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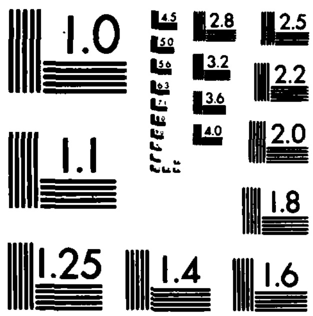

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ABSTRACT

Stollings, Michael Newton. M.S., Department of Applied Behavioral Sciences, Wright State University, 1982. Information Processing Load of Graphic Versus Alphanumeric Weapon Format Displays For Advanced Fighter Cockpits.

Twenty-four highly experienced fighter pilots were used to ascertain the relative performance effectiveness of three display format types evaluated in the context of CRT weapons displays used in advanced fighter cockpits. The formats considered were alphanumeric, which used complete words and numbers; black-and-white graphics, which used a pictorial example of the aircraft and bomb load status; and color graphics, which also used pictorial represen tation but added color-coding. The time to answer questions about the display status did not depend upon the type of display format, although complex questions took significantly longer to answer than simple questions. Nevertheless, display format differences were revealed in the error frequency when exposure durations were controlled. Color graphics formats were superior to alphanumeric and black-and-white formats when, a) short exposure durations were used, b) complex questions were used, and c) questions were presented after the subject viewed the display presentation. Overall results indicate that in combat environments that produce high levels of workload on a pilot, color-coding is superior

to other coding formats in the presentation of weapons status information.

82-2

INFORMATION PROCESSING LOAD OF GRAPHIC VERSUS ALPHANUMERIC WEAPON FORMAT DISPLAYS FOR ADVANCED FIGHTER COCKPITS

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Arts

BY

CAPTAIN MICHAEL NEWTON STOLLINGS
B.A., United States Air Force Academy, 1973

1982
Wright State University

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November, 1982

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY MICHAEL NEWTON STOLLINGS ENTITLED INFORMATION PROCESSING LOAD OF GRAPHIC VERSUS ALPHANUMERIC WEAPON FORMAT DISPLAYS FOR ADVANCED FIGHTER COCKPITS BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Thesis Director

Chairman of Department

Committee on
Final Examination

Dean of the School of Graduate Studies

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The work incorporated in this thesis has occupied my total attention for many months, and has benefited from the criticism of many persons. First and foremost has been my mentor, Dr. John M. Reising who first turned me towards the general problem of display format design and helped me maintain a sense of humor during the long hours devoted to the preliminaries associated with experimental design and implementation. Lt. Anthony Aretz and Lt. Gretchen Lizza provided valuable inputs and tremendous support in the areas of data collection and analysis. Joanne Giorlando was the typist. Last but not least, I am extremely grateful for the support and assistance I received from my thesis committee composed of Dr. Herbert Colle, Dr. Ira Fritz, and Dr. Frank Ward who were very responsive to my needs and remained totally sensitive to the time constraints that constantly plagued my very existence. Of course, I can hold none of these persons responsible for any errors remaining in my thesis, except to the extent that they all allowed me to totally disregard their counsel and forge ahead, motivated by the strong desire to finish this part of higher education.

I. INTRODUCTION

In the modern aircraft of today, there has been an increased employment of new visual display systems and sophisticated computers that present operators with increasing amounts of data in new and unusual formats. These evolutions in technology have considerably altered and extended the human sensory and motor ranges past usual capabilities. At the same time, these display systems impose time-critical overload conditions on the operator due to the rapid availability and volume of data. It is therefore essential that display systems be developed to provide aircrew information acquisition, process, and transmittal in the most rapid, accurate, and reliable manner possible. The technology to design and provide this data to the aircrews is already here; the challenge is to provide it in a form which is usable by the operators.

The variables which impact the operator's ability to acquire and process task critical information is of prime importance in the design of effective display systems. Usually the data associated with these variables does not exist in a form that is useful to design engineers. Christ (1975) conducted an exhaustive survey of 42 studies investigating the effects of graphics and color display effectiveness and found that performance is highly dependent upon the specific tasks being performed. Therefore, the design engineer and human factors specialist must study a particular application of information display systems by assessing the effects of varied display characteristics within the context of a particular system to be used and the task to be performed. A logical choice can then be made based on trade-offs between cost of implementation and human performance criteria.

