCE THE EFFECTS OF HIGH SYMBOL DENSITY

- By presenting functionally related items in the same color, or
- By presenting "target" data in a unique, prespecified color (e.g., warning light)

[37] Dyer, W.R. and R.J. Christman, "Relative Influence of Time, Complexity and Density on Utilization of Coded Large Scale Displays," RADC-TR-65-235, Rome Air Development Center, Rome, NY, AD 622-786, September 1965.

[38] Wolf, E. and M.J. Zigler, "Some Relationships of Glare and Target Perception," WADC-TR-59-394, USAF Wright Air Development Center, Wright-Patterson Air Force Base, OH, AD 231-279, September 1959.

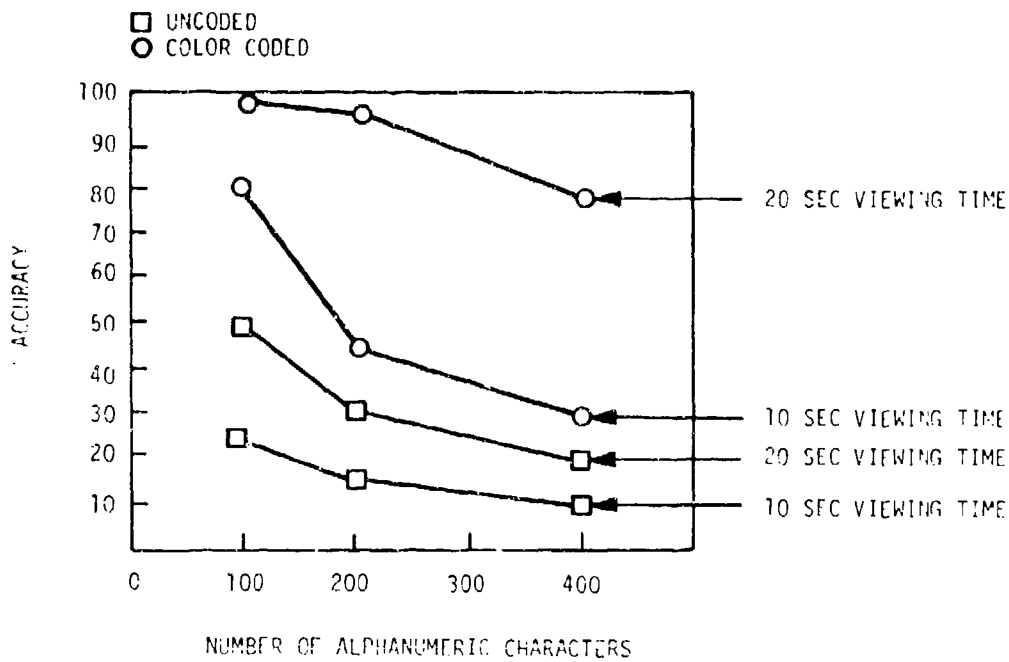

Figure 23. Effect of Density and Display Exposure Time on Accuracy

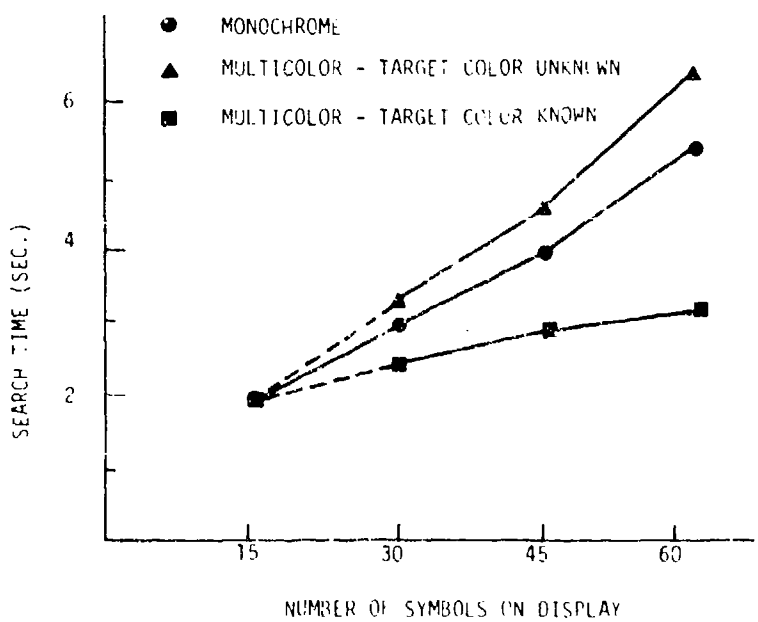

Figure 24. Effect of Color Coding as a Function of Display Density

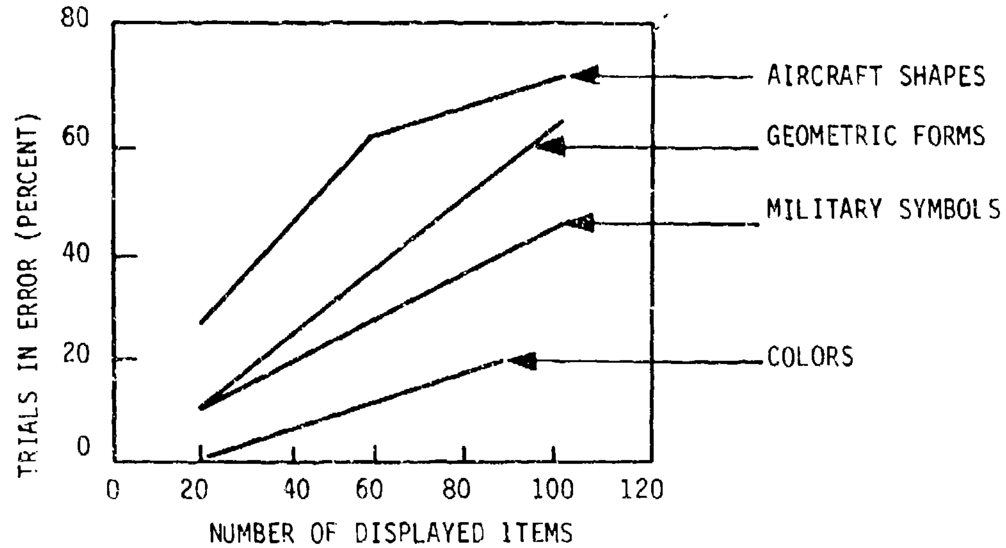

Figure 25. Counting Errors as a Function of Display Density, Comparing Color Coding With the Three Shape Codes

Coding of Multiple Display Sets

When the operator has not one but many color displays in a set, the principles discussed earlier apply not only to each display, but also to the set of displays as a whole. The designer should be aware that the displays interact in their effect on the operator. The entire set should be color coded in a coordinated, consistent way. That is, the meaning associated with a particular color on one display should be consistent with its meaning across the remaining displays in the set. For example, if red is used as a conventional warning signal on one display, it should have a similar connotation whenever it is used elsewhere. Conflicting uses of color across displays will lead to operator confusion and possibly to misinterpretation of the meaning conveyed by the color displayed.

Another consideration in designing multiple color coded displays is the use of color to group related information appearing on separate displays. Again this principle is similar to the one discussed in the context of a single display.

Application of color to a multiple display situation may become clearer if one views the set as one large display of moderate to high symbol density rather than several smaller individual displays of low symbol density.

PART II

APPLICATION OF COLOR PRINCIPLES TO FIGHTER/ATTACK AIRCRAFT DISPLAYS

Prepared by

J. D. Wolf

J. H. Sandvig

SECTION IV

PART II INTRODUCTION AND OVERVIEW

The objective of Part II is to extrapolate color coding principles developed in Part I of this design guide to a particular design/operational setting as an example of how these general principles may be applied. The application addressed here is the color coding of electronic displays in fighter/attack aircraft. An analysis framework is developed that assumes the point of view of a display system designer contemplating the use of multicolor displays, either in retrofit to an existing aircraft or as components of a new avionic system under development. With this point of view, our main concerns are (1) identification of design/operational factors that may influence color coding, and (2) definition of one or more recommended coding schemes for subsequent use in evaluating display media and computational requirements.

Background information is provided on representative fighter/attack aircraft displays and their use in realistic mission scenarios. Design and operational factors judged most relevant to display color coding are identified. These factors are classified into categories reflecting different aspects of the system/operational problem typically faced by a designer during planning and implementation of flight display systems. Issues associated with these factors and principles and recommendations stated in Part I are jointly reviewed to define tradeoffs in color application. Based on these evaluations, color codes recommended for application to electronic displays in fighter/attack aircraft are presented.

SECTION V

ELECTRONIC DISPLAYS IN FIGHTER/ATTACK AIRCRAFT

Part II of this report addresses the application of color coding principles to displays in fighter/attack aircraft. General background information on representative displays and display concepts is presented in this section.

AIRCRAFT DISPLAY TRENDS

Task analysis and other descriptive data on the following three fighter/attack aircraft were provided by the Navy in support of this study. These aircraft are illustrative of the trend toward use of cockpit electronic displays to replace electromechanical indicators.

- Vought A-7E: Upgraded version of an aircraft that has been operational since the late 1960's
- Northrop/McDonnell Douglas F-18: Advanced aircraft under development, expected to become operational in the early 1980's
- VFA-V/STOL: Conceptual design representative of the Navy Type B V/STOL aircraft expected to become operation in the 1990's

Figure 26 shows the complement and general layout of electronic displays in each aircraft. Panel displays primarily serving a single function (i.e., A-7E

- HEAD-UP DISPLAY (HUD)
- THREAT ANALYZER DISPLAY (TAD)
- RADAR DISPLAY

F-18

- HEAD-UP DISPLAY
- HORIZONTAL SITUATION DISPLAY (HSD)
- MASTER MONITOR DISPLAY (MMD)
- MULTIFUNCTION DISPLAY (MFD)
- THREAT ANALYZER DISPLAY

VFA-VSTOL

- HEAD-UP DISPLAY
- VERTICAL SITUATION DISPLAY (VSD)
- HORIZONTAL SITUATION DISPLAY
- MULTIPURPOSE DISPLAY (MPD)

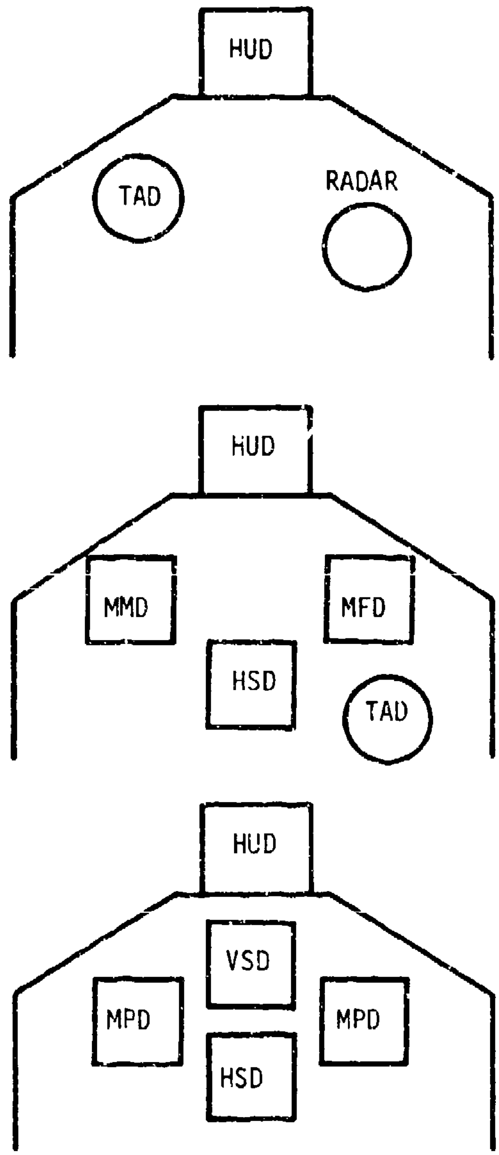

Figure 26. General Layout of Electronic Displays in Three Representative Aircraft

radar and threat analyzer displays) are shown as circles. Head-up displays and other panel displays indicated by squares typically serve multiple functions or present a greater variety of information.

Electronic displays in earlier aircraft such as the A-7 tend to be single function, but may have various modes tailored to provide information needed in specific mission phases. For example, terrain avoidance, ground map, air-to-ground ranging, and terrain following are common radar display modes.

From Figure 26 it is apparent that the number of electronic multifunction displays will increase in advanced aircraft. The VFA (vertical fighter attack) - V/STOL instrument panel is representative of the Navy's advanced integrated display system (AIDS) concept. Although the F-18 panel does not contain an electronic VSD and names assigned to other displays differ somewhat, this panel implements many of the AIDS features, especially in lay... and assignment of display functions.

ADVANCED INTEGRATED DISPLAY SYSTEM

The AIDS concept will be emphasized here since it characterizes the direction of display system development for advanced Navy aircraft. This concept encompasses a broad range of technologies including display media and processors, data processing and bussing, and multifunction controls integrated to provide an improved crew/system information interface. Because of the continuing development of AIDS for various aircraft and mission applications,[35,39,40,41,42] a singular set of system characteristics has not yet been defined. However, general features of the AIDS concept that are relevant to application of display color coding can be identified. These are briefly described in the following paragraphs.

AIDS Display Complement

Up to six electronic displays are being considered for integration into the AIDS system.[40,42] These are:

- Head-up display (HUD)
- Helmet mounted display (HMD)
- Vertical situation display (VSD)
- Horizontal situation display (HSD)
- Left and right situation advisory displays (LSAD and RSAD)

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[39] "Advanced Display Technology: Advanced Integrated Modular Instrumentation System (AIMIS)," Second Advanced Aircrew Display Symposium, Naval Air Test Center, April 1975.

[40] "Advanced Integrated Display System (AIDS)," System Design Interim Report No. 3, General Electric Co., October 1977.

[41] Dowd, C.A., "F-14 Displays Growth for 1980's and Beyond," Third Air-to-Air Fire Control Review, U.S. Air Force Academy, October 1977.

[42] Osterman, L.O. and Mulley, W.G., "Advanced Integrated Display System (AIDS) for V/STOL Aircraft," AIAA/NASA Ames V/STOL Conference, June 1977.

Although the HMD was not initially considered a component of AIDS,[35,39] more recent sources indicate that this display may become an integral part of the system.[40,42] The term "situation advisory display" is the name more recently assigned to the multipurpose displays shown in Figure 26.

AIDS Concept Description

Functions and forms of information presented on the above displays are summarized in Table 9. The primary and secondary functions listed are a composite of AIDS concepts described in References 35, 39, and 42. Detailed examples of display information contents and formats can be found in these sources. Figure 21, presented earlier in Part I, was adapted from Reference 35 and illustrates representative formats on all displays except the HMD. Forms of information presentation listed in Table 9 are defined for purposes of the present analysis as:

- Alphanumeric--letters and numbers
- Symbolic--emblematic symbols and line segments
- Sensor video--imagery from sensors such as radar, infrared, and television devices
- Projected map--map image rear-projected on display
- Direct view of outside world--portion of outside world viewed through HUD or HMD optical combiner

Information forms included on the format examples in Figure 21 are alphanumeric and symbolic elements on all displays, and sensor video on the VSD. The following paragraphs further elaborate on general features of the AIDS concept summarized in Table 9.

TABLE 9. AIDS DISPLAY FUNCTIONS

Display	Primary Functions	Forms of Information Presentation	Secondary Function
Head-Up Display (HUD)	• Flight control • Weapon delivery • Forward-looking sensor	• Alphanumeric • Symbolic • Sensor video • Direct view of outside world	Backup to HMD and VSD
Helmet-Mounted Display (HMD)	• Flight control • Weapon delivery • Slewable sensor	• Alphanumeric • Symbolic • Sensor video • Direct view of outside world	Backup to HUD and VSD
Vertical Situation Display (VSD)	• Flight control • Weapon delivery • Forward-looking sensor	• Alphanumeric • Symbolic • Sensor video	Backup to HUD, HMD, and HSD
Horizontal Situation Display (HSD)	• Navigation • Tactical situation • Threat analysis • Downward-looking sensor	• Alphanumeric • Symbolic • Sensor video • Projected map	Backup to VSD
Left Situation Advisory Display (LSAD)	• Downward-looking sensor • Navigation data • Stores management • Display options lists • System status and activities • Threat analysis	• Alphanumeric • Symbolic	Backup to RSAD
Right Situation Advisory Display (RSAD)	• Energy management • Engine status and activities	• Alphanumeric • Symbolic	Backup to LSAD

Display Malfunctions--Assuming the full complement of six displays listed in Table 9, each display has at least one backup in the event of a malfunction. If a malfunction occurs, a second display must serve both its primary and backup functions by either temporal or spatial sharing of display area. This could pose a difficult system design problem for applications where both displays may be needed simultaneously for successful mission performance. To our knowledge this problem has not been fully resolved.

Other System Malfunctions--Engine malfunction and advisory information is presented on the RSAD.[39] The LSAD presents warning, caution, and recommended course-of-action messages for malfunctions in all aircraft systems. Discrete messages appear on the HUD, VSD, and HSD to cue the pilot that malfunction and corrective-action information is being displayed on the LSAD. Since the LSAD and RSAD are also used for other purposes, display-when-needed and automatic prioritization techniques are applied to present other mission-related information only when required. Examples are threat detection/classification and countermeasures activation data displayed on the LSAD and HSD.

Cueing Messages--As with system malfunctions, discretes are presented on the HUD and VSD to cue the pilot that a critical event (e.g., detected threat) has occurred, and that related information is being displayed elsewhere (e.g., on the HSD and LSAD).

Mission-Related Modes--Multiple pilot-selectable display modes containing information and formatting tailored to specific mission phases, weapon types, or operating conditions are characteristic of advanced electronic display systems. Representative HUD formats from Reference 39 are shown as examples in Figures 27 through 30. Other HUD formats not shown include bombing mode and boresight weapon mode. The following generalizations can be made with these figures as examples:

- Computer-generated information is a mixture of alphanumerics and symbology (e.g., all HUD formats).
- Computer-generated information may be mixed with sensor video or direct view of outside world (e.g., all HUD formats, but not shown in figures).
- The same display space may be used for dimensionally different information presented in a similar form (e.g., altitude and closing-rate tapes in Figures 28 and 29).

The above comments also apply to the HMD and in most instances to the VSD and HSD.

Composite Presentations--It was previously indicated in Table 9 that as many as four AIDS displays may be capable of depicting computer-generated alphanumeric and symbolic information, and one or more forms of more complex imagery. Composite or superimposed presentations of various information forms will be typical. The following possibilities exemplify composite display presentations.

- HUD or HMD (day, good visibility)
  - -- Computer-generated information and direct outside view
- HUD or HMD (night or limited visibility) or VSD or HSD
  - -- Computer-generated information and single or multisensor video

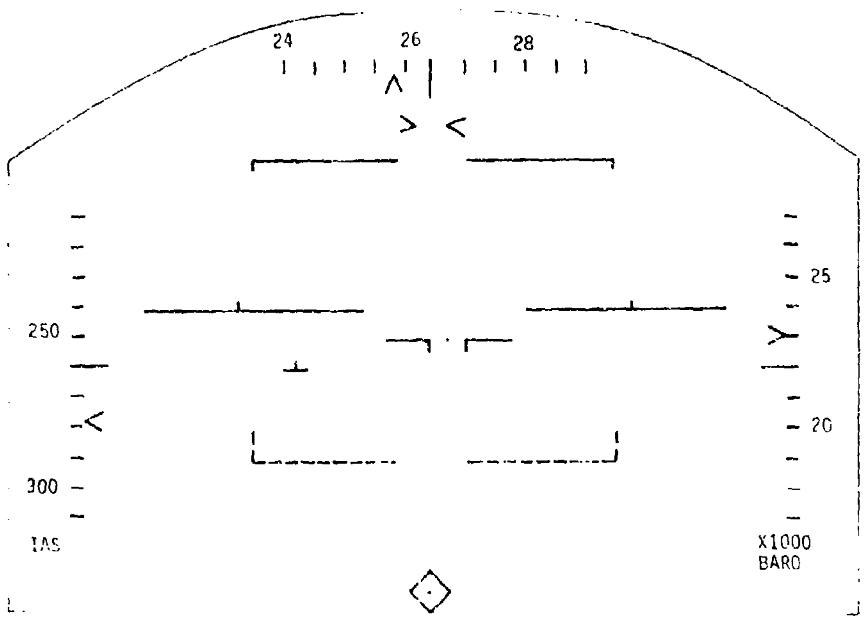

Figure 27. HUD Format, Takeoff/Navigation Mode

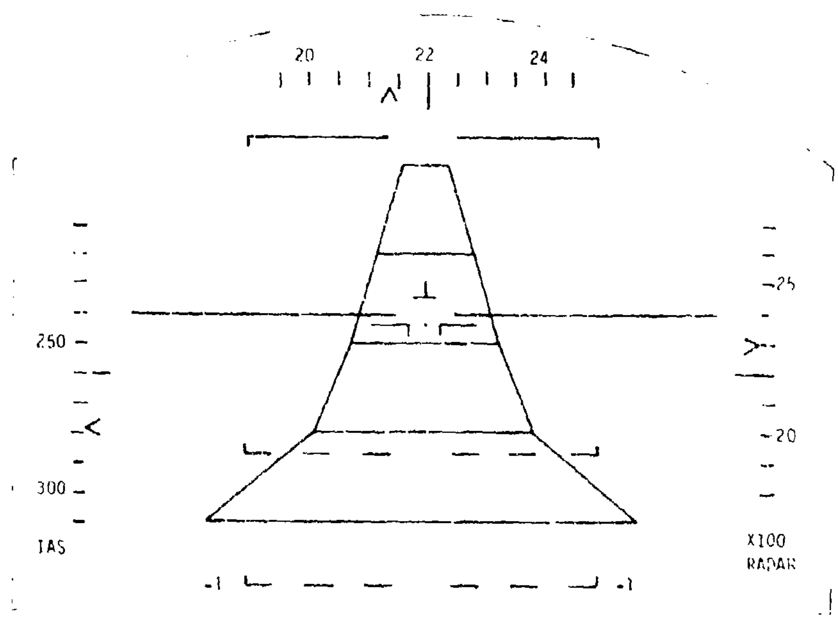

Figure 28. HUD Format, Terrain Following Mode

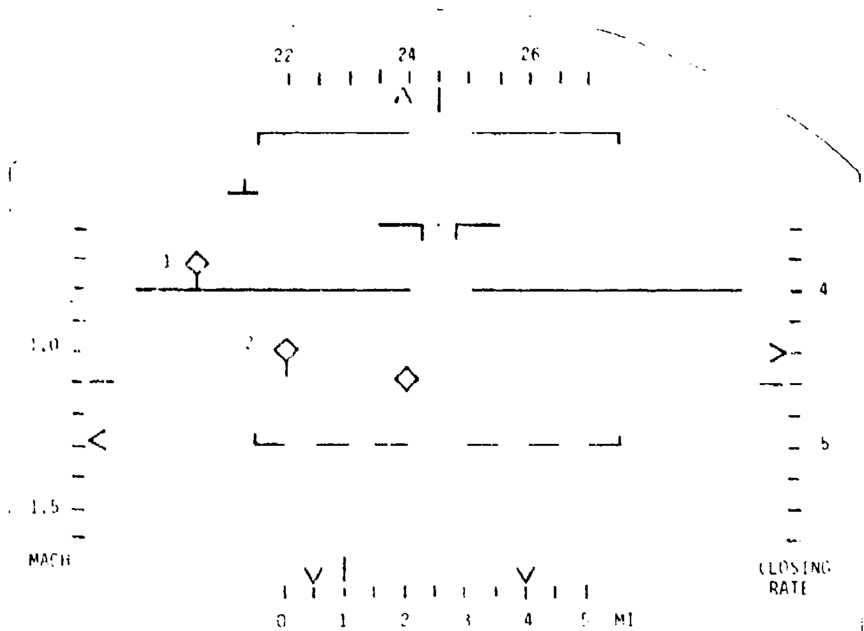

Figure 29. HUD Format, Guided Weapons Mode

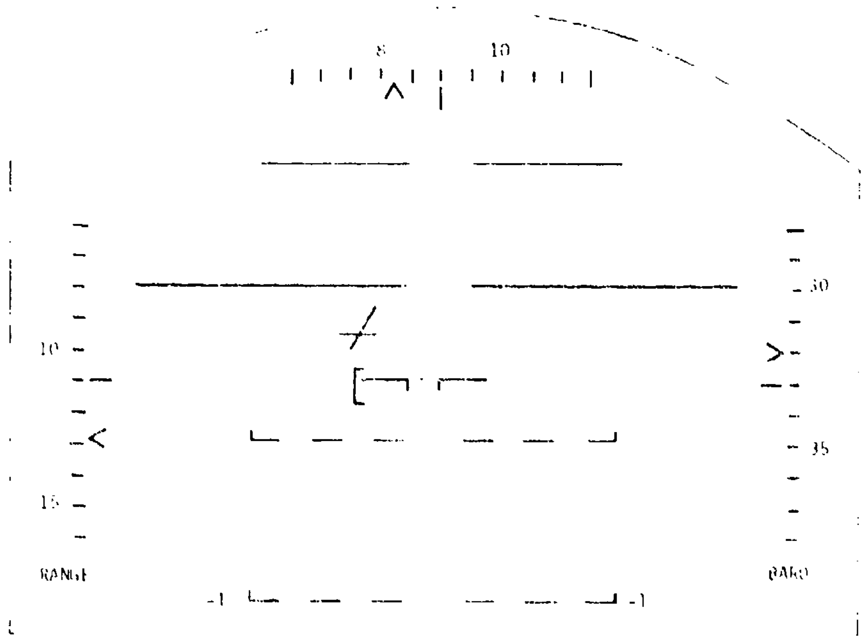

Figure 30. HUD Format, Landing Mode

- HSD
  - -- Computer-generated information and single or multisensor video
  - -- Computer-generated information, sensor video, and projected maps

Under day conditions with good visibility, direct view of the outside world through an HMD or HUD combiner is an inherent component of the information contained "on" these displays. Under low visibility or night conditions, computer-generated and/or sensor video on a HUD or HMD produces a display that appears similar to the same information presented on panel displays such as VSD or HSD. Composite presentations of video from multiple sensors operating in different regions of the electromagnetic spectrum are likely in future systems. Basic requirements for purposes of display are comparable image scaling and accurate superposition of scene features in the composite image. The HSD offers an additional option of presenting a projected map image in conjunction with computer-generated information and sensor video.