Even though the design engineer has limited access to reliable human/computer display interface data, the airborne application of color display visual systems is already here. Reising and Calhoun (1982) state that color is beginning to enter the crew station in the transport arena with the advent of six color, shadow mask CRTs in the Boeing 757/767 crew station. A similar cockpit is being designed for the Airbus A310. The high-resolution, shadow mask CRTs, when coupled with computer-generated imagery, can produce tremendous flexibility in the manner in which aircraft controls and displays are designed. Jauer and Quinn (1982) have pointed out that computer-generated imagery formats are being proposed for primary flight instrumentation, stores status, engine status, emergency procedures status, and tactical situation displays. Advanced symbol generators and special algorithms are being developed so that highly detailed display formats can be presented in real time, i.e., 30 times per second.

Several studies have been conducted to investigate the interface between the human operator and information display systems and the variables that affect this interface. Strother (1970) found that a single-seat pilot has only 1-5 seconds of observation time that can be dedicated to a display format. It takes .9 seconds to focus; .5 seconds to search and select the required information; .3 seconds to initiate a motor response to the information for a total of 1.7 seconds. Optimistically, she felt that a pilot will only be able to estimate 1-10 pieces of information from a display format in that 5-second period. Variables that affected these results were symbol size and shape, CRT scope size, static versus dynamic symbols, color versus black-and-white, and various combinations of words and number patterns.

The military establishment has long recognized the effects these variables have on the processing capability of a human operator in a complex system. MIL-STD-1472B was developed to list a number of design guidelines applicable to visual display systems. MIL-STD-1472B states that for visual displays to be useful they must be conspicuous and legible, and they must display the type of information the operator needs to know in a way he or she can understand. The format should be in a directly usable form so the operator does not need to transpose, compute, interpolate, or translate the information. These criteria imply that the operator should be able to read information quickly and accurately and to the degree necessary for required performance.

II. LITERATURE REVIEW

The literature that focuses on the empirical evidence directly related to color, black-and-white, and alphanumeric coding of various visual display systems is extensive in some areas and somewhat limited in others. One factor that appears to emerge in studies dealing with the performance advantages of color-coding point out that the effects of color-coding appear to be task dependent. Christ (1975) and Kopala (1979) feel that the question of whether or not color is better than achromatic or monochromatic displays must take into account the *purpose* of the display and the conditions in which it will be used. Christ (1975) undertook a series of studies utilizing more complex tasks and highly practiced subjects and concluded that while color is often an effective coding method, it may be a very effective performance factor under some tasks and conditions, but that it can also detract from others. The main conclusion drawn from these studies is that the effects of graphics and color on human performance are highly dependent upon the specific task to be accomplished. In support of these studies, it has been found that objective measures of relative effects of color on operator performance are much less consistent than subject reports. These studies showed that when subjects preferred color displays and even when they were convinced that color aided their performance, there was little or no objective data to support those subjective feelings. Reising poses this question, "Is it possible that we have not yet been faced with display formats of sufficient complexity that performance differences show up?" (Reising, 1982, p.3). A brief look at the information-processing theories that deal with pictorial versus alphanumeric display format may help determine why many of the visual coding methods operate the way that they do.

INFORMATION PROCESSING AND VISUAL DISPLAYS

Pictorial formats consisting of familiar geometric shapes appear to enhance or at least significantly improve the information-processing capabilities of the human operator. The adage that "one picture is worth a thousand words" appears to hold true. There appear to be several theoretical explanations for why this adage holds. Teichner (1979), in an article on color and visual information coding, discusses the characteristics and qualities of pictorial and color-coded displays by summarizing the advantages and disadvantages of color coding in terms of ten principles of human information processing. The advantages and disadvantages of color-coded visual display formats will be expanded upon in a later section of the paper.

THE PERCEPTION OF PICTURES

Biederman conducted a series of studies to investigate the ability to process pictorial displays. His studies concentrated on the characterizations of the actual visual scene that initiate processing responses. Biederman and Checkosky's 1970 study investigated the effects of excess relevant information to see if it facilitated or retarded the speed of pattern perception. The strategy of the study was to compare reaction times from a task where the stimuli differed on only one dimension with a task where the stimuli differed on two dimensions, either of which could furnish sufficient information for correct recognition. A self-terminating model was compared with an exhaustive model of the processing of redundant visual information. In the case of a redundant, relevant dimension, a response might be initiated as soon as sufficient information is available, even though some of the component processes are not yet completed. If the processes are self-terminating, one would predict that the addition of a redundant, relevant dimension should result in a shortening of reaction times compared to a task with only one dimension relevant. An exhaustive model would imply that the addition of a redundant, relevant dimension should not result in a shortening of reaction times. The results of the study showed that the redundant condition had faster reaction times than the fastest unidimensional condition. The unidimensional conditions also were characterized by higher error rates than the redundant dimension. It was concluded that the self-terminating model of processing was used when there was an excess of relevant information available.

In most natural scenes, redundancy is provided by context, not by completely correlated dimensions. Biederman (1972) conducted another study to determine if perceptual recognition is affected by the meaningful context of a visual display. Biederman's approach to this study held that various items of a visual display are treated as separate entities; that is, they are initially processed independently in a very short-term sensory store and then transferred serially to a long-term storage system. It is in this long-term system that meaningfulness and long-term memory are seen as having their effects. Biederman presented subjects with coherent and jumbled pictorial real-world scenes at exposure durations of 300, 500, and 700 msec. and had them identify a targeted item in each scene. Results showed that coherent pictures had an advantage over jumbled pictures. These results appeared to show that perceptual recognition is significantly affected by the overall meaningful context of the total display. These results caused Biederman to question the order of perceptual recognition. Does the overall characterization or scheme of a scene occur before or after individual object perception?

Biederman, et al., (1973) conducted a study to address this question. The subjects in the study were to recall and indicate, by pointing to one of four object pictures, which object had been cued in the trial pictorial scene.

Biederman jumbled half of the trial scenes by segmenting them into six sections while leaving the target object in its normal pictorial position. By using coherent scenes and target objects located in their normal position on the jumbled scenes, it was found that it takes approximately 1.5 seconds to find an object in a scene. Jumbled scene times were higher and could have been caused because the subjects would have to engage in a detailed feature processing and object identification to determine if the target was in the scene. This, Biederman felt, would support the notion that overall characterization of a scene probably occurs first.

Biederman's et al. (1974) study was concerned with the kinds of information that can be extracted from a single fixation - when perceiving a scene. The experiment was predicated on the belief that the perception of a scene might be something more than the perception of the sum of the individual objects that comprise a real-world scene. Their experiment two was designed to describe the time course of object identification using a circle as a cue to identify a particular object to be recalled at exposure durations of 20, 50, 100, and 300 msec. These durations were too brief for an eye movement. The results of experiment two showed that the mean percentage of correct identifications were significantly affected by scene version and exposure duration. Label similarity did not show any significant effects. The only interaction effect that was significant was scene version and duration. It was concluded from the analysis of the data that subjects were fully identifying the specified objects and not responding on the basis of simple physical features. They concluded that the subjects appeared to use a dual mode of processing, that is, individual objects would be identified along with the attainment of the overall scene characterization.

The theoretical support offered by the Biederman studies have shown that subjects use an overall characterization of a scene in addition to specific details in order to process the relevant information. Since the overall characterization of the scene serves as a cue in the location and identification of specified objects, it appears that subjects are able to use a self-terminated processing model in order to respond or react to a pictorial presentation. Thus, the need to engage in detailed feature processing, object identification, and cognitive storage and recall procedure does not appear to require the amount of time that is needed when alphanumeric displays must be analyzed. Usually, pictorial scenes appear to allow people to characterize and process information more quickly when compared to the processing required to identify and analyze letters and digits. The following studies lend support to the Biederman theory.

A study by Potter and Faulconer (1975) was conducted to see if the early stages of processing lead to a common abstract representation in memory, or to two separate representations, one verbal and the other image-like.