Display Media and Image Generation

A number of media and image-generation characteristics representative of current displays are anticipated to remain as characteristic of future multicolor media. Most of the electronic displays in the F-18 and current AIDS concept are cathode-ray tubes (CRTs). The liquid-crystal medium has been recommended for the AIDS situation-advisory displays.[40] Alphanumeric and symbolic images are stroke written on the F-18 CRTs, and sensor video is presented using conventional raster-scan techniques.[41]

With AIDS, there is an increased trend toward use of in-raster alphanumeric and symbol generation.[40] These information forms can be generated using stroke-written, in-raster techniques, or a combination of the two. Figure 30 is an example of a stroke-written display. Figure 31 is an example[43] of the combined stroke and raster technique as applied to the F-14 VSD. In Figure 31, stroke writing is used to outline and improve definition of the in-raster vertical white line and square near display center.

Ambient Conditions of Use

The extreme range of ambient light conditions under which displayed information must be legible in fighter/attack aircraft poses one of the most severe challenges to display designers. Display-surface illumination from direct sunlight can approach 110,000 lumens/m^2. If direct-viewed background of a HUD or HMD is snow illuminated by an overhead sun, luminance of this background may exceed 34,000 cd/m^2.

At the opposite extreme are night operational conditions, where mission requirements may dictate maximum visual dark adaptation levels to facilitate detection of targets, obstacles, and landmarks. Maximum display luminance of less than 3.5 cd/m^2 is desirable under these conditions.

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[43] Elson, B. M., "F-14 Uses Digital Display Method," Aviation Week and Space Technology, July 20, 1970.

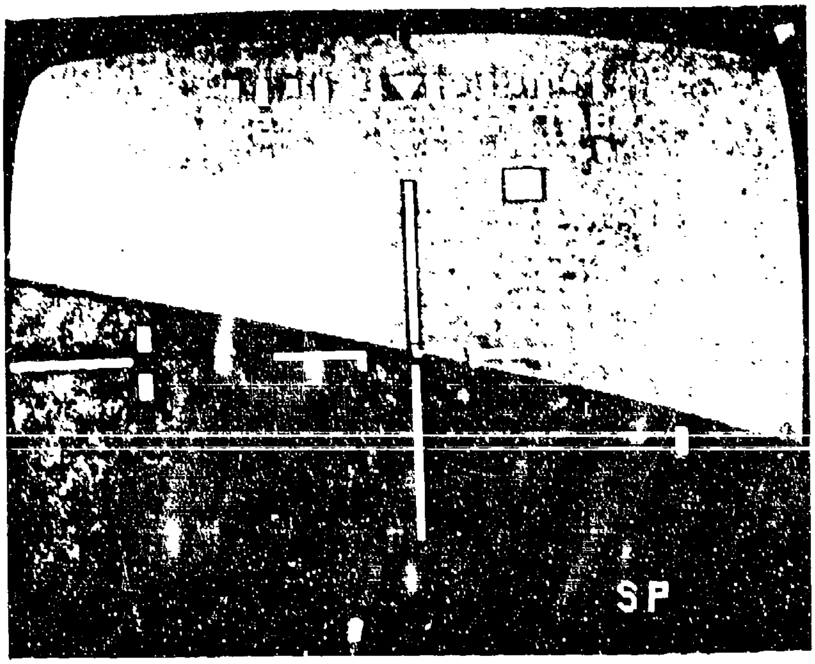

Figure 31. F-14 VSD--Combined Stroke-Written and In-Raster Image Generation

SECTION VI

DISPLAY USAGE ANALYSIS

Pilot usage of cockpit electronic displays under representative mission operational conditions is analyzed in this section. Analysis results combined with the more general background information in Section V provide the basis for evaluating color-application tradeoffs in Section VII.

Five mission segments are analyzed. A taxonomy of electronic display usage in each mission segment is developed to illustrate the types of pilot tasks and visual perceptual operations involved during use of these displays. A display use-frequency analysis quantifies the number of operations performed using the various aircraft electronic displays. Finally, a link analysis identifies the transitions of visual attention between information elements on electronic displays and other information sources.

MISSION SEGMENTS

The display usage analysis was completed for mission segments of the three aircraft introduced in Section V. Task analysis data including pilot-workload timelines were provided by the Navy for missions of the A-7E,[44] the F-18,[45,46] and the VFA-V/STOL.[35] Five mission segments involving relatively high pilot workload were selected from the following mission phases:

- A-7E--Close-air support (CAS) mission; air-to-ground attack phase
- F-18--Escort mission; ingress and medium-range-intercept (MRI) phases
- VFA-V/STOL--Deck-launched intercept (DLI) and CAS mission; target attack phases

High workload segments summarized below were chosen for the present analysis because of the relatively frequent use of a variety of different displays.

<u>A-7 Ground Attack Segment</u>

This segment begins with weapon delivery preparation including a 10-degree right turn and a climb from 1500 to 3000 meters. A straight and level

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[44] Klein, T.J., "Night Display--One-Man Aircraft Compatibility Analysis," Report No. 2-55900-OR-2806, LTV Aerospace Corp., May 1970.

[45] Asiala, C.F., "F-18 Man/Machine Evaluation Techniques," Presented at the American Defense Preparedness Association Avionics Section, Air Armament Division, Air Force Systems Command, Wright-Patterson AFB, Ohio, October 1976.

[46] Asiala; C.F. and Rosenmeyer, C.E., "F-18 Human Engineering Task Analysis Report," Report No. MDC A4276, McDonnell Aircraft Co., St. Louis, MO, August 1976.

interval follows in which the pilot must locate and identify the intended target and prepare weapons for delivery. A one-half-g nose-over initiates the delivery dive, during which the identified target is confirmed and the ordnance is released. The segment is completed by pulling out of the delivery dive and performing an escape turn.

F-18 Ingress and Intercept Segments

The scenario is that of four fighters escorting a small number of attack aircraft on an interdiction mission. The F-18's prime mission is to protect the attack aircraft from interception by enemy aircraft. Two mission segments were chosen: ingress, which is essentially the flight from the forward edge of the battle area (FEBA); and medium-range intercept (MRI), an air-to-air intercept of an enemy aircraft using the Sparrow missile.

The F-18 ingress segment of the fighter escort mission involves maintaining a weave maneuver over the strike aircraft group at constant altitude, noting the group's position relative to the FEBA and the target, and keeping watch for enemy threats (i.e., EW and SAMS). The F-18 MRI segment involves locating an enemy interceptor on radar and attacking it. The pilot must coordinate his attack on the target with his wingman, compute and fly the intercept, and launch Sparrow missiles. Finally the pilot must rejoin the attack group and assume escort responsibilities once again.

VFA Ground and Air Attack Segments

Close-air support includes support of friendly ground operations in close proximity to the enemy. The VFA CAS segment requires locating the appropriate battle area and communicating with a forward air controller, then finding the target assigned. The aircraft uses IR sensors and a laser target designator system, and attacks the ground target once with rockets and twice with guns. The VFA escapes from the battlefield area after evading a SAM.

The VFA DL1 mission segment includes an air-to-air intercept of a hostile aircraft threatening to attack friendly forces. The pilot is given information concerning the location of the target, but retains responsibility for locating the target on radar and making the final intercept. The pilot flies the command intercept parameters and uses ECCM techniques. The scenario calls for the launching of two missiles at the target, probably of the Sparrow type. This is followed by an attack break and reattack maneuver culminating in the launch of a Sidewinder missile. The mission segment is terminated upon the pilot's verification of the enemy aircraft impact.

DISPLAY USAGE TAXONOMY

Taxonomies of electronic display usage for the above aircraft/mission segment combinations were defined at the following five levels:

1. Type of aircraft (i.e., A-7, F-18, VFA)
2. Segment of a particular mission (e.g., interdiction supersonic dash, escort medium range intercept, deck-launched intercept)
3. Electronic displays available in the cockpit (e.g., HUD, HSD, VSD)
4. Pilots tasks required to successfully complete the mission segment (e.g., track target, maintain flight conditions, detect hostile targets)

5. Display elements employed and the pilot's use of display elements in accomplishing level 4, for example, in accomplishing specific tasks (e.g., identify target and aircraft symbol, observe discrepancy between the two)

In general, the information necessary to complete levels 1 through 4 of the taxonomy was provided by a crew task-analysis of a crew task time line for a particular aircraft and mission. Level 5 of the taxonomy was produced by considering the perceptual requirements of the pilot to accomplish the tasks classified in Level 4. Terminology used to describe the pilot's perceptual requirements in Level 5 was taken from a classification of perceptual processes developed by Berliner et al[47] and subsequently revised by Christensen and Mills.[48] These terms, applied here to characterize visual perceptual operations by the pilot, are listed below with definitions developed for purposes of the present study.

- Detect-- To perceive the presence of some signal not previously present and not actively sought.
- Inspect-- To peruse; to examine with attention and in detail.
- Observe--To watch; to take note of.

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[47] Berliner, C.D., et al., "Behaviors, Measures, and Instruments for Performance Evaluation in Simulated Environments," Presented at Symposium on Quantification of Human Performance, Albuquerque, NM, August 1964.

[48] Christensen, J.M. and Mills, R.G., "What Does the Operator Do In Complex Systems," Human Factors, Vol. 9, No. 4, 1967.

- Read--To take in the sense of alphanumerics or symbols.
- Receive--To assimilate passively.
- Scan--To glance from point to point in search of particular information.
- Survey--To examine the general condition or situation.
- Discriminate--To perceive the difference between elements.
- Identify--To establish the distinguishing characteristics of an element.
- Locate--To determine the position of an element.

For example, according to the mutually exclusive definitions above, it was determined that in the A-7 the functions of HUD for tracking the target would entail identifying the target and the aircraft symbol and observing the discrepancy between the two. In the F-18, on the other hand, while monitoring the radar display, the pilot must inspect the display for targets. Thus, fairly extensive knowledge of the cockpit design and the display formats as well as the pilot's perceptual needs to accomplish the tasks are required for this level of analysis.

Results of the display usage taxonomy for the five aircraft/mission segment combinations are illustrated in Figures 32 through 36.

The large majority of perceptual operations served by electronic displays in the A-7 CAS weapon delivery segment are associated with the HUD (see

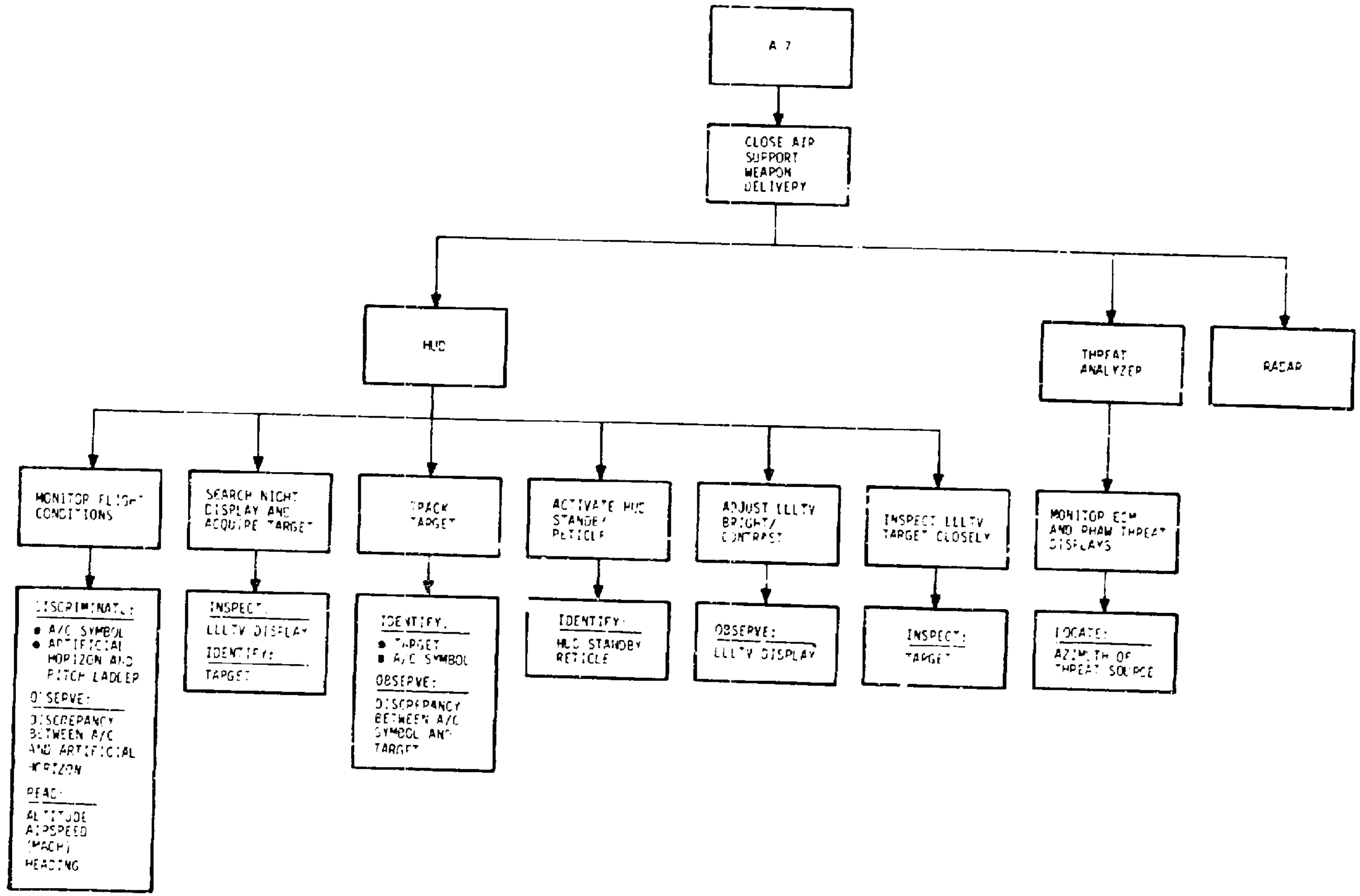


Figure 32. A-7 Close Air Support--Display Usage Taxonomy

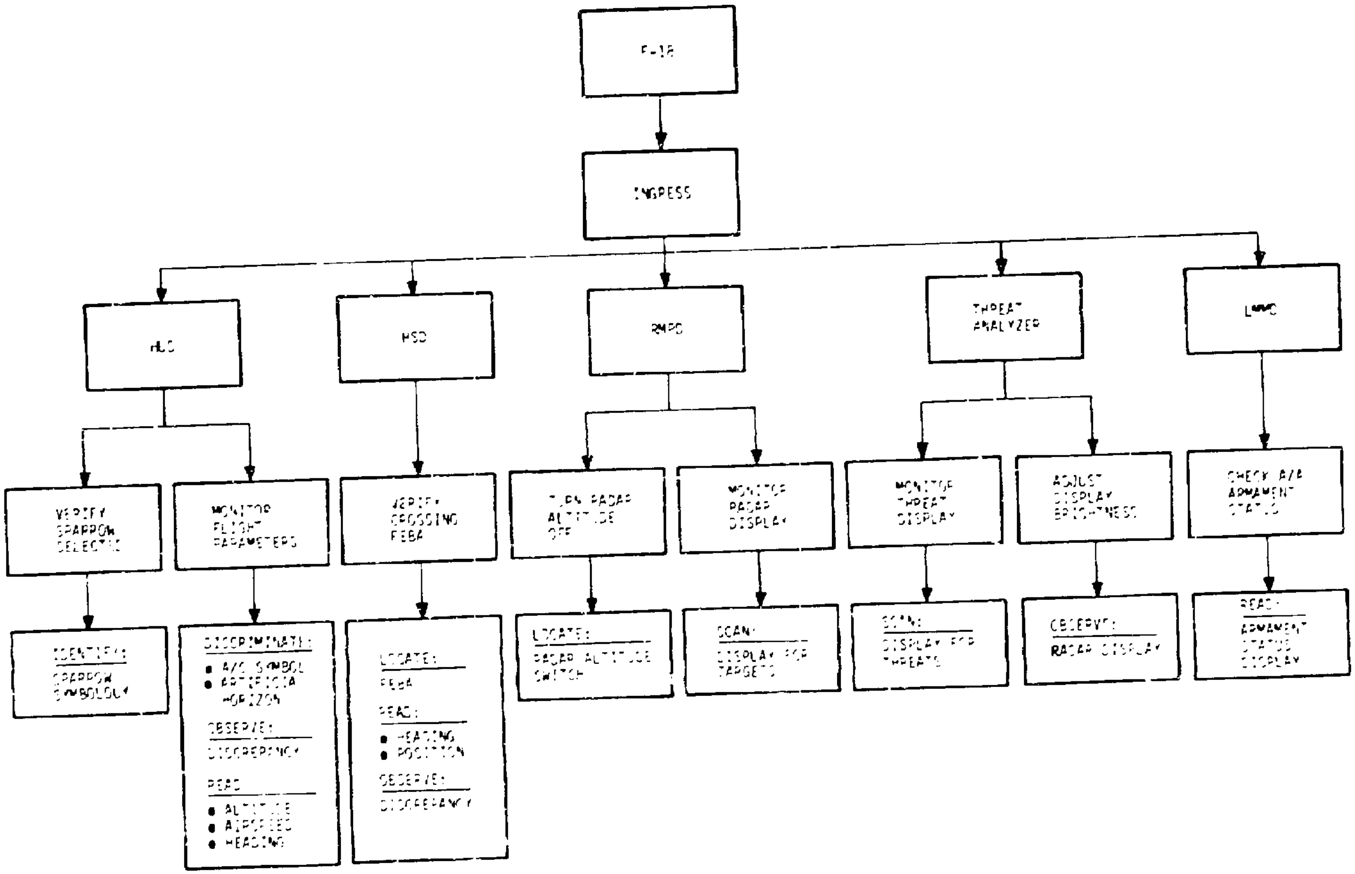


Figure 33. F-18 Ingress--Display Usage Taxonomy

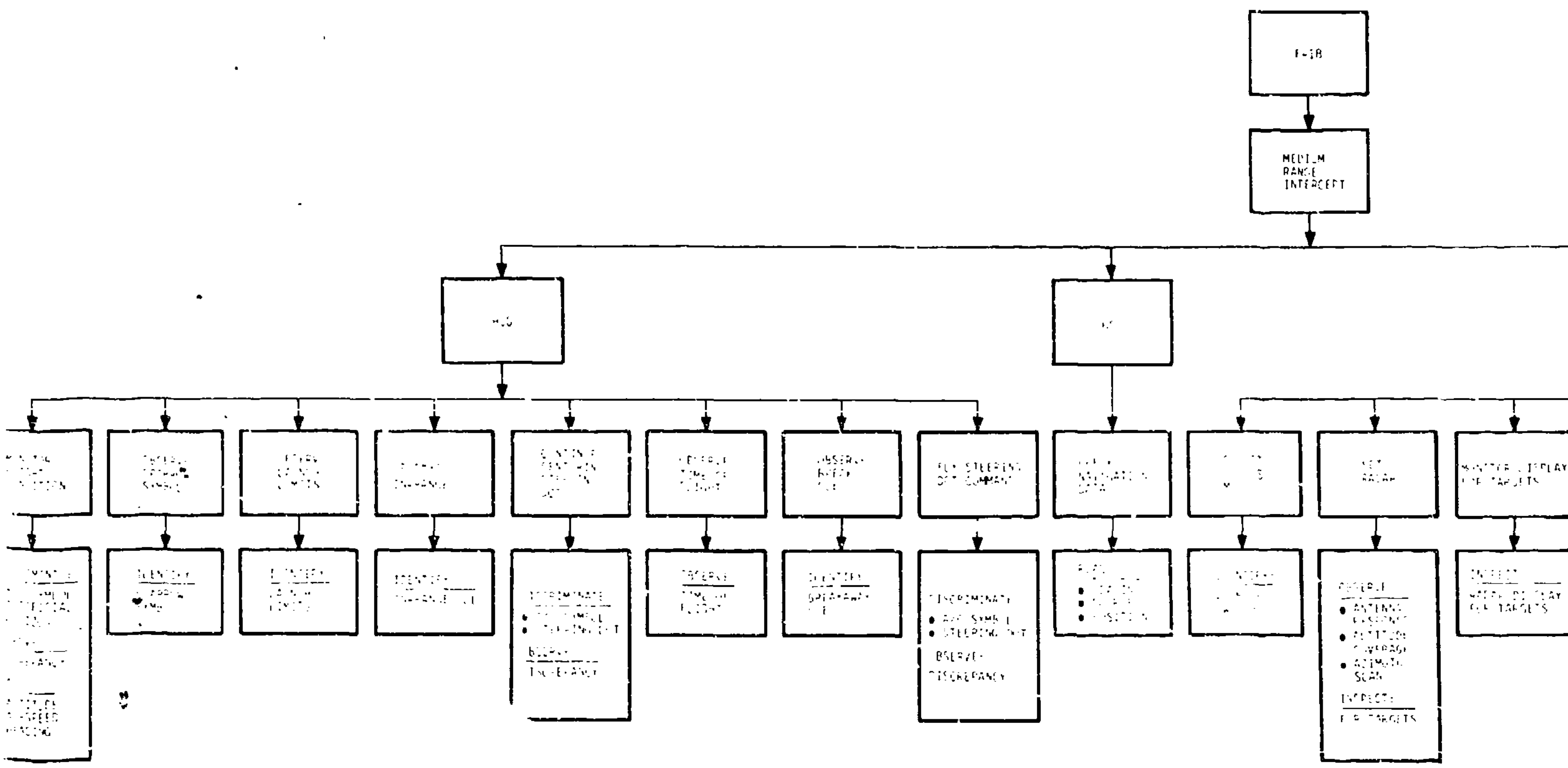
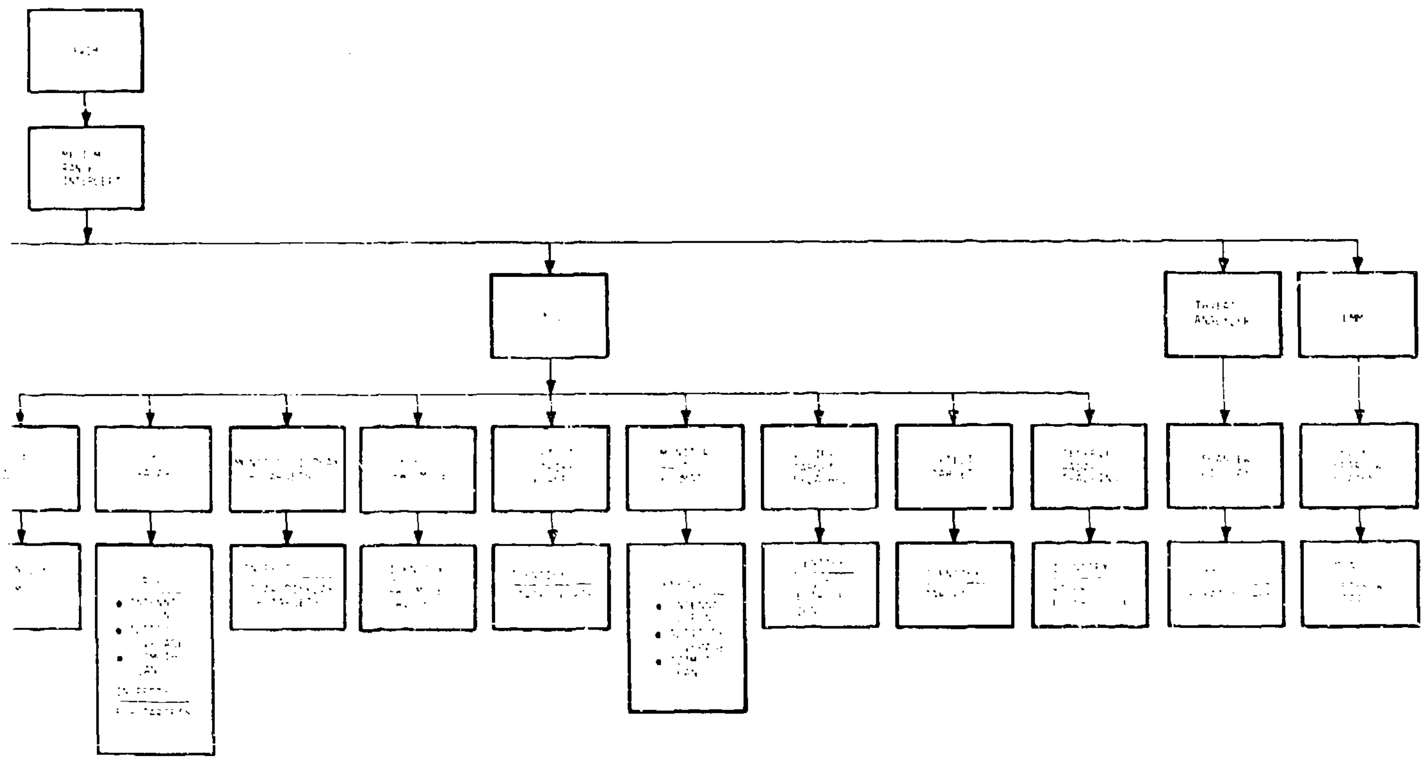


Figure 34. F-18 Medium Range Intercept--Display



ıge Intercept--Display Usage Taxonomy

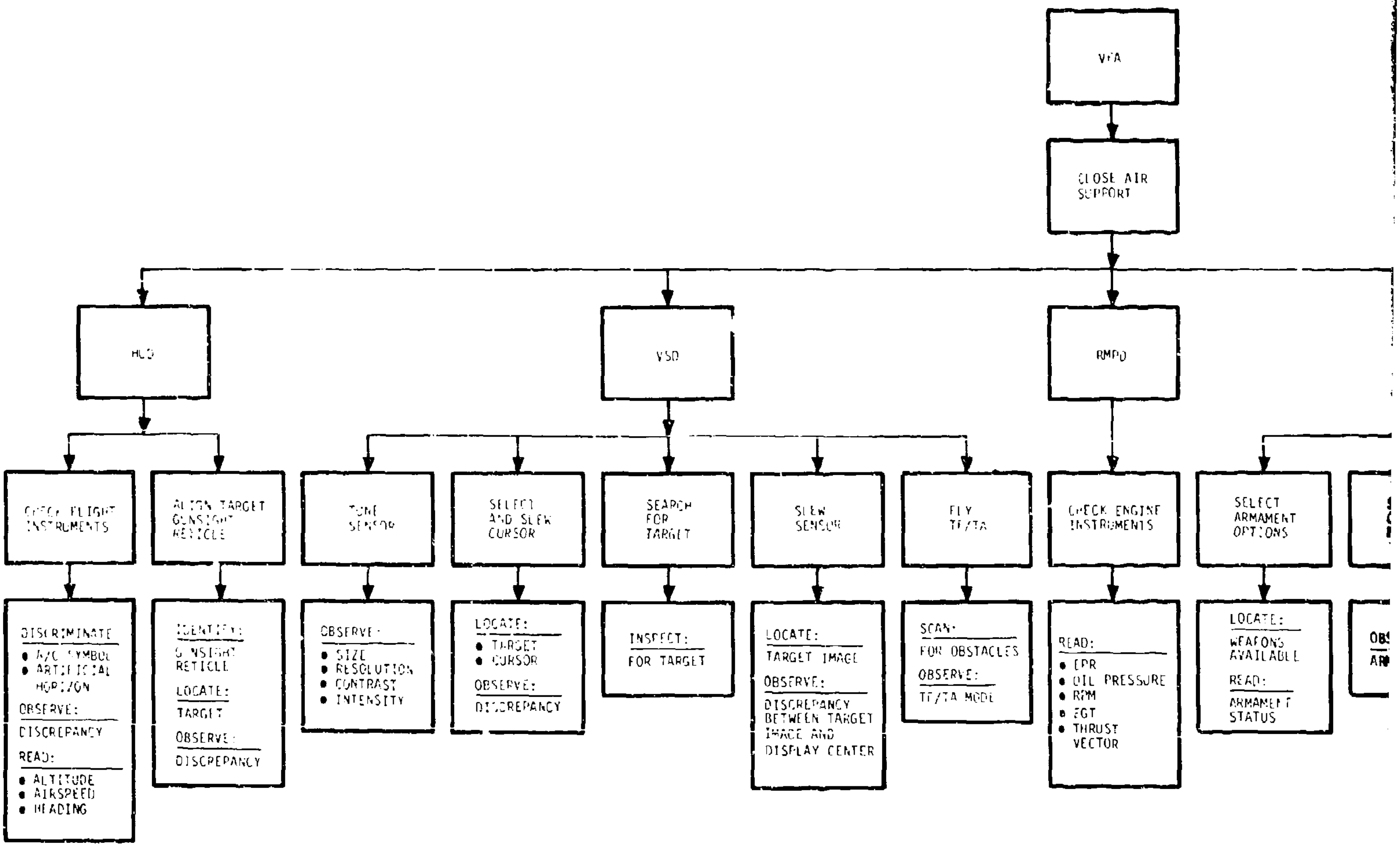
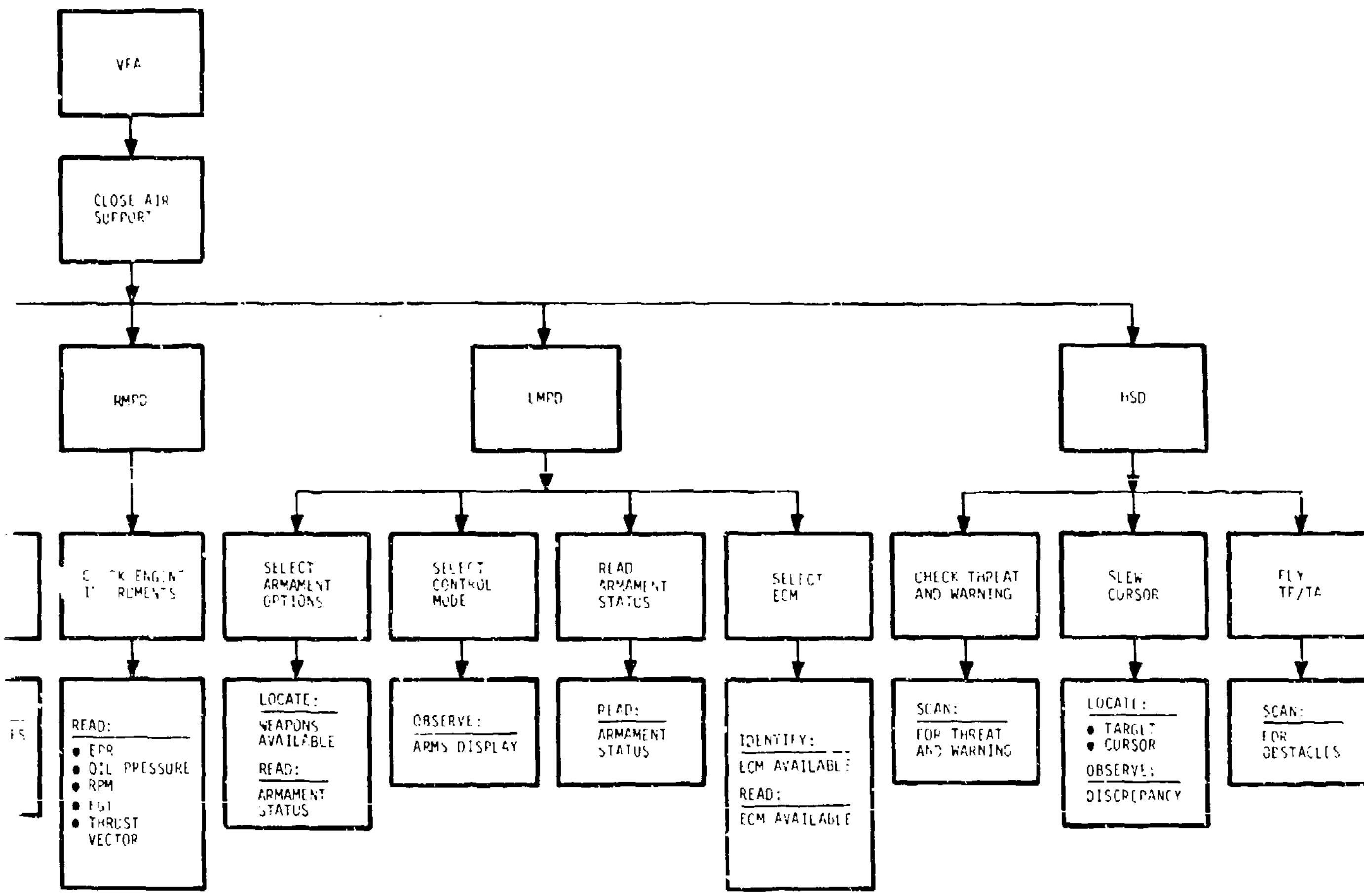


Figure 35. VFA Close Air Support--Display Usage



: Air Support--Display Usage Taxonomy

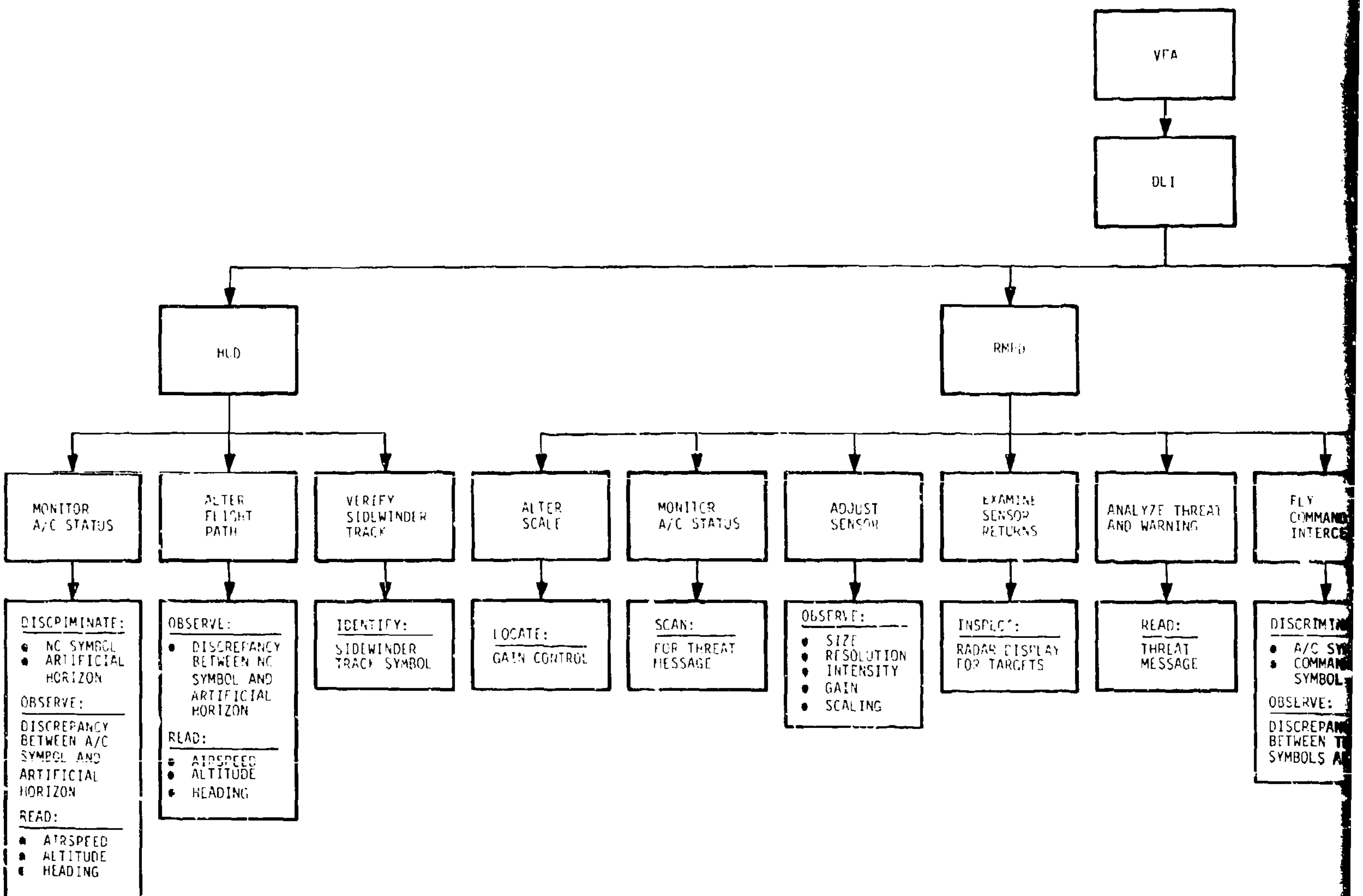
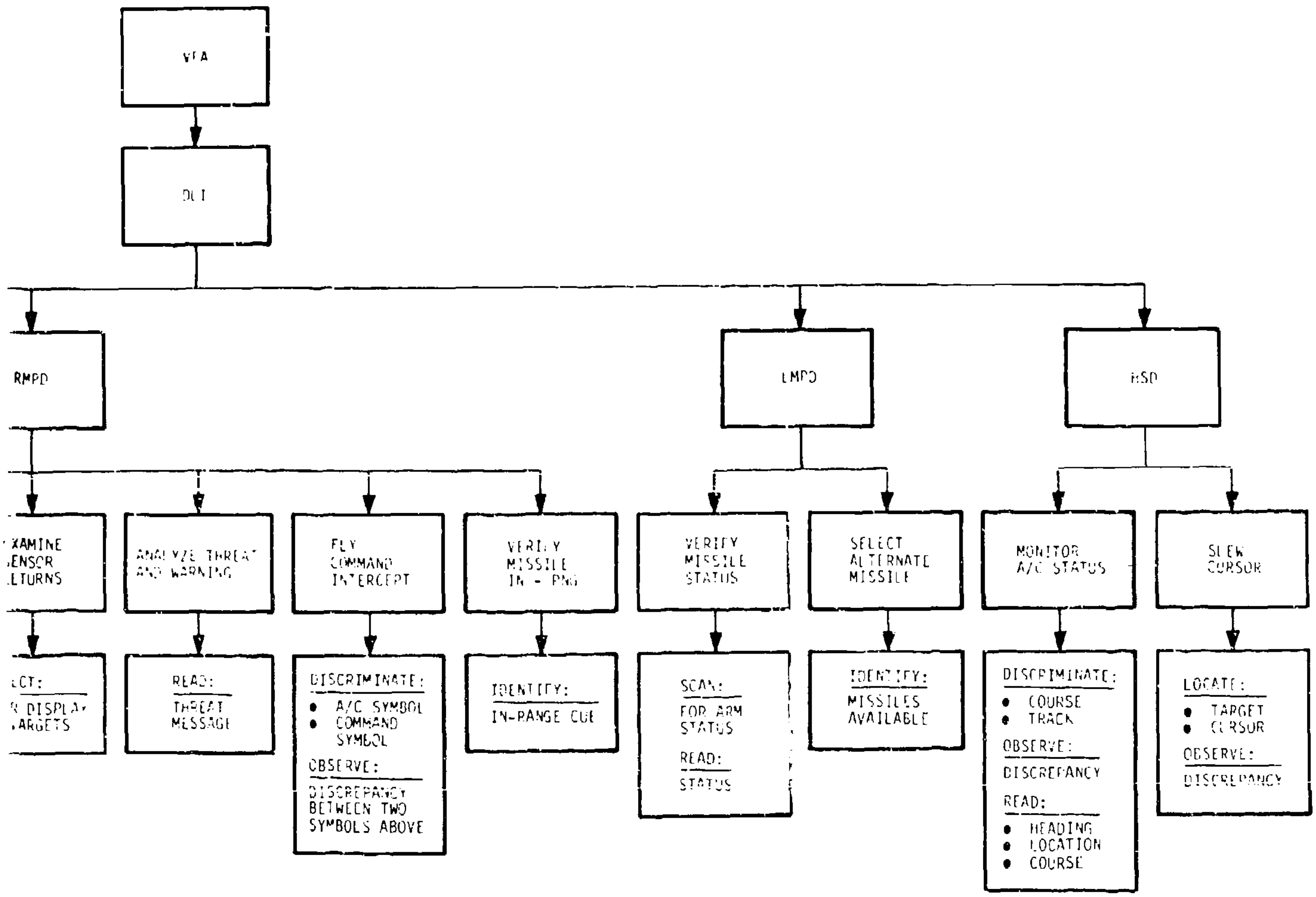


Figure 36. Deck Launched Intercept--Display Us



ched Intercept--Display Usage Taxonomy

Figure 32). The reader is reminded that analysis data for this aircraft were based on an A-7E equipped with a low-light-level television sensor with sensor video presented on the HUD.

Perceptual operations for the F-18 escort ingress segment (Figure 33) are fewer and more evenly spread across displays than is the case during the MRI segment (Figure 34). The F-18 ingress is the only segment analyzed that does not involve some form of target attack. Although the MRI segment lasts three times as long as the ingress segment (190 vs. 60 seconds), the greater number of different piloting tasks during MRI is indicative of higher pilot workload in this segment. A number of features concerning the use of displays in the two segments are evident from the diagrams. In the ingress segment, the pilot's primary tasks are to assure that the aircraft is properly configured to counter an enemy interceptor, to verify passing into hostile territory, to keep watch for enemy threats of different types, and to maintain aircraft control. During the intercept segment the pilot is required to perform essentially the same tasks, in addition to finding, intercepting, and destroying hostile aircraft. From Figure 34 it can be seen that these additional tasks demand that a great deal more information be presented, particularly on the head-up and multifunction displays, than is necessary in the ingress segment. The extra information requirements are a direct result of the additional pilot tasks.

In the ground attack segment of the VFA-V/STOL CAS mission (Figure 35), perceptual operations are distributed across the five electronic displays. In the air attack segment, however, a relatively large number of operations involve use of the RMPD while the VSD is not used at all (see Figure 36).

Comparison of similar mission segments across different aircraft types is also highly informative. For example, the VFA deck-launched intercept taxonomy in Figure 36 represents a mission similar to the F-18 MRI. The VFA DLI differs from the F-18 MRI to the extent that the DLI is purely an intercept mission, the pilot being given certain information concerning the target from a command center. The F-18 MRI pilot, meanwhile, is responsible for finding targets as well as intercepting and destroying them. Given this difference, the missions are largely the same once contact has been made between each aircraft and its target.

In Figures 34 and 36 it can be seen that the RMPD is called upon to provide information for a larger proportion of pilots' tasks in the VFA than is the MFD in the F-18, even though the F-18's MFD generally serves the same purposes as the VFA's RMPD. Judging from the more extensive use of the HUD in the MRI than in the DLI segment, it is reasonable to conclude that in the VFA the RMPD is an essential display and that the mission in this aircraft is flown "head-down," while the F-18 intercept mission relies more on the HUD and is flown more with vision directed outside the cockpit.

DISPLAY USE FREQUENCY

The second part of this analysis involved determining the frequency with which each of the visual perceptual operations is employed on each electronic display and for each of three types of presentations: images of objects (e.g., objects appearing on FLIR, radar); emblematic symbols (e.g., artificial horizon, aircraft symbol); or alphanumerics. With data from a task time line or a crew-task analysis, it was assumed that all the perceptual operations in Level 5 of the taxonomy (within a task in Level 4) occur simultaneously and continuously with that task. Thus if data are available that describe a pilot's tasks in Level 4, the same data apply to the associated perceptual operations in Level 5.

Results of this analysis are summarized in Tables 10 through 14. These tables serve to quantify information schematically illustrated in Figures 32 through 36.

Visual perceptual operations defined earlier appear along the left margin of each table. The form of information attended to by the pilot is indicated for each perceptual operation. Abbreviations used are "obj" (objects appearing in sensor-video imagery or in a direct view of the outside world), "symb" (computer-generated emblematic symbols and line segments), and "A/N" (alphanumerics). Following are definitions of other terms used in Tables 10 through 14:

n1 = Number of pilot tasks involving a particular perceptual operation (e.g., inspect), information form (e.g., object), and display (e.g., HUD).

n2 = Number of tasks involving a particular perceptual operation and display.

n3 = Number of tasks involving a particular display.

N = Total number of tasks involving perceptual operations.