Subjects were shown 96 line drawings of objects or their names written in lower case letters. In the first experiment, subjects were shown items for brief durations of 40, 50, 60, and 70 msec. The durations were presented in a random order and each item was shown equally often at each duration. The exposure duration required to identify 50% of the items correctly was 44 msec. for the drawings and 46 msec. for the words. In the second experiment using a 250 msec. duration, subjects were required to name the line/verbal drawing as rapidly as possible. Drawings took longer to name verbally than did words by an average of 260 msec. In their third experiment, the subjects were to use a yes or no response to indicate if each presentation belonged to a specified category. It was found that line drawings were categorized faster than words by an average of 51 msec. Their results are consistent with the view that the knowledge of an object category is associated with an abstract idea of the object rather than directly with its name or appearance. The actual naming of an object can be slow (Experiment two) because it requires an extra step from the abstract concept to its associated name, whereas naming a word only requires that the word pattern itself be identified and then it may be articulated even before the concept is evoked.

A somewhat different approach in the investigation on how we process pictorial scenes was conducted by Loftus and Kallman (1979). This study references several other studies that have shown that memory or recall performance is better for pictures than for verbal labels. The explanation offered for this finding is that people spontaneously generate both verbal labels and images when pictures are presented but only generate verbal labels when words are presented. A central claim in this model of picture-encoding is that two types of information are acquired during the viewing of a picture, which are termed general visual information and specific detail information. Twenty subjects were shown 320 slides at exposure times of either 50, 100, 250, 500, or 1000 msec. The nature of the experiment was a yes/no recognition test with half of the subjects instructed to find specific details of a picture and half only viewing the picture. Results showed that the group searching for specific details in a picture showed a superior recognition memory performance relative to the other group. They concluded that this superiority stemmed from two sources: the detailed group encoded details at a faster rate than did the other group (focus of attention) and that an encoded detail in a picture provided a better discriminative feature for the detailed group of subjects.

Snodgrass and McClure (1975) conducted an experiment using the recognition memory paradigm to study the storage and retrieval properties of pictures and words. Retrieval properties were studied by testing memory of old items either with the same representational form as the study item (pictures tested with pictures and pictures tested with words) or with the opposite form (pictures tested with words and words tested with pictures). Storage properties were manipulated by instructing subjects either to image or to verbalize to both word and picture stimuli during the study sequence. Snodgrass and McClure felt that if recognition required an active retrieval process, then a decrement in recognition performance should occur with a change in form. But, if recognition does not require a retrieval process, or if the information is stored in some abstract conceptual form, then it could be conceivable that the form of the test item would have no overall effect. In their experiment, the subjects were presented with all picture-word pairs and the verbal instruction group was told to name and rehearse the names of all the stimuli, while the imagery group was told to form visual images of all the stimuli. The pictures used were simple line drawings of common objects and the words were the verbal labels of the pictures. The subjects were required to correctly identify the presentations in a later recognition test as either old or new as per pre-briefed instructions. Snodgrass and McClure calculated an overall recognition memory performance index by comparing hit rates with appropriate false alarm rates. Results indicated that picture memory in the verbal instruction condition was far superior to word memory. Another finding was that imagery instructions improve the recognition of words over verbal instructions, but that verbal instructions do not improve recognition of pictures over imagery instructions. It was also found that subjects in both instructional conditions showed superior memory of form for old pictures than for old words. Results showed that both concept and form memory for pictures were unaffected by instructions, whereas concept and form for words showed improvement by instructions to image over instructions to verbally rehearse the material. These results might be interpreted as follows: In memory experiments, adult subjects appear to naturally store both pictorial and verbal codes to simple pictures, whereas they do not naturally store dually encoded words (Paivio, 1971). Storage of pictures appeared to be unaffected by instructions, since subjects under both instructional conditions encoded stimuli identically. Storage of words is affected by instructions. The subjects under imagery instructions encoded words dually, using both pictorial and verbal codes; whereas subjects under verbal instructions encoded words singly, using only the verbal code.