Although rows in these tables are additive, columns are not in many cases since simultaneous perceptual operations are possible. As an example, in Table 10, note the value n1 = 77 for both observe/symbology/HUD and

TABLE 10. A-7 CLOSE AIR SUPPORT, DISPLAY USE FREQUENCY

		HUD	Threat Analyzer	Radar	Row Sum
Inspect	obj	28 (7.7)			28 (7.7)
	symb				
	A/N				
	n2	28 (7.7)			28 (7.7)
Observe	obj	14 (3.9)			14 (3.9)
	symb	77 (21.2)			77 (21.2)
	A/N				
	n2	91 (25.1)			91 (25.1)
Read	obj				
	symb				
	A/N	116 (32.0)			116 (32.0)
	n2	116 (32.0)			116 (32.0)
Scan	obj				
	symb				
	A/N				
	n2				
Discriminate	obj				
	symb	77 (21.2)			77 (21.2)
	A/N				
	n2	77 (21.2)			77 (21.2)
Identify	obj	28 (7.7)			28 (7.7)
	symb	15 (4.1)			15 (4.1)
	A/N				
	n2	43 (11.8)			43 (11.8)
Locate	obj				
	symb		4 (1.1)		4 (1.1)
	A/N				
	n2		4 (1.1)		4 (1.1)
Total	obj	42 (11.6)			42 (11.6)
	symb	78 (21.5)	4 (1.1)		82 (22.6)
	A/N	116 (32.0)			116 (32.0)
	n3	236 (65.0)	4 (1.1)		240 (66.1)

N = 363

n1
* 100(n1/N) = %

TABLE 11. F-18 INGRESS, DISPLAY USE FREQUENCY

		HUD	HSD	MFD	MMD	Threat Analyzer	Row Sum
Inspect	obj						
	symb	2 (5.9)					
	A/N						
	n2	2 (5.9)					
Observe	obj						
	symb		1 (2.9)			2 (5.9)	5 (14.7)
	A/N	2 (5.9)					
	n2	2 (5.9)	1 (2.9)			2 (5.9)	5 (14.7)
Read	obj						
	symb						
	A/N		1 (2.9)		1 (2.9)		4 (11.8)
	n2		1 (2.9)		1 (2.9)		4 (11.8)
Scan	obj			2 (5.9)			2 (5.9)
	symb					1 (2.9)	1 (2.9)
	A/N						
	n2			2 (5.9)		1 (2.9)	3 (8.8)
Discriminate	obj						
	symb	2 (5.9)					2 (5.9)
	A/N						
	n2	2 (5.9)					2 (5.9)
Identify	obj						
	symb	1 (2.9)					1 (2.9)
	A/N						
	n2	1 (2.9)					1 (2.9)
Locate	obj						
	symb		1 (2.9)				1 (2.9)
	A/N			2 (5.9)			2 (5.9)
	n2		1 (2.9)	2 (5.9)			3 (8.8)
Total	obj			2 (5.9)			2 (5.9)
	symb	3 (8.8)	1 (2.9)			3 (8.8)	7 (20.6)
	A/N	2 (5.9)	1 (2.9)	2 (5.9)	1 (2.9)		6 (17.6)
	n1	3 (8.8)	1 (2.9)	4 (11.8)	1 (2.9)	3 (8.8)	12 (35.3)

N = 34

n1
100(n1/N) = %

TABLE 12. F-18 MEDIUM RANGE INTERCEPT, DISPLAY USE FREQUENCY

		HUD	HSD	MFD	MMD	Threat Analyzer	Row Sum
Inspect	obj			14 (7.9)			14 (7.9)
	symb						
	A/N						
	n2			14 (7.9)			14 (7.9)
Observe	obj	1 (0.6)**		1 (0.6)			2 (1.1)
	symb	94 (53.1)		1 (0.6)			95 (53.7)
	A/N						
	n2	95 (53.7)		2 (1.1)			97 (54.8)
Read	obj						
	symb						
	A/N	91 (51.4)	1 (0.6)		1 (0.6)		93 (52.5)
	n2	91 (51.4)	1 (0.6)		1 (0.6)		93 (52.5)
Scan	obj						
	symb						
	A/N						
	n2						
Discriminate	obj						
	symb	94 (53.1)					94 (53.1)
	A/N						
	n2	94 (53.1)					94 (53.1)
Identify	obj			4 (2.3)			4 (2.3)
	symb	4 (2.3)		4 (2.3)			8 (4.5)
	A/N						
	n2	4 (2.3)		8 (4.5)			12 (6.8)
Locate	obj						
	symb					1 (0.6)	1 (0.6)
	A/N						
	n2					1 (0.6)	1 (0.6)
Total	obj	1 (0.6)		20 (11.3)			21 (11.9)
	symb	98 (55.4)		5 (2.8)		1 (0.6)	104 (58.8)
	A/N	91 (51.4)	1 (0.6)		1 (0.6)		93 (52.5)
	n3	99 (55.9)	1 (0.6)	25 (14.1)	1 (0.6)	1 (0.6)	127 (71.8)

N = 177

n1

100(n1/N) = %

TABLE 13. VFA CLOSE AIR SUPPORT, DISPLAY USE FREQUENCY

		HUD	VSD	RMPD	LMPD	HSD	Row Sum
Inspect	obj		5 (3.3)				5 (3.3)
	symb						
	A/N						
	n2		5 (3.3)				5 (3.3)
Observe	obj	3 (2.0)	19 (12.5)				22 (14.5)
	symb	15 (9.9)	9 (5.9)		1 (0.7)	8 (5.3)	33 (21.7)
	A/N						
	n2	15 (9.9)	19 (12.5)		1 (0.7)	8 (5.3)	43 (28.3)
Read	obj						
	symb						
	A/N	12 (7.9)		9 (5.9)	14 (9.2)		35 (23.0)
	n2	12 (7.9)		9 (5.9)	14 (9.2)		35 (23.0)
Scan	obj		3 (2.0)			1 (0.7)	4 (2.6)
	symb					14 (9.2)	14 (9.2)
	A/N						
	n2		3 (2.0)			15 (9.9)	18 (11.8)
Discriminate	obj						
	symb	12 (7.9)					12 (7.9)
	A/N						
	n2	12 (7.9)					12 (7.9)
Identify	obj						
	symb	3 (2.0)			2 (1.3)		5 (3.3)
	A/N						
	n2	3 (2.0)			2 (1.3)		5 (3.3)
Locate	obj	3 (2.0)	14 (9.2)				17 (11.2)
	symb		9 (5.9)		10 (6.6)	8 (5.3)	27 (17.8)
	A/N						
	n2	3 (2.0)	14 (9.2)		10 (6.6)	8 (5.3)	35 (23.0)
Total	obj	3 (2.0)	24 (15.8)			1 (0.7)	28 (18.4)
	symb	15 (9.9)	9 (5.9)		13 (8.6)	22 (14.5)	59 (38.8)
	A/N	12 (7.9)		9 (5.9)	14 (9.2)		35 (23.0)
	n3	15 (9.9)	24 (15.8)	9 (5.9)	15 (9.9)	23 (15.1)	86 (56.6)

N = 152

n1

100 (n1/N) = %

TABLE 14. VFA DECK LAUNCHED INTERCEPT, DISPLAY USE FREQUENCY

		HUD	VSD	RMPD	LMPD	HSD	Row Sum
Inspect	obj			5 (6.1)			5 (6.1)
	symb						
	A/N						
	n2			5 (6.1)			5 (6.1)
Observe	obj			15 (18.3)			15 (18.3)
	symb	9 (11.0)		1 (1.2)		13 (15.9)	23 (28.0)
	A/N						
	n2	9 (11.0)		16 (19.5)		13 (15.9)	38 (46.3)
Read	obj						
	symb						
	A/N	9 (11.0)		1 (1.2)	3 (3.7)	8 (9.8)	21 (25.6)
	n2	9 (11.0)		1 (1.2)	3 (3.7)	8 (9.8)	21 (25.6)
Scan	obj						
	symb				3 (3.7)		3 (3.7)
	A/N			8 (9.8)			8 (9.8)
	n2			8 (9.8)	3 (3.7)		11 (13.4)
Discriminate	obj						
	symb	8 (9.8)		1 (1.2)		8 (9.8)	17 (20.7)
	A/N						
	n2	8 (9.8)		1 (1.2)		8 (9.8)	17 (20.7)
Identify	obj						
	symb	1 (1.2)		2 (2.4)	1 (1.2)		4 (4.9)
	A/N						
	n2	1 (1.2)		2 (2.4)	1 (1.2)		4 (4.9)
Locate	obj						
	symb					5 (6.1)	5 (6.1)
	A/N			1 (1.2)			1 (1.2)
	n2			1 (1.2)		5 (6.1)	6 (7.3)
Total	obj			20 (24.4)			20 (24.4)
	symb	10 (12.2)		3 (3.7)	4 (4.9)	5 (6.1)	22 (26.8)
	A/N	9 (11.0)		10 (12.2)	3 (3.7)	8 (9.8)	30 (36.6)
	n3	10 (12.2)		33 (40.2)	4 (4.9)	13 (15.9)	60 (73.2)

N = 82

n1
100(n1/N) = %

discriminate/symbology/HUD. Seventy-seven tasks involved both observe and discriminate operations on symbolic information presented on the HUD display. This is only one instance of simultaneous perceptual operations in Table 10. Therefore, the value n3 = 236 is not the sum of n2 values in the HUD display column.

The row sum of n3 represents the total number of tasks involving perceptual operations on the A-7's electronic displays. The difference N - (row sum n3) = 363 - 240 = 123 is the number of tasks in the mission segment involving perceptual operations not directed toward the A-7's electronic displays.

All subsequent reference to pilot tasks will be to the N tasks included in this analysis that involved visual perceptual operations.

Analysis results on the A-7 in Table 10 are summarized below.

- The pilot made use of electronic displays during 100 (240/363) = 66.1 percent of the tasks.
- The HUD was used most frequently--on 65 percent of the tasks.
- Perceptual operations on information forms were primarily observe and discriminate symbols (21.2 percent of the tasks) and read alphanumerics (32 percent of the tasks).

The following summarizes results from the two F-18 mission segments analyzed (Tables 11 and 12):

- Electronic displays were used on 35.3 percent of the tasks during the ingress segment and 71.8 percent of the tasks during the MRI segment.

- Most frequently used displays during ingress were MFD (11.8 percent of the tasks), HUD (8.8 percent of the tasks), and threat analyzer (8.8 percent of the tasks).

- During MRI the most frequently used displays were HUD (55.9 percent of the tasks) and MFD (14.1 percent of the tasks).

- During ingress the most frequent perceptual operations on information forms were <u>observe</u> symbols (14.7 percent of the tasks) and <u>read</u> alphanumerics (11.8 percent of the tasks).

- During MRI the most frequent perceptual operations on information forms were <u>observe</u> symbols (53.7 percent of the tasks), <u>discriminate</u> symbols (53.1 percent of the tasks), and <u>read</u> alphanumerics (52.5 percent of the tasks).

- Each of the F-18's five electronic displays was used at least once during both the ingress and MRI segments.

Display use frequency data from the VFA-V/STOL analysis (Tables 13 and 14) are summarized below.

- Electronic displays were used on 56.6 percent of the tasks during the CAS segment and 73.2 percent of the tasks during the DLI segment.

- Most frequently used displays during CAS were the VSD (15.8 percent of the tasks), HSD (15.1 percent of the tasks), LMPD (9.9 percent of the tasks), and HUD (9.9 percent of the tasks).

- During the DLI segment, displays most frequently used were the RMPD (40.2 percent of the tasks), HSD (15.9 percent of the tasks), and the HUD (12.2 percent of the tasks).

- During CAS the most frequent perceptual operations on information forms were read alphanumerics (23 percent of the tasks), observe symbols (21.7 percent of the tasks), locate symbols (17.3 percent of the tasks), observe objects (14.5 percent of the tasks), and locate objects (11.2 percent of the tasks).

- During DLI the most frequent perceptual operations on information forms were observe symbols (28 percent of the tasks), read alphanumerics (25.6 percent of the tasks), discriminate symbols (20.7 percent of the tasks), observe objects (18.3 percent of the tasks), and scan alphanumerics (9.8 percent of the tasks).

- With the exception of the VSD during deck-launched intercept, each electronic display on the VFA was used at least four times during both CAS and DLI segments.

This analysis also highlights other characteristics of the various cockpits, missions and displays. Results indicate that when inspect is a perceptual operation, it is accomplished only on the RMPD or VSD as in the VFA and F-18 missions, or on the HUD when there is no MPD present, as in the A-7. Read or observe operations on the other hand, for most missions, occur on nearly all the displays at some time during the mission. Tables 10 through 14 also indicate that three of the perceptual operations defined earlier were not applied to characterize pilot visual activities. These are detect, receive, and survey. The operations receive and survey are apparently defined in terms too general to describe pilot visual activities typically included in published task analyses. Conversely, the definition of detect was formulated to be more restrictive than traditional definitions of this term in order to obtain a mutually exclusive category clearly distinct from inspect, discriminate, and identify. Our definition would apply to detection of advisory messages, failures, or other contingencies--events of the type not occurring in the scenarios analyzed.

LINK ANALYSIS

The third part of the display usage analysis was a link analysis accomplished by examining a list of operator tasks for a mission segment and determining the order in which the displays are referenced in performing the mission tasks.

A count was made of the number of transitions between any two electronic displays, or between an electronic display and any "other" display/control device, or between a specific electronic display and itself. A link is considered to be the visual transition from one display to another between tasks. Of course, it is possible that the same task may have to be accomplished twice in a row, or the same display may be used several times in succession in accomplishing several different tasks. Either case would be an example of a link between a display and itself. Finally, a proportion of links was computed between each pair of displays relative to the total number of links in a mission segment.

Results of this analysis are presented in Tables 15 through 17. Link analysis results are included only for the A-7 and VFA mission segments. Data on the F-18 were in a form that precluded similar analyses on this aircraft.[44, 45]

TABLE 15. A-7 CLOSE AIR SUPPORT, LINK ANALYSIS

From ↓ / To →	HUD	Threat Analyzer	Radar	Other
HUD	146* (40.3)**	2 (0.6)		87 (24.0)
Threat Analyzer	2 (0.6)			2 (0.6)
Radar				
Other	87 (24.0)	2 (0.6)		34 (9.4)

*Number of links
**Percentage of total links
(total links = 362)

TABLE 16. VFA CLOSE AIR SUPPORT, LINK ANALYSIS

To → / From ↓	HUD	VSD	RMPD	LMPD	HSD	Other
HUD	1 (0.7)**		6 (4.0)		2 (1.3)	6 (4.0)
VSD	2 (1.3)	14 (9.3)		1 (0.7)	1 (0.7)	6 (4.0)
RMPD					8 (5.3)	1 (0.7)
LMPD	1 (0.7)			11 (7.3)		3 (2.0)
HSD		4 (2.6)			6 (4.0)	13 (8.6)
Other	11 (7.3)	6 (4.0)	3 (2.0)	3 (2.0)	6 (4.0)	36 (23.8)

Number of links
Percentage of total links
(total links = 151)

TABLE 17. VFA DECK LAUNCHED INTERCEPT, LINK ANALYSIS

To → / From ↓	HUD	VSD	RMPD	LMPD	HSD	Other
HUD	1 (1.2)**				8 (9.9)	1 (1.2)
VSD						
RMPD	1 (1.2)		20 (24.7)	1 (1.2)	2 (2.5)	8 (9.9)
LMPD			2 (2.5)	1 (1.2)		1 (1.2)
HSD			8 (9.9)	2 (2.5)	3 (3.7)	
Other	8 (9.9)		2 (2.5)			12 (14.8)

*Number of links
**Percentage of total links
(total links = 81)

Links are defined here as transitions of visual attention occurring between tasks or display information elements. Since the link-analysis summary tables indicate number and percentage of transitions between various areas in the pilot's field of view, these data provide basic information on dynamics of visual activity associated with performance of mission tasks. Links of the following types are included:

- Between information elements on the same electronic display
- Between electronic displays
- Between electronic displays and "other" areas of visual attention (e.g., from HUD to an electromechanical indicator or switch)
- Between areas of visual attention not involving electronic displays (e.g., from one switch to another)

In the A-7 CAS mission, Table 15 shows that 40.3 percent of the links are between information elements on the HUD and that 24 percent are from some "other" (nonelectronic display) source to the HUD. Combined with the 0.6 percent of links from threat analyzer to HUD, these figures suggest that about 65 percent of the tasks were performed using the HUD. This proportion is consistent with the value n3 = 0.65, shown in Table 10 for the HUD. Another way of interpreting these figures is to characterize the percentage values as transition probabilities. If the pilot is accomplishing a task by reference to the HUD, the probability that he used the HUD on the previous task is about 0.40, and the probability that he will use this display on the next task is the same. The probability that he will next use the HUD, regardless of the display presently in use, is 0.65.

These values for the A-7 CAS are in sharp contrast to the corresponding values for the VFA-CAS mission. For the VFA-CAS, it can be seen from Table 18 that the probability of the next task being accomplished on the HUD (assuming that the present task employs the HUD) is 0.007. The probability that the next task is accomplished on the HUD, regardless of the present task and display being employed, is only 0.01. It is of course true that the VFA has several electronic displays to employ in presenting the same information that the A-7 must present on the HUD.

Links between information elements on the same display tend to be concentrated on the VSD during the VFA CAS segment and on the RMPD during the DLI segment.

Since the A-7 contains only one multipurpose electronic display (the HUD) while the VFA - V/STOL contains five, a substantially greater number of links to other points of attention could be anticipated in the A-7. This is not the case, at least in the mission segments analyzed here. Links to other points of attention account for 34, 43, and 27 percent of all links during the A-7 CAS, VFA CAS, and VFA DLI segments, respectively.

CONCLUSIONS OF DISPLAY USAGE ANALYSIS

The following conclusions of the display usage analysis are considered most relevant to the application of color as a coding dimension on aircraft electronic displays. Although these conclusions are stated in general terms, it is emphasized that they are based on analysis of a limited sample of aircraft types and mission segments.

- For a given aircraft, the variety and form of information and perceptual operations performed on this information can vary substantially with mission segment (e.g., F-18; ingress and MRI segments).

- Presentation of sensor imagery can be on either a head-up (combiner) or panel display. Displays depicting sensor imagery or direct-view scene are typically the most frequently used electronic displays (e.g., A-7's HUD; F-18's HUD and MFD; VFA's HUD, VSD, and RMPD).

- Perceptual operations on information forms most common during pilot tasks involving electronic displays are: observe symbols; read alphanumerics; discriminate symbols; observe objects; locate symbols; locate objects; scan alphanumerics.

- Advisory messages, failures, and other contingencies did not occur in scenarios analyzed. Had such events been included, the following perceptual operations on information forms would become important because of their critical nature: detect alphanumerics, detect symbols.

- In general the various perceptual operations on information forms are distributed across multifunction displays with no consistent trend toward particular operations being performed on specific displays.

- Visual transitions between information elements on the same display are as common, and in some instances more common, than transitions between electronic displays.

- Primary displays (those used most frequently) can be either head-up or panel-mounted. The display most frequently used is a function of aircraft type, information assigned to a particular display, and information requirements imposed by a particular mission.

- Although each electronic display is obviously a critical display when needed and viewed foveally when in use, in the general case a particular display should also be considered as a device viewed peripherally most of the time.

The last conclusion listed above is an important qualifier of other conclusions drawn from the analysis of display usage. Of the 13 electronic displays included in this analysis of mission segments involving relatively high perceptual-information workload, only two displays were used during more than half of the pilot's tasks. The A-7 HUD had maximum use, in 65 percent of the tasks during the CAS mission segment.

Only tasks having visual perceptual components were included in the analysis (e.g., voice communication tasks were excluded). Of the 808 tasks included, fully 35 percent did not use any of the 13 electronic displays.

SECTION VII

EVALUATION OF TRADEOFFS IN COLOR APPLICATION

Based on background information and analyses in the two preceding sections, general principles of display color coding developed in Part I are applied in this section to the coding of electronic displays on fighter/attack aircraft. Design and operational factors relevant to this area of application are evaluated to identify recommended coding schemes and practical constraints on use of color coding. Specific recommendations are summarized in Section VIII.

EVALUATION FRAMEWORK

Consider the designer contemplating use of multicolor displays, either in retrofit to an existing avionic system or as components of a new system under development. A useful evaluation scheme should provide this designer with a systematic means for answering the following questions:

- What factors should influence decisions concerning color coding of display information?
- What are the recommended guidelines for application of color coding associated with these factors?

Design and operational factors to consider in color coding aircraft displays were identified from a review of findings in Part I of this report and the preceding Sections V and VI. Factors identified are listed below in five categories. These categories introduce an increasing number of factors to consider as the system/operational problem addressed by the designer becomes defined in greater detail.

1. <u>Prescribed Requirements</u>
   - Applicable standards
2. <u>Natural Environment</u>
   - Ambient lighting
   - Vibration
3. <u>System Concept</u>
   - Display layout
   - Color generation capability
   - Combiner or panel display
   - Failure backup availability
   - Display when needed
4. <u>Information Content</u>
   - Primary functions
   - Secondary functions
5. <u>Mission Operations</u>
   - Mix of information forms
   - Perceptual operations required
   - Display use frequency
   - Mission modes
   - Pilot workload

Implications of the above factors on display color coding are discussed below. Designers should review the following information, in the context of their specific application, to aid in evaluating relative merits of alternative color coding schemes. These coding schemes are summarized in Section VIII.

Prescribed Requirements

Applicable Standards --Military standard MIL-STD-1472B prescribes color codes for transilluminated displays such as indicator and legend lights. Although the current standard for electronic flight displays (MIL-STD-884B) does not prescribe color codes, future standards for electronic displays are likely to include codes similar to those for indicator and legend lights.

Standardized codes for increasingly higher priority information are yellow, red, and flashing red. These indicate cautionary, danger or failure, and emergency conditions, respectively. Other colors including green, white, and blue are specified for coding less critical information such as in-tolerance or nominal system status and advisory information. Of these colors, green is preferable as a nonalerting color to contrast with red and yellow. White is more easily confused with yellow, and blue produces poorer legibility of alphanumerics than either green or white.

Compliance with future color codes for aircraft electronic displays will be mandatory where applicable. Continued use of red and yellow codes with their present standardized meanings is most probable. As concluded in Part I of this design guide, green is the recommended additional color for other display information in a basic three-color code. Green provides good legibility of lower-priority information while maintaining the attention-getting value of red and yellow.

Natural Environment

Ambient Lighting--Information on electronic displays in fighter/attack aircraft must be clearly legible, and chromatic contrasts clearly discernible under the full range of natural illumination conditions. Under low ambient conditions, acceptable luminance and chromatic contrasts must be maintained while minimizing interference with visual dark adaptation.

Recommendations are provided in Part I for luminance contrast ratio, chromatic contrast (defined in terms of perceptibly different colors), minimum luminance for color perception, character size and resolution, and stroke width. These recommendations can most readily be applied to conditions of low or moderate ambient lighting.

As ambient illumination approaches levels experienced in direct sunlight, color saturation and luminance contrast on electronic displays tend to degrade. Extent of degradation varies with display medium as well as spectral transmittance of filter media in ambient-to-display and display-to-eye light paths. In system development programs these effects should be measured for specific media under consideration to verify that luminance and chromatic contrasts do not degrade below acceptable levels.

Under low ambient conditions, use of display colors other than red does not have an appreciable effect on visual dark adaptation. Advantages of dark adaptation from red are relatively small and can be easily lost at minimum levels of display illumination required for good legibility.[22]

Vibration--Visual acuity can be reduced by aircraft vibrations conducted to the crew member's eyes.[22] Since adverse effects of vibration are a complex function of vibration frequency and amplitude as well as seat and restraint design, the most practical approach is to experimentally evaluate these effects for the specific vibration environment of a system under development. The possibility of vibration causing degraded display legibility is greatest if legibility is already marginal under static viewing conditions due, for example, to use of minimal-sized blue characters viewed with high ambient lighting.

In general, adverse effects of both high ambient lighting and vibration can be reduced by avoiding use of the color blue on alphanumerics or symbols whose shape code conveys most of the character's information.

System Concept

Display Layout--All the panel-mounted electronic displays in aircraft and concepts discussed in Section V are located on the forward instrument panel within approximately 20 to 25 degrees of nominal line of sight. Layouts of primary flight displays (HUD, VSD, and HSD) and other multifunction displays (MPD, MFD, SAD, etc.) conform to formal standards for layout of electromechanical indicators, or informal standards that appear to be evolving for advanced concepts such as AIDS. However, design constraints on cockpits of future fighter/attack aircraft may dictate substantial changes in display layout to accommodate smaller front panels and reclined seat positions. Examples include relocation of MPDs to lower center console or side console--locations that are both nonconventional and more peripheral. Also, in concepts where displays serve as failure backups to each other, recovery from a failure is equivalent to revising the display (information) layout. In a display failure mode, primary information normally presented in a central location may have to be displayed more peripherally.

Red and yellow in the three-color code described above are cues that high-priority information is being displayed. The fact that peripheral color sensitivity of the eye is greatest for white, yellow, and blue suggests that a different scheme may be more suited to coding priority information on peripherally located displays. Differential coding in this manner is definitely not recommended. Accepted and standardized meanings of red and yellow dictate use of these colors to code priority information on all displays regardless of their panel location. Consistency in application of coding rules is also a well-accepted human engineering practice to minimize confusion and response delay under high work load conditions.

Where peripheral detectability of priority color coded messages is in question, use of a centrally located master annunciator is recommended to cue the pilot that priority information is being presented elsewhere. Color of this indicator should be consistent with the highest priority information being displayed (i.e., red or yellow). Both the central annunciator and associated display information would be coded flashing red in the event of an emergency condition.

Color Generation Capability--System designers may in some instances be required to use electronic displays with a mix of different color generation capabilities. Certain displays may have only achromatic, single color, or two-color capability. This constraint can develop in retrofit situations, or because of cost, computational, space, or other design limitations.

Tradeoffs concerning use of achromatic (black and white) displays and various common colors of monochromatic displays are summarized below.

- Achromatic--good character legibility but white-level symbols and alphanumerics would reduce attention-getting value of yellow
- Monochromatic red or yellow--not recommended because of conflict with standardized use of these colors on multi-color displays
- Monochromatic green--recommended since green is predominant color in previously described three-color code for multi-color displays
- Monochromatic blue--good peripheral visibility but character legibility is poorer than with other colors

Legibility of blue is improved as this color is desaturated toward white. The extent to which blue can be desaturated for improved legibility without introducing problems of discriminability between white and yellow is not known.

Regardless of which colors are chosen for single and two-color displays, the benefits of having unique colors to denote both caution and warning (yellow and red) cannot be realized. If use of one or more displays with limited color capability is required, the most practical solution may be to selectively assign information requiring yellow and red coding only to displays that have at least three-color capability.

Combiner or Panel Display--Background luminance and color on a panel display can be controlled to a large extent by the designer. On a combiner display (HUD and HMD), background luminance and color are primarily a function of the operating environment. The unique feature of a combiner display is that uncontrolled luminance and chromatic characteristics of the real-world background become part of the image seen on a HUD or HMD.

One difficulty that may be anticipated with multicolor combiner displays is maintenance of chromatic contrast between yellow symbology or alphanumerics and real-world backgrounds such as snow or sand. Other examples of minimal chromatic contrast are green and blue display information viewed against grass-covered areas and clear sky.

High levels of chromatic contrast between many common display colors and natural backgrounds cannot be anticipated under daytime conditions. Careful selection of spectral transmittance and luminance contrast characteristics is therefore necessary to insure good visibility of all information on multicolor combiner displays viewed against natural backgrounds.

Failure Backup Availability--Advanced display system concepts such as AIDS have a sufficient number of displays to allow each to have at least one backup in the event of a display failure (see Section V, Table 9). If one display serves as a backup to another, problems in color coding may arise from differences in color-generation capability (discussed above) or the need to combine dissimilar information from two displays onto one. Use of color to visually group related information was suggested in Part I and has potential application to backup-display coding in a failure mode. This application would benefit from use of colors in addition to the recommended three-color code to visually separate functionally different types of information on a single display (e.g., flight systems versus stores management information).

Blue is conditionally recommended for this purpose since it provides good contrast with green, yellow, and red in the three-color code. If alphanumerics in the recoded information are of a size for which blue coding may create legibility problems, viable alternatives to blue are desaturated orange or desaturated green. The latter would provide the least chromatic contrast with other more-highly saturated green information. However, color discriminability for this application is not considered as critical as the information prioritizing function served by the green-yellow-red code. Desaturated orange is less likely to interfere with the attention-getting value of yellow and red than a more highly saturated orange color.

Additional applications of desaturated orange are discussed below. This color is brown in appearance and, in Munsell terms, has a hue of 7.5 YR and chroma of /4. Chromaticity coordinates in the CIE system range between ($x = 0.47$, $y = 0.37$) and $x = 0.37$, $y = 0.36$) for Munsell brightness values between 2/ and 8/. The color is attainable on a display device having the capability for additive mixture of red, green, and blue colors at CIE-standard wavelengths of approximately 700, 546, and 436 nm, respectively. Although this can be approximated on conventional three-gun CRT displays over a range of luminance levels, similar capabilities of other display media were not determined in this study.

Display When Needed--The display-when-needed philosophy is becoming increasingly necessary in advanced systems to avoid excessive display information density or clutter. Certain critical system and mission events (e.g., failures and threats) do not occur with sufficient frequency in the time span of a mission to justify committing display space on a continuous basis. When these events do occur, and related warning and advisory information is presented, quick pilot detection and response is required.

Discussions of preceding factors have emphasized the need to apply red and yellow colors only to the coding of high-priority information, and to avoid use of other colors that may detract from the attention-getting value of these priority codes. Use of a centrally-located master annunciator was recommended to draw attention to appearance of priority information on a display. Since these concepts are intended to minimize pilot detection and response delays, they should be an effective means for improving pilot performance in systems using the display-when-needed philosophy.

Information Content

Primary Functions--Examples of primary functions of a display are to present flight control, weapon delivery, stores management, or sensor information. The list of primary functions in Table 9, Section V, indicates types of mission-related information that may be presented on AIDS displays. For the most part, primary functions of the same displays in current aircraft are similar where the respective displays are included. Each display contains a subset of mission information that may be similar to, or totally different from, information assigned to another display.

Red and yellow priority coding applies to much of the display information content associated with these primary functions. Assume for purposes of discussion that only the basic green-yellow-red code is used on all displays. Under nominal mission-operational conditions, all display information associated with primary functions in Table 9 would be coded green. Following are examples of events that could cause yellow or red information to appear, either as newly displayed information (display when needed) or due to change in value of previously displayed information.

- Flight control function
  - --High angle of attack
  - --Pullup command during terrain following
- Weapon delivery
  - --Airspeed, dive angle, or acceleration limits
  - --Pullup command during delivery dive
- Engine status
  - --Low oil quantity or pressure
  - --Fuel main or boost pump failure
- System status
  - --Abnormal hydraulic pressure
  - --Speed brake failure to retract
- Stores management
  - --Failure of stores to release
  - --Asymmetric load limits

- Tactical situation

  --Known enemy air defense locations

- Threat analysis

  --Threat bearing, range, and type

Color illustrations applying yellow and red codes to some of the above information are presented in the next section. Effectiveness of the use of yellow and red codes for the above types of information is derived from the same principles that justify use of advisory, caution, and warning lights on conventional instrument panels. However, on conventional panels, illumination of a light typically cues the pilot that information is being presented on an adjacent instrument or indicator. On multicolor electronic displays the priority coding is applied directly to the display information itself.

Decisions concerning specific information parameters or variables to the priority coded, and priority-code levels to be assigned to specific system/ operational states, must be resolved during system development. For instance, the numeric values of oil pressure associated with normal (green), cautionary (yellow), or dangerous (red) states will vary with the engine used. Asymmetric stores load information may justify priority coding only under certain conditions (e.g., landing approach with degraded flight control system or damaged control surfaces). Coding of threat information could vary between green and flashing red depending on type, bearing, and range of threat, as well as countermeasures and performance capability of the fighter/attack weapon system being developed.

If a difficult operational situation develops and multiple out-of-tolerance conditions occur, sudden appearance of numerous yellow and red display elements could further confuse the situation. The following approaches are recommended to alleviate this potential problem:

- Formulation and use of prioritization algorithms that limit the number of display-element color changes to only the two or three of highest priority.
- Limited application of yellow and red coding to only caution or warning messages, and to display elements representing variables not under continuous pilot control (e.g., engine-status and threat information).

A potential application in addition to priority coding is the use of color to distinguish between basic functional groupings such as flight control, weapon delivery, and navigation information. General application of color for this purpose is not recommended. The number of functional groupings is potentially very large. Implicit in this fact is the need for a large number of colors (other than red or yellow) to code different functional groupings of information. Most of these groupings also tend to share common information forms: namely, alphanumerics and symbols. If, for example, flight control information on the HUD format shown earlier in Figure 29 were coded one color and the weapon delivery information another, colors of range and range-rates tapes would differ from colors of speed and heading tapes. Switching to a landing-mode format (see Figure 30) would produce a change in colors appearing on the display as well as where various colors appear on the display.

Although formulation of coding rules related to all functional groupings of information would be difficult to define, limited use of color coding to distinguish certain functional groupings from all others is more practical. Coding applications of this type are considered in the following two subsections.

Secondary Functions--If a display system concept is configured such that each display has at least one backup with equivalent color generation capability, color coding could aid in separating unrelated functional groupings on the backup display.

Assume, for example, that at some point in a mission, stores management and engine status are presented on LSAD and RSAD, respectively (see Table 9). If the LSAD fails, the RSAD must serve its primary and secondary functions by presenting both sets of information. Since display failures are relatively rare events, pilot confusion that may otherwise result from the "new" RSAD combined format could be reduced by applying different color codes to the two sets of information. An effective approach would be to always apply the same color on all displays to denote secondary-function information so the pilot can easily identify the functional grouping displaced from a failed display.

Green is the recommended predominant color for display primary-function information. Color alternatives recommended for secondary-function information were described in the subsection on Failure Backup Availability. Options include blue (if legibility is not a problem), desaturated green, and desaturated orange.

Mission Operations

Mix of Information Forms--Information forms displayed in the AIDS concept are listed in Table 9. Under some mission conditions as many as four information forms may be presented simultaneously. For example, during an enroute mission phase an HSD could reasonably depict a composite of alphanumerics (range and bearing to next waypoint), symbols (route, waypoints, and compass), sensor video (weather radar returns), and a projected map.

More typical is the combination of only alphanumerics and symbols. These two information forms constit the formatted portions of electronic display presentations. The pilot must be able to quickly scan an array of dynamic displays, (see Part I, Figure 21), and selectively attend to specific alphanumeric and symbolic elements needed for system management or control. This is especially true under high work load conditions such as the weapon delivery segments analyzed in Section VI. Figures 35 and 36 indicate the variety of display usage during the brief segments of VFA-V/STOL missions analyzed.

Fewer electronic displays are involved during similar missions segments with less advanced aircraft (see Figure 32), but comparable perceptual demands can also occur within the confines of a single display. Under high work load conditions, quick glances at display elements must frequently suffice to obtain desired information (e.g., deviations from command mach or closing rate shown in Figure 29). While attending to flight path commands

(⊥ and ⊤⊤ symbols in Figure 29), the pilot should be able to peripherally monitor other command deviations on the same display. Importance of such perceptual demands is apparent from Table 15, where 40 percent of the visual attention transitions analyzed during the A-7 segment were found to be between information elements on the same display.

Assume again the green-yellow-red code as a baseline. Under nominal system/operational conditions all alphanumerics and symbols would be green. This may degrade the pilot's ability to selectively attend to information elements during brief glances. Limited use of blue is recommended to perceptually separate related or adjacent symbolic elements that may otherwise be confused in a monochromatic presentation.

Examples of symbols for which blue coding could be beneficial are the command symbols (>) located on HUD and VSD formats in Figures 21 and 27 through 30. Primary information content of such symbols is associated with their displayed position rather than shape code. For this reason, the generally reduced legibility produced by blue should not cause a problem in most similar applications.

The preceding discussion has addressed information forms that constitute the formatted portion of an electronic display image. Other information forms are direct view of outside world, sensor video, and projected maps. These forms tend to have higher information density (information content per unit display area), and are typically superimposed on formatted information to produce a composite image.

Colors in real-world backgrounds viewed through HUD and HMD combiners are influenced primarily by spectral transmission of coatings applied to combiner surfaces. With monochromatic displays, coatings are designed to reflect a narrow band of wavelengths corresponding to the projected image color. This produces maximum projected-image brightness, and has only minimal affect on natural colors and luminance of outside scenes. Coating design becomes a more complex problem with multicolor displays. The combiner must effectively reflect all colors of the projected display image. Resulting reduction in transmission of similar colors from the outside scene may distort scene colors and reduce brightness of real-world objects (e.g., flares and landing lights). Thus, combiner spectral transmission and reflection are important design variables that must be considered during development of a multicolor HUD or HMD.

Projected maps and sensor video images are the two remaining high-density information forms. These forms frequently have symbolic or alphanumeric information superimposed or adjacently presented in a composite display image. Applying the basic three-color code to the VSD in Figure 21, for example, all computer-generated and sensor video information would be green with various elements separated only by contrasting luminances and shape codes. The desaturated orange color previously described under Failure Backup Availability is recommended for coding map and sensor images to improve separation and visibility of other superimposed information. Desaturated green is a possible alternative but would provide less chromatic contrast. Blue is not recommended in this application because perception of high-resolution map and sensor information would be degraded.

Projected maps used with tactical displays may have an established color code already applied to distinguish between map detail features. If revision of map color coding is not a design option, this constraint should be considered in selecting colors for superimposed computer-generated symbology and alphanumerics.

Perceptual Operations Required--The display usage analysis in Section VI indicated that perceptual operations defined as observe, read, discriminate, locate, and scan were most common in the relatively high-workload mission segments analyzed. The perceptual operation, detect, would also be a critical but not frequently occurring visual activity. (Detect is defined in Section VI to include perception of information not previously present or actively sought; examples are detection of advisory messages, failures, and other contingency events).

Many of the color-coding principles developed in Part I are applicable here since the basic concern is with perception of colored stimuli. Guidelines from Part I have been discussed with regard to other design/operational factors throughout most of this section. Elements of a coding scheme consisting of three basic colors (red, yellow, and green), with optional additional colors for information grouping and separation (blue, desaturated orange, and desaturated green) have been recommended for use on aircraft electronic displays. The following paragraphs review this coding scheme in the context of perceptual operations commonly required in fighter/attack aircraft.

Two commonly required perceptual operations (observe and read) would be influenced primarily by the legibility of displayed information. The predominant color of alphanumerics and symbols in the recommended code is green. While this color rates better than blue in terms of its effect on character legibility, other colors including white, yellow, and red yield better legibility. A compromise is apparent since the predominant color representing nominal system/operational states produces somewhat poorer legibility, but the colors representing priority or critical states (yellow and red) produce improved legibility. These differences also lend support to the use of a color such as low-saturation orange (brown) to code sensor and map information. This color is spectrally most similar to red, yellow, and white; but because of its low saturation it is not likely to be confused with yellow or red.

Three other common perceptual operations (scan, discriminate, and locate) are concerned primarily with distinguishing one display information element from another. These elements are typically symbols or alphanumeric messages. The basic three-color code aids in distinguishing between these elements only when elements represent different levels of priority or criticality. Under nominal mission-operational conditions, all symbols and alphanumerics would be green.

Limited use of blue rather than green coding on selected symbolic elements provides a means for facilitating the three perceptual operations above. In event of a display failure, scan and locate operations could be facilitated by coding functional groupings of information on a backup display with blue, desaturated orange, or desaturated green. Some discriminate operations involve distinction of symbols and alphanumerics superimposed on maps or sensor video. In these instances, use of desaturated orange to code the high density information forms provides a chromatic contrast to aid discrimination of superimposed green elements.

The perceptual operation, detect, is the remaining operation discussed in Section VI that warrants evaluation here. The process of "detecting," as defined in this report, can only occur with a preceding change in some system or operational state (e.g., appearance of a threat warning or oil pressure warning message).

Detect operations are more likely to involve peripheral vision since information associated with a state change may not appear in the vicinity of instantaneous line of sight. Since state changes are also likely to be associated with priority information, peripheral visual sensitivity to yellow and red is a relevant consideration. Peripheral perception of color in the horizontal plane extends to about $\pm$ 60 degrees for yellow and about $\pm$ 30 degrees for red. The more limited peripheral sensitivity to red should be sufficient for peripheral detection of color if a centrally located master warning or cueing display is used.

For scan operations, peripheral limits of color perception are of less relevance. Under the reasonable assumption that a pilot knows which display to observe in order to obtain the information desired, total subtended angle of the area to be searched would be less than 20 degrees for an 18 cm diagonal display viewed at a distance of 50 cm. Data in Part I indicate that chromatic contrast contributes to substantially reduced search time on tasks involving location of targets in unformatted images. Improved performance can therefore be expected in scan operations requiring location of objects in sensor video or map images if the desired target object(s) can be color coded. If pattern recognition or multiple-sensor techniques are available for automatic classification of potential targets in sensor video, targets should be highlighted by a contrasting color to facilitate their location. Similar coding of selected objects on map presentations would be possible in a system having a computer-generated rather than projected map capability.

Yellow or red coding should be applied as contrasting colors if objects are classified as priority information (e.g., known or suspected threats). Coding of non-priority objects can be accomplished with other colors included in the recommended coding scheme. If symbols are drawn around non-priority objects to denote their presence, blue symbols would be adequate on unformatted images of either green or desaturated orange color. If areas of uniform color are placed over non-priority objects, use of green highlighting is recommended on desaturated orange images and desaturated orange highlighting on green images.

Display Use Frequency--Analyses in Section VI indicated that display use frequency varies with aircraft, information assigned to displays, and mission information requirements. A substantial percentage of visual tasks analyzed (35 percent) did not involve use of any electronic display.

Generally, display use frequency should not be a primary consideration in color coding. Recommendations made previously under Display Layout also apply here. Application of different codes, depending on display use frequency, would violate a fundamental requirement for consistency in application of a selected coding scheme to all displays.

Mission analyses for a system under development may indicate that one or more electronic displays are used only infrequently during certain missions. If this is the case, a centrally located master annunciator would become increasingly important to cue the pilot to priority information appearing on these displays.

Mission Modes--In addition to their multi-function capabilities, advanced aircraft electronic displays have multiple modes with information content and format tailored to meet varying mission-phase information requirements. Examples of HUD formats for various modes were previously illustrated in Figures 27 through 30. The number of modes and extent of format change between modes may vary with aircraft, mission, and generic display type (e.g., HUD vs. SAD).

The recommendation for consistency in applying a selected color coding scheme to all displays also applies to all modes of a given display. During the course of system development, a designer can initially select a coding scheme based on factors discussed earlier in this section. As system definition progresses and specific display formats for various mission phases are defined, each format must be colored according to the selected coding rules. The selected coding scheme should be frequently evaluated during this process to determine if revisions in coding rules are required to gain increased benefit from color as a coding dimension.

Assume, for example, a case where the designer initially selects a three-color code (green, yellow, and red) as sufficient based on preliminary definition of display formats. More detailed information analysis subsequently indicates that additional command symbols will be required on a HUD weapon delivery format and missile launch envelope symbology will have to be overlayed on VSD sensor imagery. These format changes suggest that consideration be given to use of additional display colors. Possible options are 1) blue coding of all command symbols on the HUD to perceptually separate these symbols from other non-command elements, and 2) desaturated orange coding of VSD sensor imagery to provide a contrasting color background for overlayed symbology. If the designer elects to use these colors for the purposes indicated, the revised five-color code should be applied to similar information on all formats.

Predominant colors appearing on a display may change during an operational mission with progression from one mission phase to the next, or in response to system/environmental contingency events. In the above example, blue and desaturated orange colors would not appear unless information of the type associated with these colors is displayed. Yellow and red colors applied as recommended in this report would not appear unless priority information justifying use of these colors is presented.

Pilot Workload--The display usage analyses in Section VI encompassed tactical mission segments imposing relatively high workload demands on the pilot. Under conditions of high workload, maximum efficiency in transfer of display information to the pilot is essential. Quick detection of threats, critical system failures, and other types of priority information are essential regardless of pilot workload level.

Color coding schemes developed in this section represent just one approach to potentially improving speed and efficiency of display information transfer. Other more traditional techniques include use of indicator lights, buzzers, and flash coding as well as careful attention to display layout, information assignment, and formatting. Display color coding should be viewed as a supplement to these other approaches for reducing perceptual workload or improving pilot-system performance.

All the above techniques including display color coding are of greatest potential benefit in helping to achieve prescribed system performance capabilities under peak workload conditions and in event of system degradation or failure. These conditions and operating modes, as defined for a particular system under development, should therefore be the primary basis for deciding which color coding scheme will be most useful.

The basic three-color code (green, yellow, and red) may be sufficient in systems where pilot workload is not excessive. If peak workload levels are high, use of additional color codes described earlier under Mix of Information Forms is recommended.

SECTION VIII

SUMMARY OF CODING RECOMMENDATIONS WITH SAMPLE APPLICATIONS

The objective of Part II of this design guide has been to extrapolate principles developed in Part I to color coding of electronic displays in fighter/attack aircraft. Design and operational factors relevant to this area of application were evaluated in the preceding section to identify recommended coding schemes and practical constraints on the use of color coding. The purpose of this section is to summarize these recommendations. Examples of coding schemes applied to representative display formats are provided.

RECOMMENDED DISPLAY COLOR CODES

Recommended display colors and their associated functions are summarized as follows:

- Green--The recommended predominant color for all display information not assigned one of the other codes listed below.
- Yellow--Recommended for moderate priority or cautionary information, consistent with standardized usage of this color.
- Red--Recommended for higher priority information representing danger or threat conditions, also consistent with standardized usage of this color. (A third level of information priority coding can be obtained through use of flashing red for emergency or highest priority information.)

- Blue--Recommended as an alternative to green on selected symbols to perceptually separate related or adjacent symbolic elements that may otherwise be confused. Since blue contributes to reduced legibility, blue coding should generally be limited to symbols whose primary information content is derived from symbol position rather than shape code (e.g., command or tracking symbols rather than alphanumerics).

- Desaturated Orange--Recommended as an alternative to green for coding of sensor imagery or computer-generated map information. This color provides a chromatic contrast with overlayed or adjacent symbology. An optional use of desaturated orange is to code information transferred from a failed display to aid in distinguishing this information from information normally on the backup display.

- Desaturated Green--Recommended as an alternative to desaturated orange for purposes indicated above. Provides less contrast with more highly saturated green elements, but generally improved contrast with yellow and red elements.

ALTERNATIVE CODING SCHEMES

Two basic alternatives are recommended, with various options available for the second alternative.

The least complex is a three-color coding scheme consisting of green, yellow, and red. These colors provide the minimum number necessary to code display elements according to information priority. This coding scheme may be sufficient if peak information workloads imposed on the pilot are not excessive. It may also be the most practical alternative in cases where design constraints such as media or computational limitations must influence code selection.

The second basic alternative is a more complex coding scheme, consisting of the three preceding color codes plus one or more of the additional colors recommended above. Number and functional assignment of these supplementary color codes can be selected by the designer to meet specific system requirements and constraints. Use of these codes offers a means for potentially improving efficiency of information transfer to the pilot under high workload conditions.

CONSTRAINTS

Applicable Standards

Although current standards for aircraft electronic displays do not specify color code requirements, standardization can be anticipated in the future as color display media become a more viable design option. Compliance with applicable standards will be mandatory if imposed by design specification. Functions of yellow and red codes recommended above are consistent with current standardized usage of these colors on indicator and legend lights. As a minimum, extension of current standards for use of yellow and red (and flashing red) on electronic displays can be anticipated.

Consistency in Color Code Application

Consistency in application of a selected color coding scheme to all electronic displays is a fundamental requirement to minimize pilot confusion and response delay under high workload conditions. If a designer identifies ambiguities or other limitations in assignment of codes selected, the coding scheme should be revised to produce a set of coding rules which can be applied to all displays and display information formats.

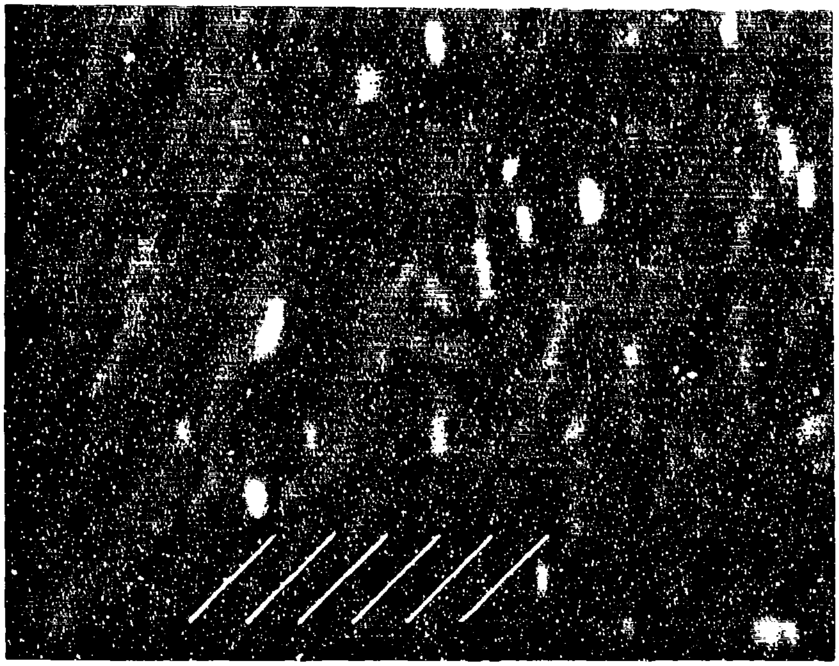
Projected Maps

Projected maps may have an established color code. If revision of map coding is not a design option, this constraint should be considered in selecting colors for superimposed computer-generated symbols and alphanumerics.

SAMPLE COLOR CODE APPLICATIONS

Electronic Displays

Figures 37 through 41 contain examples of color coding schemes applied to representative aircraft electronic display formats. Illustrations are based on art work prepared for this report rather than photographs of actual displays. Although display element brightness and chromatic characteristics are not accurately reproduced by this process, color code assignments are apparent in the illustrations.



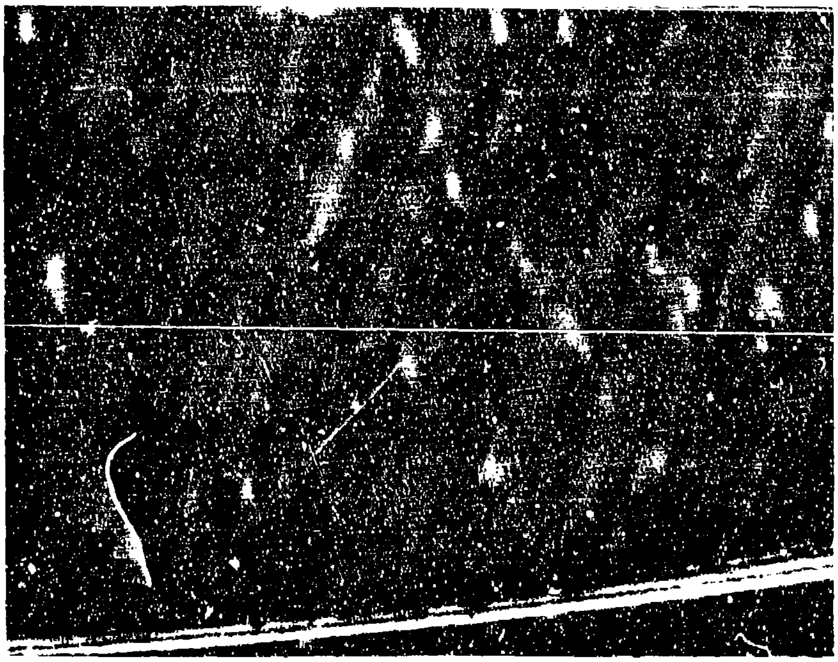
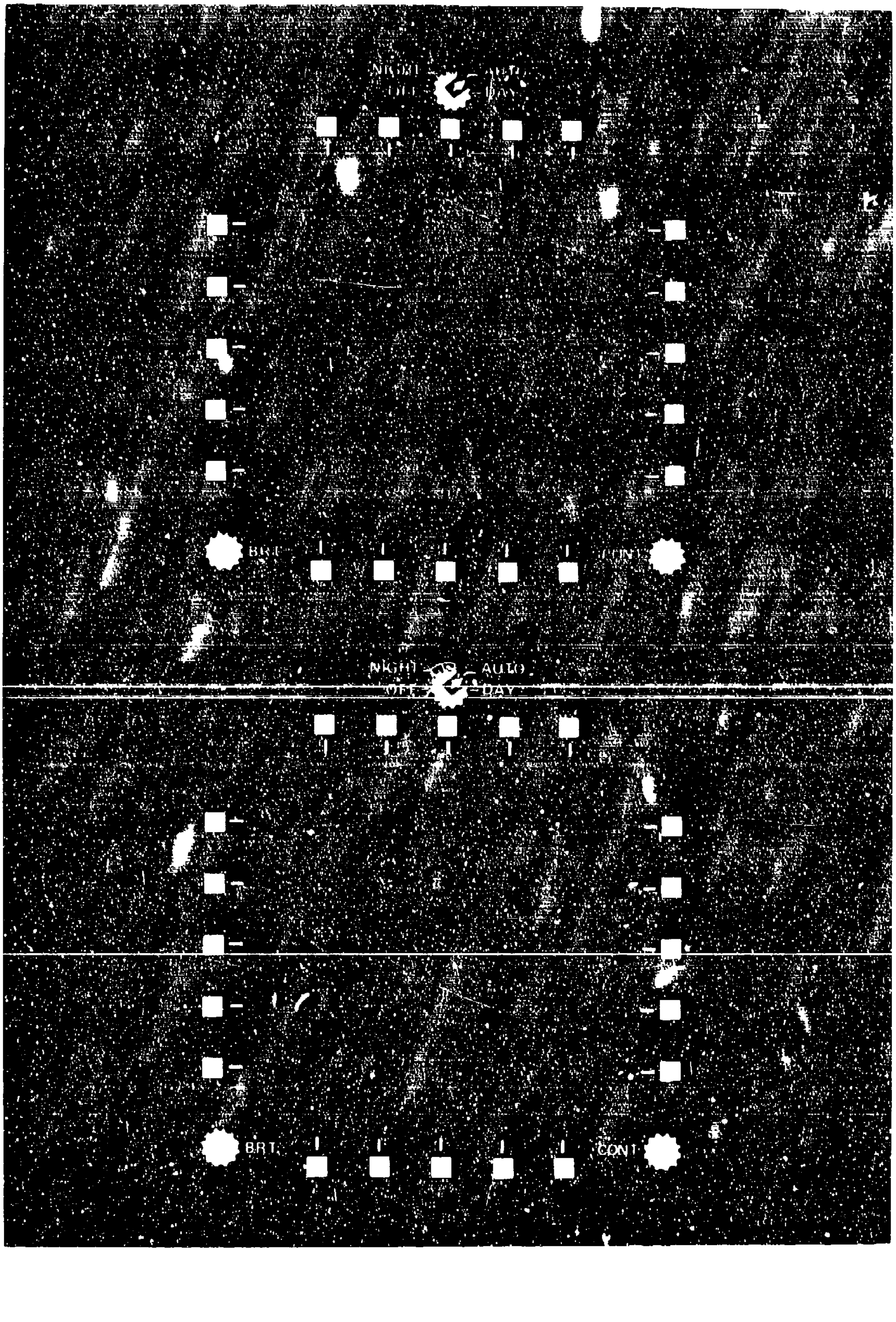


Figure 37. Representative A-7 HUD Format With and Without Three-Color Coding Applied.


NIGHT
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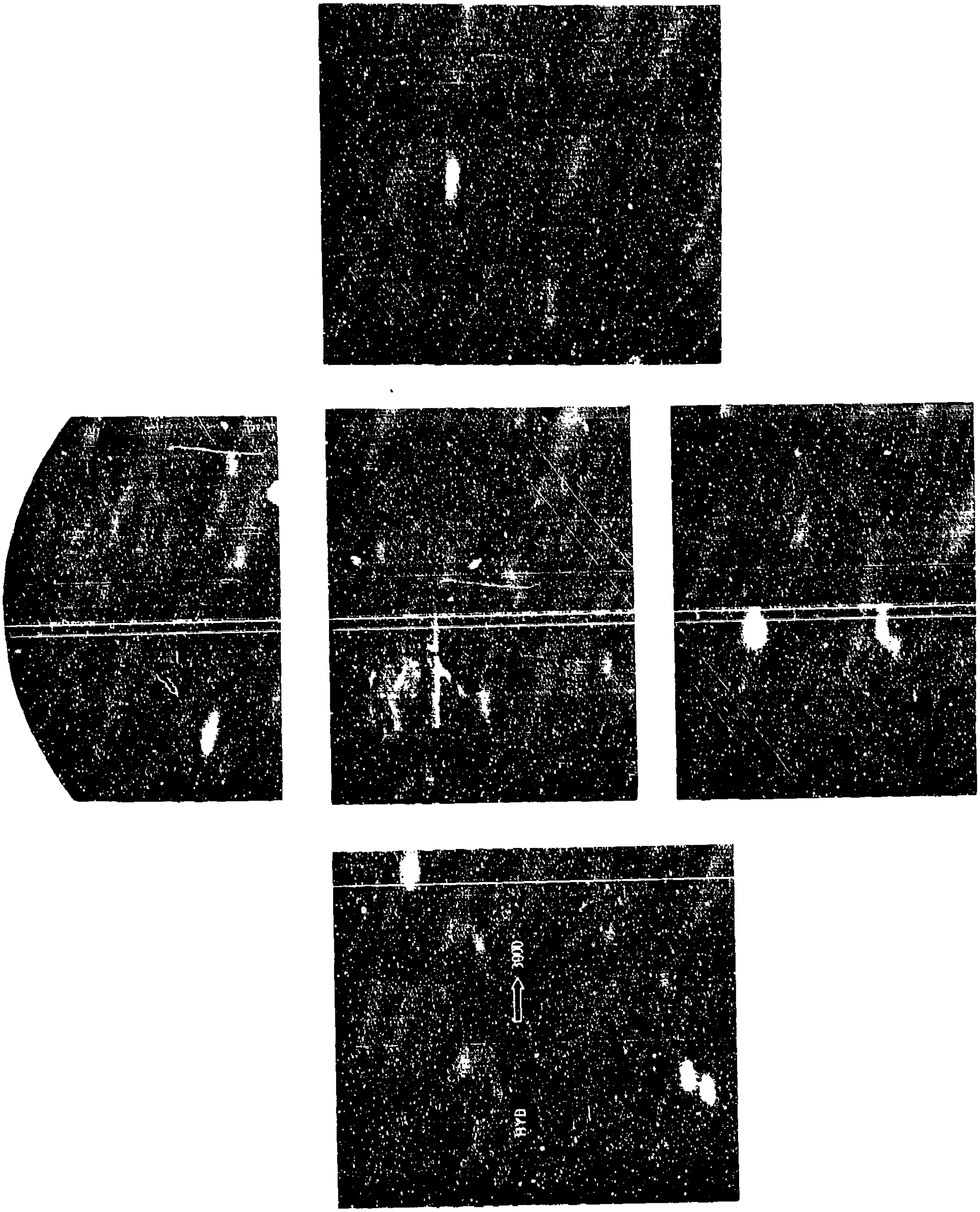
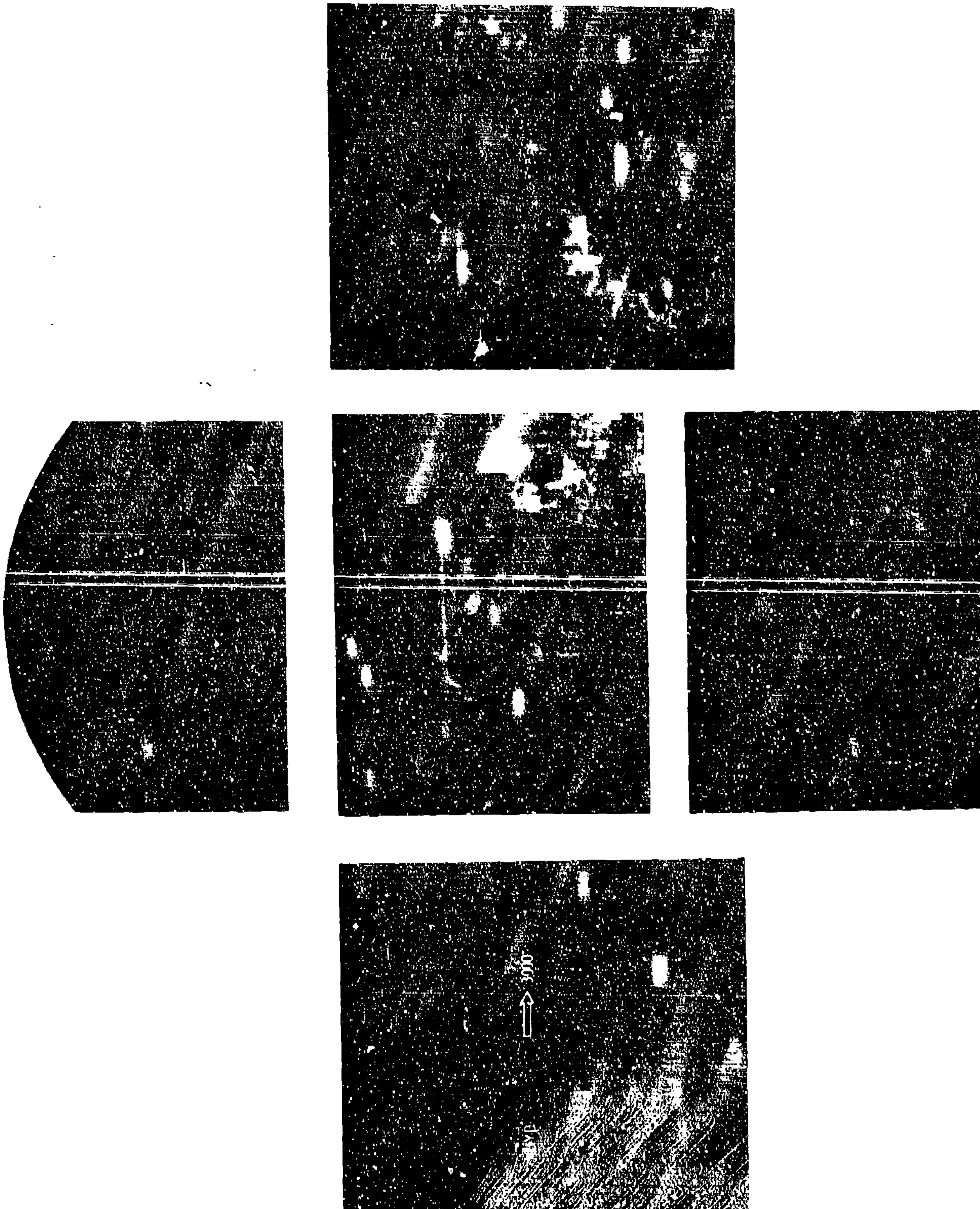
CONT


3900
HYD



3000
VP

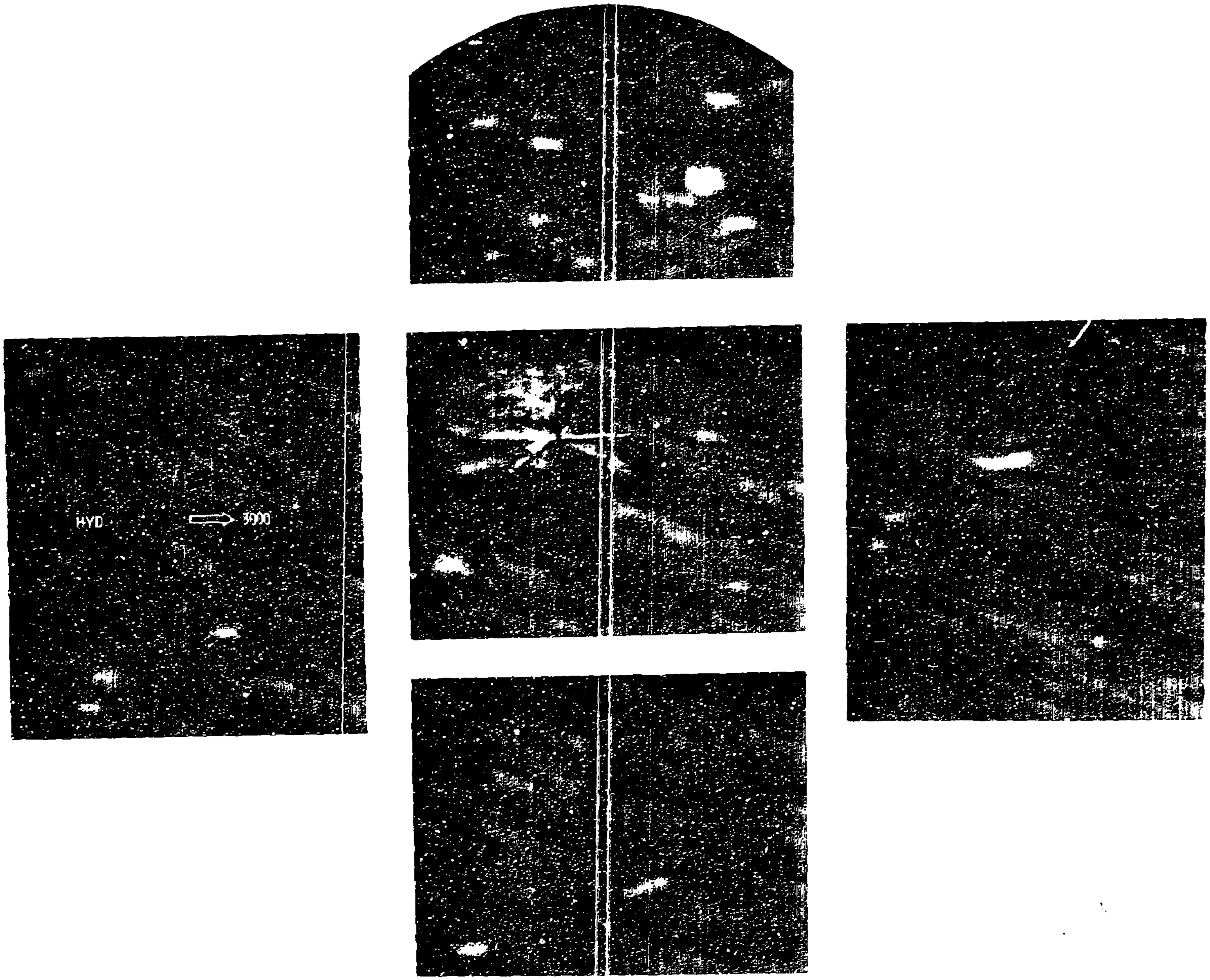

HYD
3900

Figure 37 depicts information representative of an A-7 HUD navigation and terrain-following mode. The background image is terrain seen through the transparent HUD combiner under daytime conditions. The recommended three-color coding scheme is applied in the top illustration of Figure 37. In the absence of the yellow "warning indicator" (denoting some cautionary level of system status) and the red "pullup command," all display information under nominal operating conditions would be monochromatic green. Flash coding used on the A-7 pullup command symbol could be maintained for increased attention-getting value. The warning indicator shown in yellow may also be coded red to communicate more critical levels of aircraft systems status. The bottom illustrations in Figure 37 is shown in monochromatic green for comparison with the color coded version.

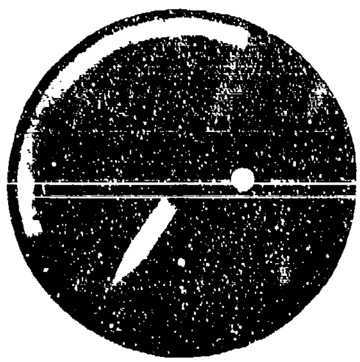
Representative F-18 stores management display formats are shown in Figure 38. These illustrations are intended to depict night viewing conditions with only display information, push buttons, and controls around the display periphery illuminated. Formats depicting information before and after stores selection are illustrated at the top and bottom of the figure, respectively. Since the display elements constitute routine or non-priority information, all display information would be coded green if the three-color coding scheme were to be applied. The coding scheme shown in Figure 38 includes use of blue on all symbolic information to provide a chromatic contrast with green alphanumeric information.

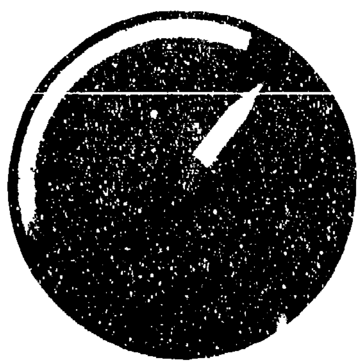
Figures 39, 40, and 41 illustrate coding variations applied to a complement of five electronic displays representative of the AIDS concept. Yellow coded information on the LMPD indicates that a cautionary level of hydraulic pressure exists. Higher priority information is also included in these examples. Oil temperature on one engine has reached a warning level (RMPD display) and a threat vector is being presented on the HSD. Desaturated green and orange colors are applied to sensor imagery in Figures 39 and 40, respectively. Selected status and command elements in Figure 41 are coded blue to illustrate representative approaches to use of this color for perceptual separation of related or adjacent symbols.

Electromechanical Displays

Part II of this report has concentrated on color coding of electronic displays. It is interesting to postulate how color codes recommended from the present study might be extrapolated for use on conventional electromechanical instruments. Figure 42 illustrates an approach using the green-yellow-red coding scheme applied to a typical engine instrument.

Green bands indicating normal operating range are common on engine instruments but not on flight instruments. These bands would be maintained where applicable, as in the example shown. Pointer and scale markings are coded green to maintain consistency with use of this color on electronic displays. Marginal or cautionary levels of the displayed parameter are indicated by onset of an integral yellow light. Onset of an integral red light indicates that minimum or maximum values have been exceeded. Use of other recommended codes such as blue and desaturated orange would be of most potential benefit to provide chromatic contrast between elements on more complex electromechanical displays, such as attitude-director and horizontal-situation indicators.





Advanced aircraft designs may include both electromechanical instruments and multicolor electronic displays. If so, consideration should be given to the feasibility of implementing a selected color code on all visual information sources to achieve an overall consistency of functional color usage in the cockpit.

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APPENDIX A

DEFINITIONS OF TERMS AND CONCEPTS

APPENDIX A

DEFINITIONS OF TERMS AND CONCEPTS

In this appendix the major terms and concepts used in the Color Display Design Guide are defined in greater detail. Other selected terms that are relevant to human vision and to displays in general are included. Major terms appear in alphabetical order. The list below provides an index to the contents of this appendix.

Adaptation

Additive color process

Ambient illumination

Anomalous color

Brightness

Chromaticity

Chromaticity diagram

Color coding

Contrast

- Contrast percent
- Contrast efficiency
- Contrast ratio

Display

Dominant wavelength

Hue

Irrelevant color

Luminance

Munsell color notation

Noise

Phosphor

Redundancy

- Total redundancy
- Partial redundancy

Resolution

Saturation

Self-luminous color

Signal-to-noise ratio

Subtractive color process

Surface color

Target acquisition

- Detection
- Location
- Identification

Threshold (visual)

Visual acuity

Visual angle

Visual sensitivity

Foveal vision
Peripheral vision

Wavelength

* * *

Adaptation

The adjustment to a new level of ambient illumination. When the illumination is suddenly changed, the eye requires a period of time to become maximally sensitive to the new level. The greater the change in illumination, the longer the adaptation time. Adaptation is typically faster to a bright environment than to a darker one. A person going from a normally lighted room to a light-tight dark room may require up to 40 minutes to adapt completely. The reverse may require about ten minutes. In practice such extremes seldom occur and adaptation to a dark environment may take as little as five to ten minutes depending on the difference in lighting.

Ambient Illumination

Light provided in the working area or from an external source such as the sun. Ambient illumination affects both the adaptation of the eye and the symbol to background contrast on the display. Light shining on a display surface will sum with both symbol and ground. The result will be a lower contrast. High ambient illumination can produce display washout (i.e., the symbols can no longer be seen).

Additive Color Process

When the additive primaries red, green, and blue are combined, the radiant energy spectral distribution is the sum of the distributions of the three primaries. Color television is an example of color produced by the additive process.

Anomalous Color

A color perception that is markedly different from the physical stimulus. For example, if yellow is seen at the boundary between a red and green strip when no yellow is actually present, the perceived yellow would be anomalous (i.e., out of correspondence with the physical nature of the area in question).

Brightness

Although this term is often used interchangeably with lightness or luminance, technically (in visual terms) it more accurately refers to a subjective impression of relative luminance. That is, a symbol of fixed luminance will appear "brighter" on a dark background than on one whose luminance is very similar to the reference symbol (e.g., a white symbol on a black vs. a light gray background). Thus, brightness judgments are influenced by both contrast and absolute luminance.

Chromaticity

The color quality of light as defined by chromaticity coordinates of the Commiss i Internationale de l' Eclairage (CIE) color coordinate system. The CIE diagram represents an attempt to specify the various parts of the color spectrum in terms of three primary colors: red, green, and blue. These tristimulus specifications were obtained using the data from a large number of observers and are expressed in terms of three primary components: $\overline{X}$ (red), $\overline{Y}$ (green), and $\overline{Z}$ (blue). Any color in the visible spectrum can be obtained from an appropriate mixture of these three.

Chromaticity Diagram

Shown in Figure A-1, the chromaticity diagram is a system in which all colors possible with real stimuli are represented within the bounds of the solid outer line. The axes X and Y are called chromaticity coordinates and are defined as follows:

$$x = X/(X + Y + Z)$$

where X, Y, and Z represent particular proportions of $\overline{X}$, $\overline{Y}$, and $\overline{Z}$, respectively. Similarly,

$$y = Y/(X + Y + Z)$$

Since $X + Y + Z = 1$, knowing the value of any two (usually X and Y) determines the value of the third. Thus, using chromaticity coordinates, we have the relative proportions of each of the primaries required to generate any color.

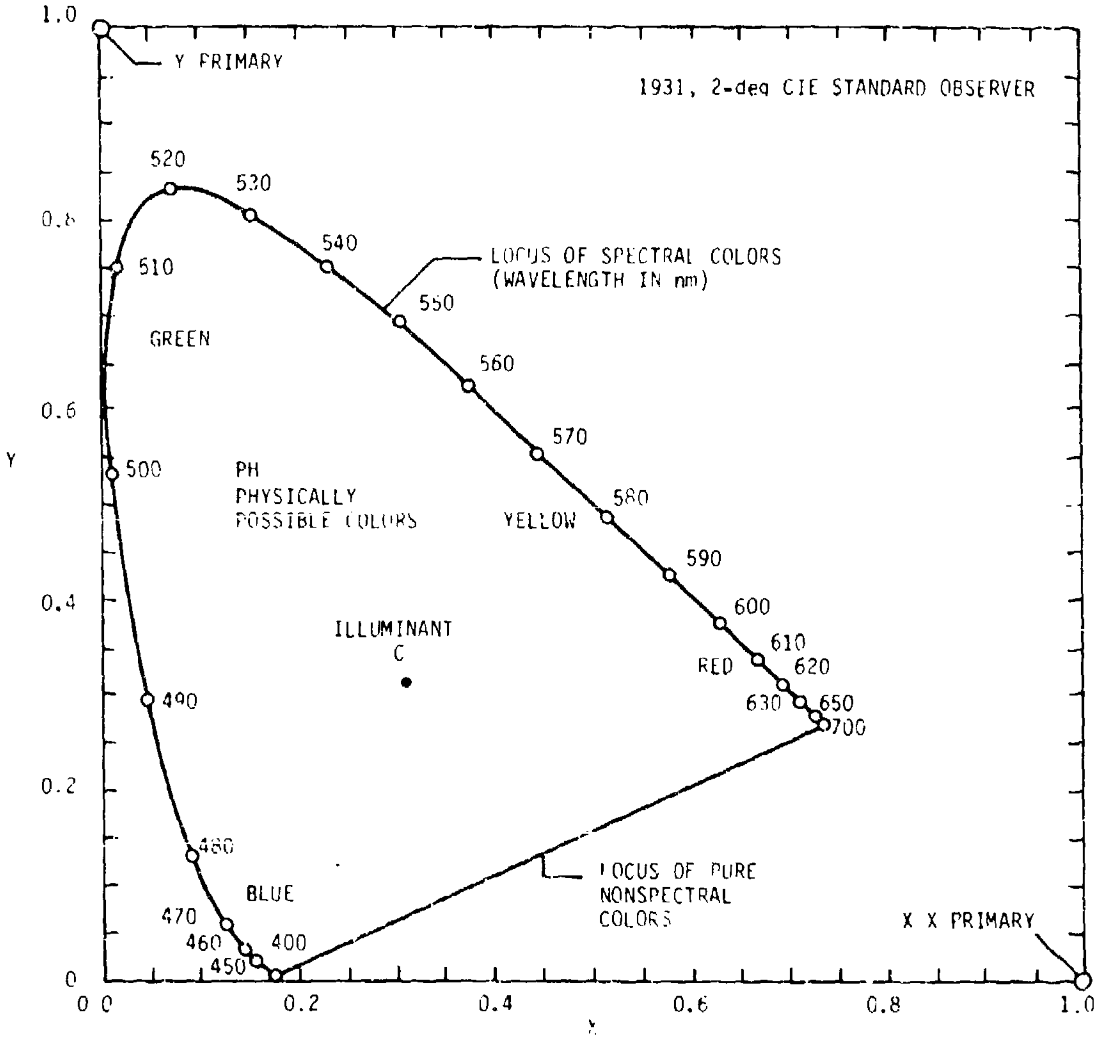

Figure A-1. CIE Chromaticity Diagram

In Figure A-2, common color names have been assigned to areas within the diagram. Note that the area represented by different color names is far from equal. A practical result of this is that certain colors (e.g., yellow) must be more rigidly specified and controlled, for display purposes, than others (e.g., green) to avoid color confusion. It also suggests that adjacent color names (color areas) should not be used on the same display to avoid possible confusion.

The central, partial ellipse around point E in Figure A-2 represents a "colorless" area, which is seen as shades of white to gray. These data were obtained using self-luminous light on a dark background.

Color

The characteristic appearance of an object or signal to which the common labels red, green, blue, etc. are assigned. Color has three dimensions: hue, saturation, and brightness. (See Figure A-3 and definitions for each of these terms.) Color is not a property of the object or of physical energy but refers to the perceptual experience of the human observer.

Color Coding

Use of color to convey information on a visual display. Each particular color represents a value on some information dimension. Color coding may be used alone or in conjunction with another dimension such as shape. Most factors governing the effective application of color to coding apply to other codes.

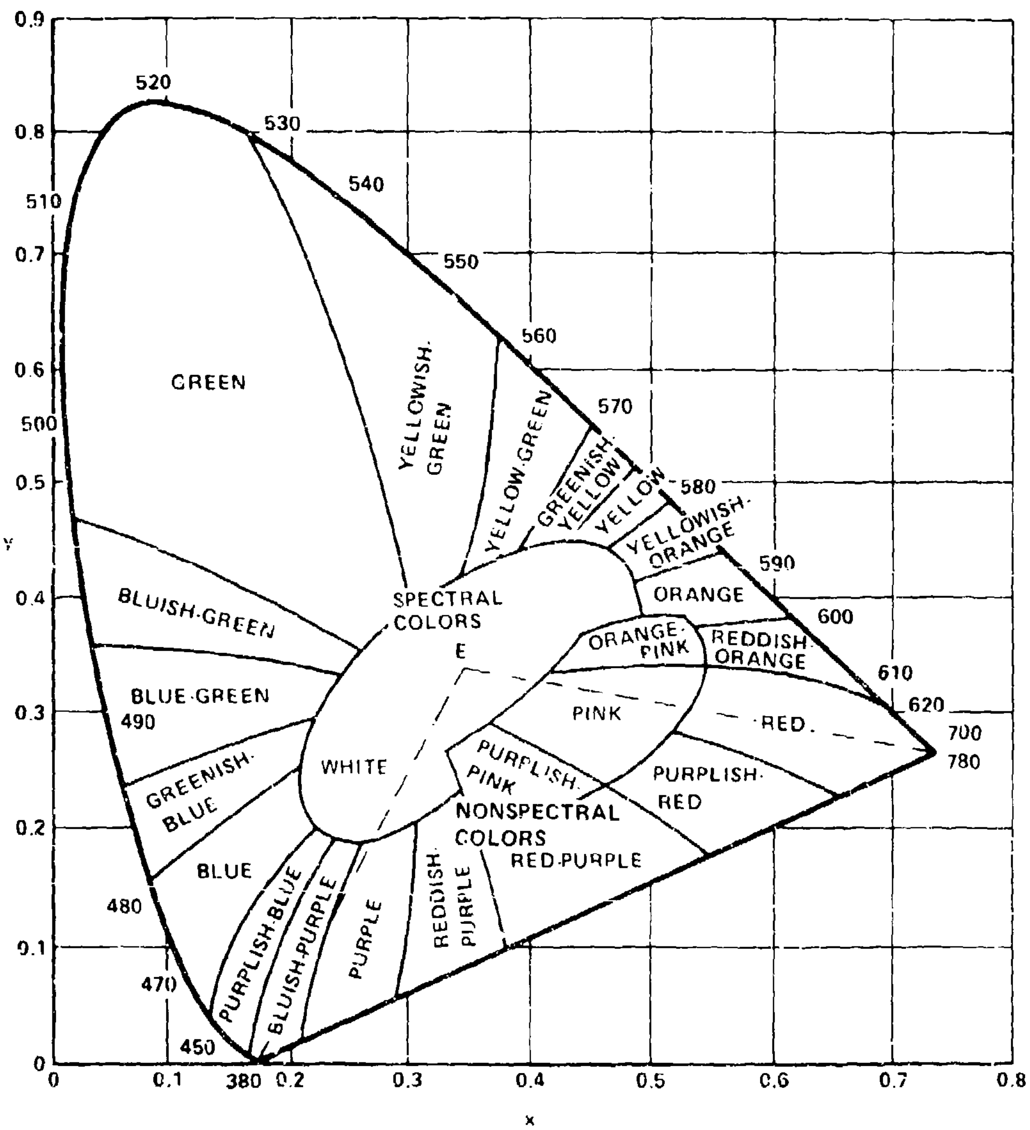

Figure A-2. Regions of the CIE 1931 XYZ Chromaticity Diagram with Color Names Assigned to Categories

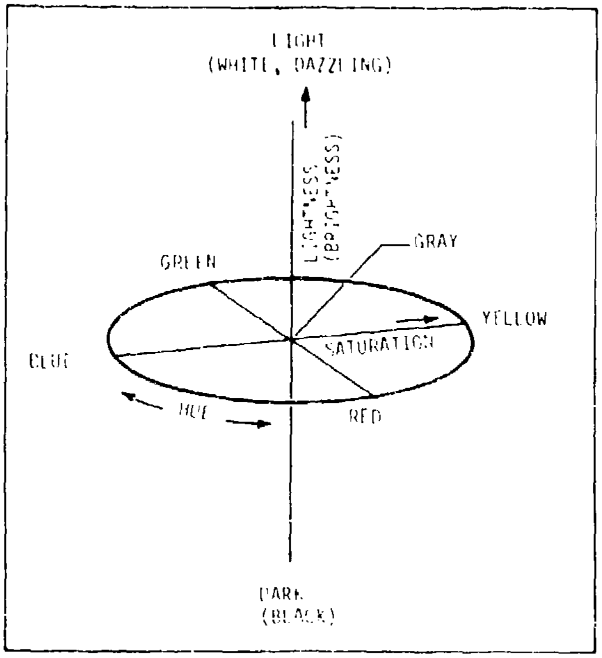

Figure A-3. Subjective Dimensions of Color

Contrast (Luminance)

A measure of the relationship between the luminance of a symbol and its immediate surround or background. A variety of different methods of expressing luminance contrast are reported in the literature. It is important to determine which type of calculation is being used when interpreting these results or in evaluating your own display data. Several of the most common calculations are presented below.

Contrast (Percent)--Ratio of the difference between target and background luminance. Percent contrast may be defined as follows:

$$\%C = \frac{|L_o - L_b|}{L_b} \times 100$$

where

L_o = object luminance

L_b = background luminance

$|L_o - L_b|$ = absolute value of the difference between object and background luminance

For objects darker than their background, contrast can vary between zero and 100 percent. For objects brighter than their background, percent contrast can vary from zero to infinity.

<u>Contrast Efficiency</u>--Another measure of contrast, defined as the ratio of the sum of the background luminance and symbol luminance and their difference

$$C = \frac{L_{Max} - L_{Min}}{L_{Max} + L_{Min}}$$

where

L_{Max} = the higher of the two luminances (symbol or background)

L_{Min} = the lower of the two luminances

This measure has also been called modulation, contrast sensitivity, and visibility ratio.[1] It can assume values between zero and one.

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[1] Meister, D. and D.J. Sullivan, "Guide to Human Engineering Design for Visual Displays," Contract No. N00014-68-C-0278, Engineering Psychology Branch, Office of Naval Research, Washington, DC, AD 693-237, 1969.

Contrast Ratio--This term has been used in at least two ways. One is the simple ratio of one luminance to another:

$$\text{Luminance ratio} = \frac{L_1}{L_2}$$

We will refer to this as the luminance ratio (LR) for the sake of clarity. A more common expression of contrast ratio is the following:

$$CR = \frac{L_{Max} - L_{Min}}{L_{Min}}$$

Contrast ratio for CRT displays is a special case where the symbol is usually brighter than the surround. To compute this contrast, a frequently used equation[2] that takes ambient light into account is

$$C_T = \frac{L_S + L_W}{L_S}$$

where

L_S = luminance of the symbol measured in ambient illumination

L_W = screen luminance with ambient light excluded

Maximum contrast on CRT displays is typically about 2 to 1 (C = 90 percent).[1]

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[2] Bryden, J.E., "Design Considerations for Computer-Driven CRT Displays," Computer Design, March 1969, pp. 38-46.

Display

Any device or medium used to convey information to an operator. A visual display could be as simple as a digital readout or a meter, or as complex as a battlefield map or sensor imagery on a CRT.

Dominant Wavelength

A term used to describe the subjective appearance of a color mixture. Using the chromaticity diagram (see Figure A-4), a line is drawn between the color expressed in X, Y coordinates and illuminant C. When this line is extended to the outer rim of the diagram, the wavelength at which it intersects will indicate its color appearance. The distance along the line drawn between illuminant C and the outer rim at which the plotted color appears indicates its purity. Thus, a point three-quarters of the way up the line would have a purity of 75 percent.[3]

Hue

The attribute of a color to which commonly used labels such as red, green, or blue are assigned. The color label assigned to an object or signal usually corresponds to its dominant wavelength.

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[3] Geldard, F.A., The Human Senses, Second Edition. New York: Wiley, 1972.

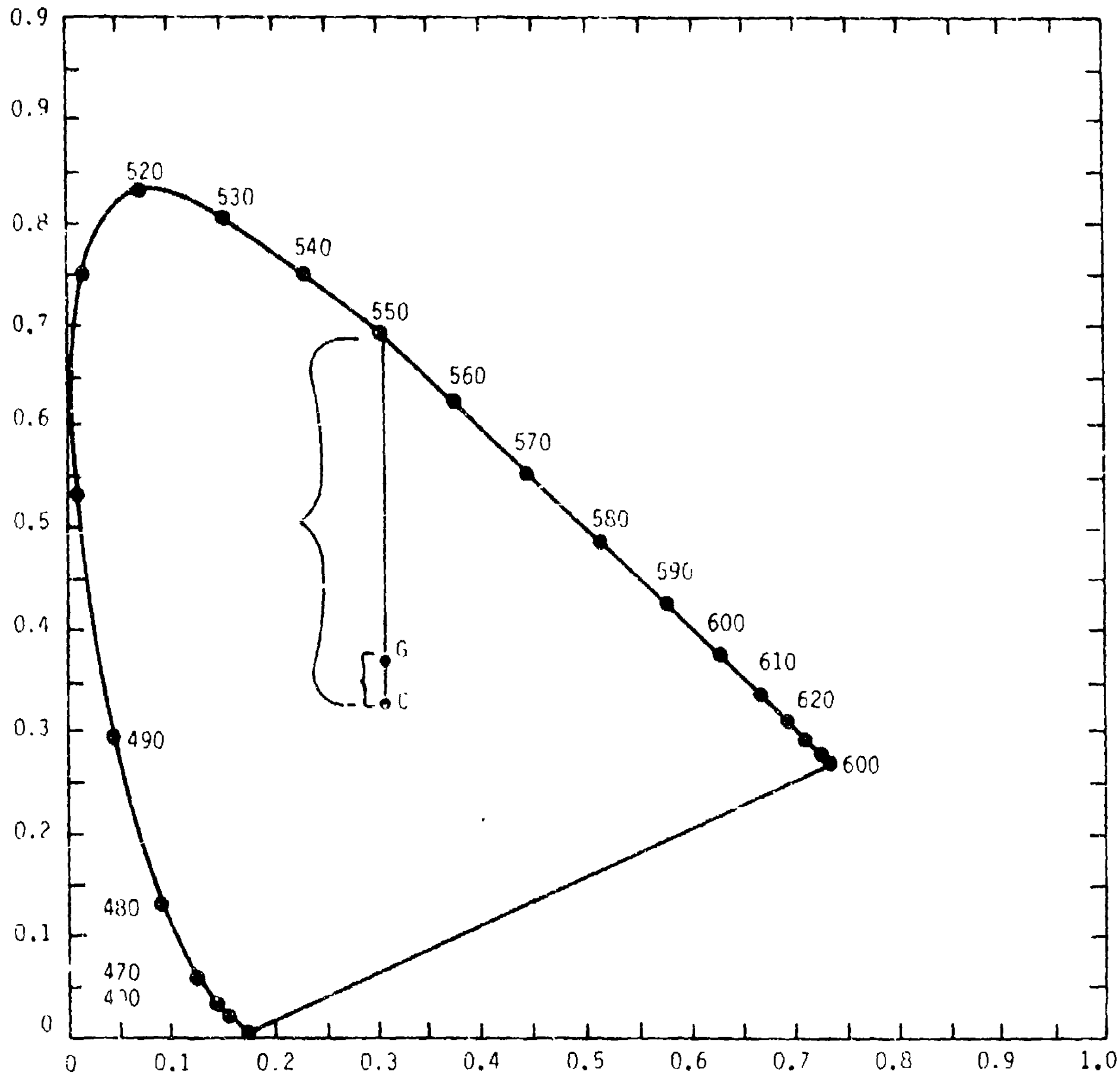

Figure A-4. Dominant Wavelength and Purity (Saturation) Defined on Chromaticity Diagram

Irrelevant Color

Color added to a display that has no task-related meaning (i.e., conveys no information). If the task changes, an irrelevant color might become relevant. Color that is irrelevant to a task may have either a neutral effect on operator performance or it may be distracting, producing performance decrement.

Luminance

The amount of light emitted from a display surface or the luminous intensity of any object as viewed by an observer. Many different units have been used to quantify luminance. The currently acceptable measure is candelas per square meter (cd/m^2). In Table A-1, conversion factors are provided for commonly used units.[4] The subjective measure of luminance is brightness. Figure A-5 provides some common luminance values.

Munsell Color Notation

There are several prominent systems of notation used for specifying a particular color. One of the best known is the Munsell color system. In this system, a color notation is obtained by matching a test patch against a series of paint chips. Each color chip is specified by three alphanumeric

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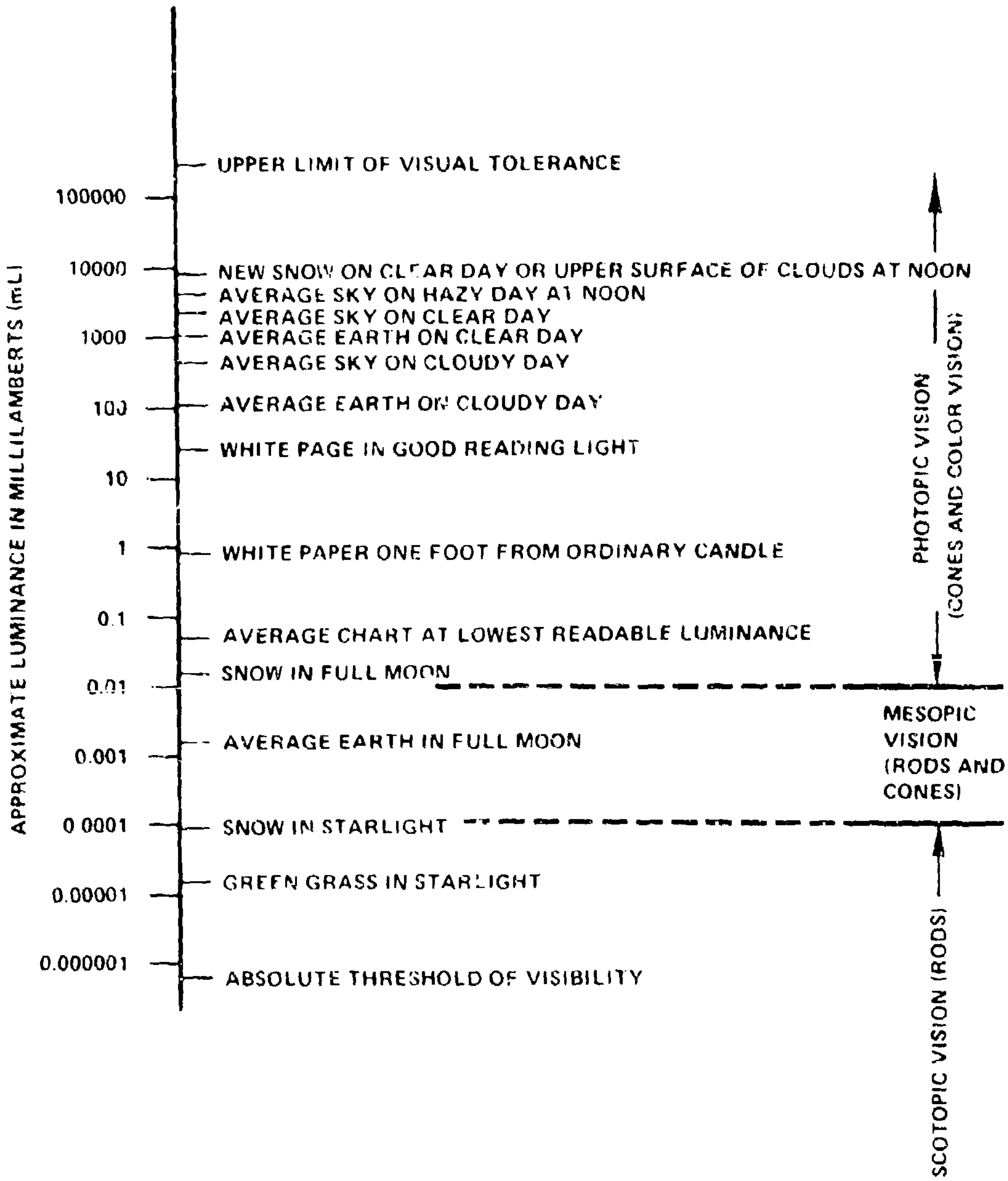
[4] Bioastronautics Data Book. Washington, DC: National Aeronautics and Space Administration, SP-3006.

TABLE A-1. CONVERSIONS AMONG COMMONLY USED MEASURES OF LUMINANCE

Number of → Multiplied by → Equals Number of ↓	cd/m^2	cd/cm^2	cd/ft^2	cd/in^2	millilambert	foot-lambert
cd/m^2	1	10,000	10.764	1,550	3.183	3.426
cd/cm^2	0.0001	1	0.001076	0.155	0.0003183	0.0003426
cd/ft^2	0.0929	929	1	144	0.2957	0.3183
cd/in^2	0.000645	6.452	0.00694	1	0.002054	0.002211
millilambert	0.31416	3,141.6	3.382	486.9	1	1.0764
foot-lambert	0.2919	2,919	3.1416	452.4	0.929	1



NOTE: 1 FOOT-LAMBERT = 1.0764 MILLILAMBERT

Figure A-5. Some Common Luminance Values terms corresponding to hue, lightness, and saturation. The Munsell terms for these dimensions are hue, value, and chroma, respectively. Figure A-6 shows the elements of the Munsell system notation.[5] The Munsell system is used primarily for specifying surface colors.

Noise

In electronic displays, noise is defined in terms of unwanted interference with the presentation of the signal produced by graininess or electrical interference in TV systems. The magnitude of the noise relative to the signal at any point is expressed for the entire display by the signal-to-noise ratio.

A less traditional definition of noise in a symbolic or alphanumeric display considers all irrelevant symbols as display clutter or noise. What is relevant (the signal) will vary according to the present information requirements of the user. An ideal display would contain only the information required and thus be "noise-free."

Phosphors

An inorganic material exhibiting a nonthermal emission of electromagnetic radiation upon excitation. Phosphors used for screens of CRTs have two important characteristics: color and persistence. These characteristics

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[5] Farrell, R.J. and J.M. Booth, "Design Handbook for Imagery Interpretation Equipment," Boeing Aerospace Company, December 1975.

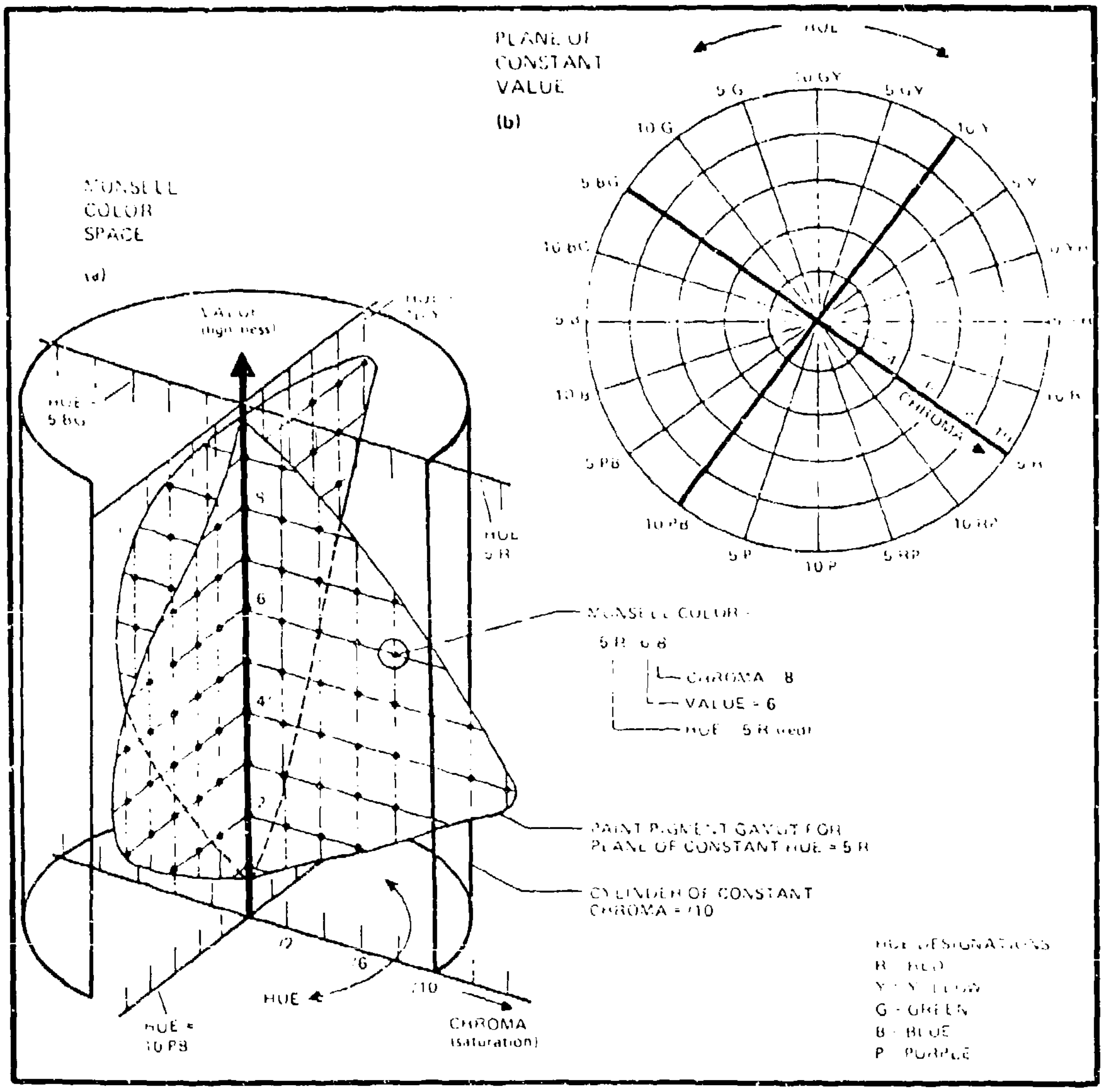

Figure A-6. Munsell Color System

are used to define the phosphor. Phosphor persistence is an important consideration in color selection since, if it is too brief, the display may exhibit flicker. If phosphor persistence is too long, it could interfere with the subsequent presentation of other colors in the same area. In Figure A-7, critical flicker fusion frequency (CFF) or phosphor refresh rate at which no flicker is seen is shown for some common phosphors.[2] In that figure the relationship between refresh rate and display luminance is shown.

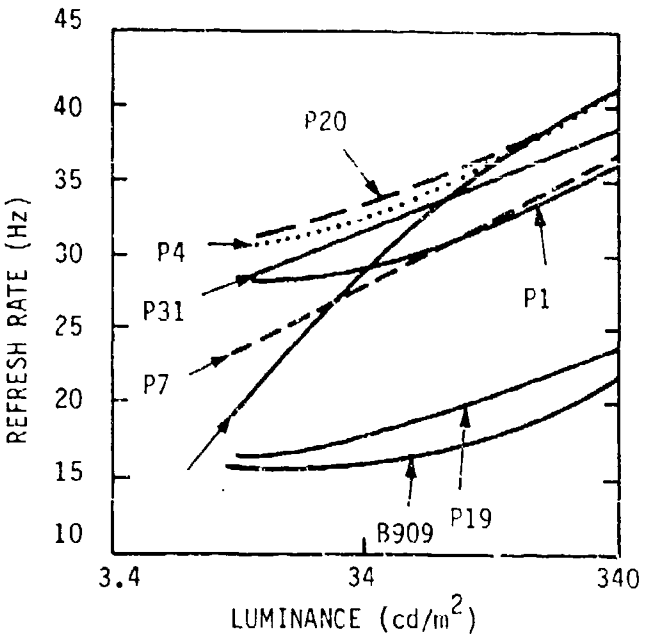

Figure A-7. Critical Flicker Fusion Frequency or Phosphor Refresh Rate at Which No Flicker is Seen is Shown for Some Common Phosphors

Redundancy

The repetition of information provided in one code by another code. Values on the two codes are correlated with each other. Redundancy can be total or partial.

Total Redundancy--A perfect correlation between values on two or more codes. Knowing the value on one code provides complete information about the value of another code. For example, by knowing that all circles are red and all squares are green, if a given object is a circle, its color (red) will also be known.

Partial Redundancy--A correlation between values on two coding dimensions in which only limited overlap occurs. Knowing the value on one code does not completely determine the value on another. For example, a digital readout may be color-coded as red = high, green = medium, and yellow = low. Knowing the color of the readout will specify a range of numbers but not the exact numerical value.

Resolution

In a CRT-type display, resolution is defined in terms of the number of line-space pairs that can be seen per unit linear dimension. In Figure A-8, a standard resolution target is shown.[1] Patterns of this general type are used to measure the resolving capability of optical systems. Television systems are generally designed to have equal horizontal and vertical resolution. Vertical resolution for an interlaced TV system equals the number of active lines per frame times 0.7. In normal room

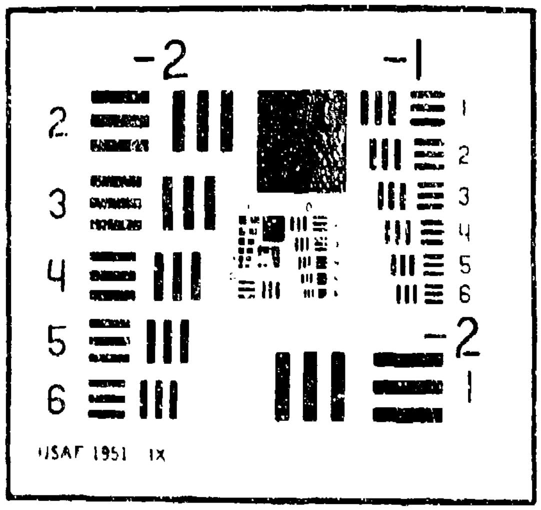

Figure A-8. Standard Resolution Target

light the average eye can discriminate 40 parallel lines alternating black and white (i.e., 80 TV lines) per degree of arc.

Saturation

The relative purity of a color defined in terms of its departure from a white or gray of the same lightness. For example, the two colors labeled pink and red have approximately the same hue but the red would be highly saturated and the pink would be low in saturation or desaturated. Zero saturation colors are black, gray and white. (See Figures A-3 and A-4.)

Self-Luminous Color

Typified by a color CRT, the color sensation is not produced by reflected, ambient illumination; the symbol itself is the light source. On a CRT, different colors are produced by using different phosphors. Because of its lack of dependence on reflected light, a self-luminous color display can be viewed over a wider range of ambient illumination than can a surface color display. At high levels of illumination, however, colors may not be visible because of reduced contrast. Color of ambient illumination has less effect on self-luminous displays than on surface colors.

Signal-To-Noise Ratio

Typically defined as the relationship between signal magnitude and noise. Noise is usually thought of as anything that is displayed that is not part of the signal and thus contains no information. In projected displays such as TV, graininess or electrical interference is present in every frame. The signal-to-noise ratio (SNR) for such systems can be quantified and compared to desired values. An SNR of 30:1 is considered good quality for television systems. The SNR required depends on the object to be detected; a bar-type resolution pattern requires an SNR of 3:1 to be visible.[1]

Subtractive Color Process

Color achieved by mixing dyes or pigments that selectively absorb the radiant energy in a portion of the visible spectrum. Color photographs and various other surface colors are achieved by this process.

Surface Colors

As the term implies, surface colors are an integral part of the object (examples include photographs, printed maps, decals, paint). Color is determined by light reflected off the surface of that object. Any surface absorbs certain wavelengths of the light shining on it and reflects others. The one(s) reflected determine(s) the perceived color. For example, if white light is directed at an object and the object absorbs all but the longest wavelengths that it reflects, the object will be seen as red. The appearance of a surface color may vary drastically if the color of the ambient illumination is changed. Surface colors are seen only at moderate to high ambient illumination in the photopic range (see Figure A-5). Below this range, objects appear colorless or as shades of gray.

Target Acquisition

A general term used to describe the process of searching for and/or labeling a target. The following subtasks may or may not all be part of this process depending on the situation:

Detection--Determining that a given signal or target is present when its onset or occurrence is either not expected or is uncertain.

Location--Determining the position of a target in an informatted display or among randomly positioned non-target objects.

Identification--Labeling a symbol or shape by a name that has task-related meaning or determining the status of some variable by reading and interpreting a coded message.

Threshold (Visual)

A measure of maximum sensitivity to a stimulus. For example, the lowest luminance at which a small spot of light can be seen is the luminance threshold. Usually a threshold value is reported at the point where the stimulus is seen 50 percent of all the times it is presented, unless another percentage value is specified. In adapting such data to operational systems, care should be taken to revise the threshold value upward to permit 99 to 100 percent detectability under typical operational viewing conditions. If the standard deviation (SD) is given, the 50 percent threshold value should be increased by at least three SDs.

Visual Acuity

The minimum detail resolvable by the human eye. This absolute threshold will vary depending upon such factors as signal luminance, contrast, signal duration, and, to a more limited extent, signal hue or wavelength.

Acuity is measured in a variety of ways. One common device is the Landolt Ring shown in Figure A-9. The Landolt Ring has a break in it at one of four possible locations. The observer indicates where the break is (top, bottom, left, or right). The smallest opening that can be detected in the ring is an indication of visual acuity. Another measure of acuity, the Snellen Eye Chart, is similar to the Landolt Ring, except the observer must identify letters viewed at a fixed distance.

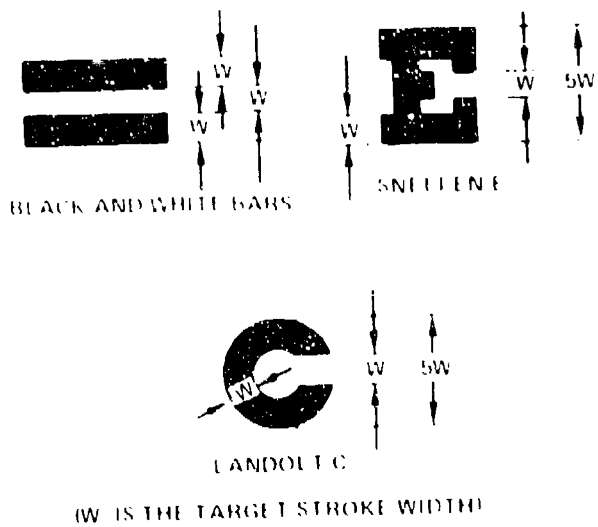

Figure A-9. Common Visual Acuity Test Targets

Another type of acuity measure is the minimum separation acuity defined as the smallest separation that can be resolved by the eye or by a given display medium.

Visual Angle

The size of the object at the eye of the observer. Visual angle takes into account the actual size of the object and the distance of that object from the eye. It is usually expressed in degrees, minutes, or seconds of arc. Equation (A-1) below can be used to calculate the visual angle subtended by an object or symbol of known size at a specified distance. Using Equation (A-2), the symbol size required to achieve a specified visual angle can be calculated.

$$\text{Visual angle in degrees} = 2 \arctan {}^{h}/2d \qquad \text{(A-1)}$$

where h = linear symbol dimension (height)

d = distance from eye measured perpendicular to line of sight

A close approximation to Equation (A-1) can be computed for angles of less than ten degrees (600 minutes), using constants as follows:[6]

$$\text{Visual angle in degrees} = \frac{57.3h}{d}$$

where h and d defined as in Equation (A-1)

[6] Baker, C.A. and W.F. Grether, "Visual Presentation of Information," Wright Air Development Center, WADG-TR 54160, AD43-064, 1954.

To convert from angular to linear measure

$$h = 2d \tan \text{visual angle}/2 \qquad \text{(A-2)}$$

In Table A-2, some typical values are provided as examples of the relationship betwen size, viewing distance and visual angle.

TABLE A-2. SYMBOL SIZES REQUIRED TO ACHIEVE GIVEN VISUAL ANGLES AT SEVERAL VIEWING DISTANCES (Cell values, in parentheses, represent symbol size in inches and centimeters.)

Viewing Distance		Symbol Size (Minutes of arc)						
Inches	(Centimeters)	5	10	15	21	30	40	45
36	91	0.05 (0.13)	0.10 (0.27)	0.16 (0.40)	0.22 (0.56)	0.31 (0.80)	0.42 (1.06)	0.47 (1.20)
32	81	0.05 (0.12)	0.09 (0.24)	0.14 (0.35)	0.20 (0.50)	0.28 (0.71)	0.37 (0.95)	0.42 (1.06)
28	71	0.04 (0.10)	0.08 (0.21)	0.12 (0.31)	0.17 (0.43)	0.24 (0.62)	0.35 (0.83)	0.37 (0.93)
24	61	0.03 (0.09)	0.07 (0.18)	0.10 (0.27)	0.15 (0.37)	0.21 (0.53)	0.28 (0.71)	0.31 (0.80)
20	51	0.03 (0.07)	0.06 (0.15)	0.09 (0.22)	0.12 (0.31)	0.17 (0.44)	0.23 (0.59)	0.26 (0.66)

Visual Sensitivity

The human eye is divided into two major areas, fovea and periphery, each of which has different levels and types of sensitivity to visual stimulation (see Figures A-10 and A-11.)

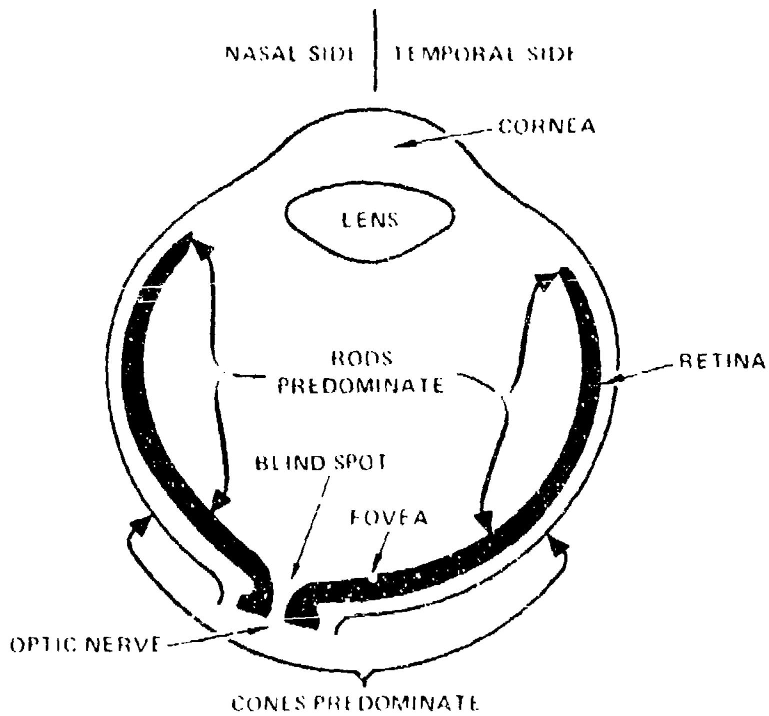

Figure A-10. Horizontal Cross Section of the Right Eye

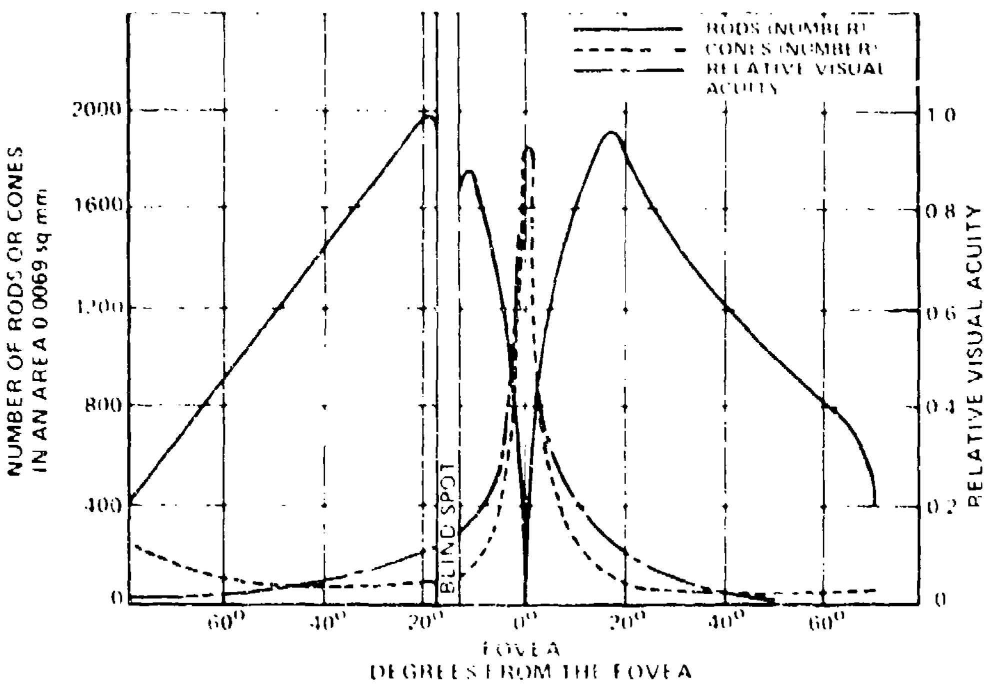

Figure A-11. Relationship of Visual Acuity to the Distribution of Rods and Cones

Foveal Vision--Foveal vision covers an area within about ± 1 degree from the center of the line of sight; both visual acuity and color vision are maximum in this area. The fovea contains only cones.

Peripheral Vision--The remainder of the visual field that lies outside the foveal field of view. Sensitivity to low levels of light is much greater in the periphery. Acuity is substantially lower, however, so the periphery is not sensitive to fine detail. Color sensitivity also decreases as the signal moves out into the periphery. The periphery contains both rods and cones but the number of cones decreases markedly as the distance from the fovea increases. Peripheral vision extends 180 degrees from the line of sight and about 130 degrees in the vertical direction. (see Figures A-12 and A-13.)

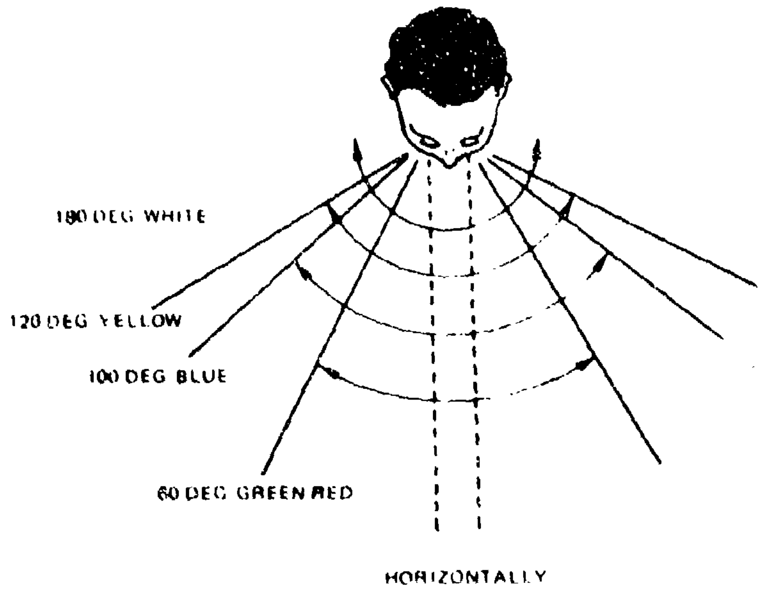

Figure A-12. Horizontal Angular Color Limits

NWC TP 5922

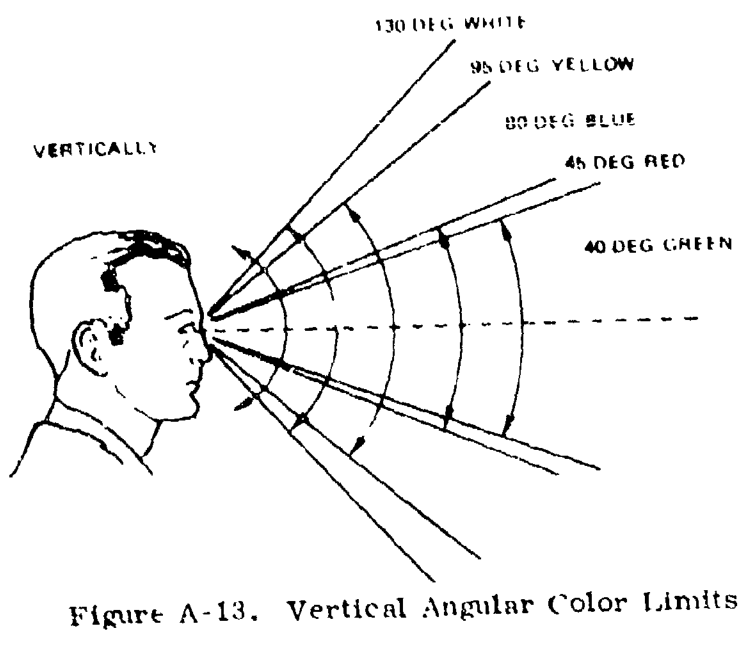

Figure A-13. Vertical Angular Color Limits

These figures also indicate that the visual field is maximum for white signals, and that the field for color signals is more restricted, with green and red having much smaller areas of sensitivity than other colors.

Wavelength

A specific point on the visible portion of the spectrum (see Figure A-14). Usually used to describe the characteristic of a signal of some specified hue as shown in Figure A-14. Most real-world signals are not produced by one wavelength but are a mixture of more than one. The particular color seen in such a mixture is determined by the dominant wavelength.

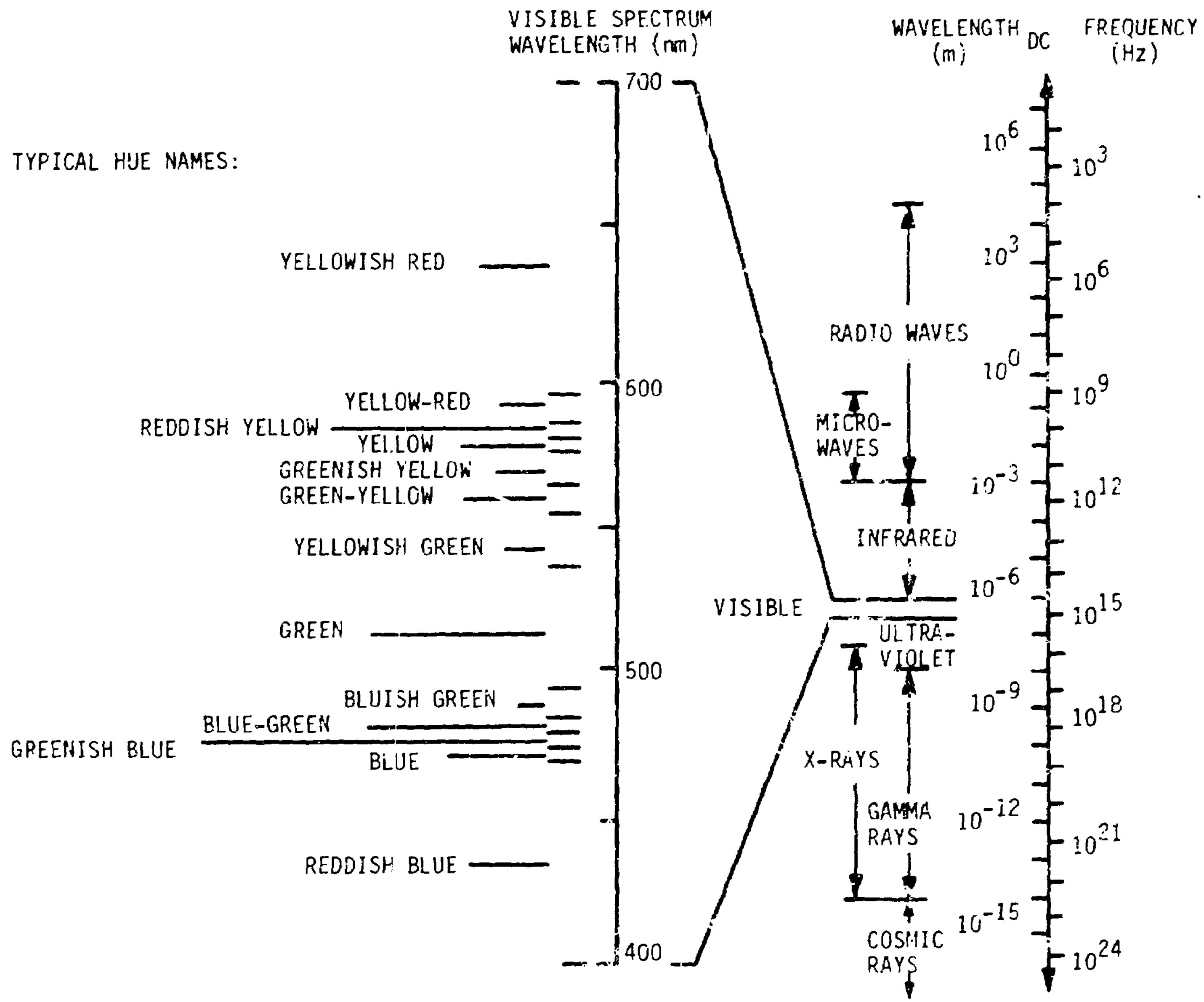

Figure A-14. *The Visible Spectrum*

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