King and Bevan (1979) used a reduction-cueing method to investigate the dual coding hypothesis of recall, which states that separate, functionally independent memory codes exist for pictorial and verbal stimuli. Subjects were presented a series of labeled drawings depicting a simple action involving an agent and an object acted upon as stimuli for recall. The label consisted of a written trigram (noun-verb-noun) describing the drawing. Each cueing condition was formed by a combination of individually presented single or double cues that were either pictorial or verbal in nature. Data analysis suggested that cueing with pictures in mixed pairs resulted in access to parts of the trace not available to verbal cues and not vice versa. Overall, their results did not totally support the dual-coding hypothesis. This was because there are aspects of the memory trace accessible to pictorial cues that are immune to verbal cues, therefore, no part of the memory trace can be simultaneously accessible to verbal cues and unaccessible to pictorial cues. Using a transformational hypothesis, King and Bevan assumed that, when an observer sees a pictorial cue, he names the picture and uses both pictorial and verbal aspects of the memory trace for processing. Therefore, results should find high overall recall with pictorial cues as well as large reduced valences associated with the pictorial components of mixed cues. They also point out that if the observer attempts to call up a pictorial process in the presence of a verbal cue, they are faced with a more difficult task.

A study conducted by Nelson, Reed, and Walling (1976) was designed to investigate conceptual similarity between visual stimuli to determine if the superiority effect of pictures could be attributed to differences in the efficiency of the sensory codes. Previous conceptual similarity results indicated that equivalent interference was generated between conceptually similar and nonsimilar paired-associate stimuli, suggesting that pictures and their labels contacted comparable semantic representations and therefore, the pictorial superiority effect may not be the result of more effective meaning codes. Nelson, et. al., also varied schematic similarity among pictorial representations. Schematic similarity was high when all of the pictures appeared similar, sharing a common configuration, and was low when the pictures were drawn to share a minimum of physical features. They argued that if the picture-word difference is primarily related to differences in the sensory codes, then high schematic similarity should eliminate and possibly reverse the usual pictorial superiority effect. In addition, schematic similarity among pictures should therefore have little effect if their visual configurations are not processed or if the resulting sensory codes are highly transitory. Subjects in the study viewed slides at 1.1 sec and 2.1 sec that were designed to manipulate stimulus type, schematic similarity, conceptual similarity and rate of presentation. Results of the study showed that the usual pictorial superiority effect was obtained when schematic similarity among the pictures was low. However, when the semantic similarity was high the effect was reversed. Nelson, et al., felt that the reversal of the pictorial superiority effect depended upon the rate of presentation. Overall, the poorest performance was obtained when pictures served as the paired-associate stimuli and interference was present at both the sensory and meaning levels. Nelson, et al., concluded that both pictures and their verbal labels have forms of sensory expression in the physical world and both types of stimuli can process content, and that both can signify meaning. The manipulation of schematic and conceptual similarity indicate that the principal difference between simple pictures and their labels is inherent in their expression as physical stimuli. They conclude that the sensory code for a picture is apparently more differentiating and less susceptible to interference from successively occurring items. Nelson, et al., also argued that the meaning codes associated with pictures are superior to and totally independent of the meaning codes associated with labels, and that the conceptual similarity among the two types of stimuli generate the same amount of interference among both types of meaning codes. Their findings suggest that pictorial stimuli provide a qualitatively superior sensory code for simple pictures, and the semantic representation for pictures and their corresponding labels may be identical.

Snodgrass and Asiaghi (1977) compared concept memory against stimulus meaning to test the hypothesis that pictures are more memorable than words because of a superior sensory rather than conceptual code. Seventy-two subjects viewed slides of line drawings or their corresponding verbal names and were to identify them as old or new depending on instructions given to their experimental group. Data analysis revealed that there appeared to be no differences between experimental and control groups in memory performance, and no differences between instructed and uninstructed groups in memory performance but that there were large differences between pictures and words. Their results indicated that the memory advantage enjoyed by pictures is unaffected by test modality, which suggests that pictures are superior to verbal labeling in producing better conceptual rather than sensory memory. There was also a suggestion that the sensory code for pictures helps recognition memory performance, since no evidence of sensory code facilitation was observed for correct responses and false alarms. Their overall finding was that the superiority effects of pictures in recognition memory primarily was due to the superior ability of pictures to establish conceptual memory codes, rather than to their distinguishability at the sensory code level as either old or new items.

Again, these studies support the view that pictorial displays are more easily processed than verbal labeling. This is because spontaneous verbal processing is accomplished when pictures are presented whereas verbal labeling requires the subject to analyze and recognize letters and digits, then search for comparative concepts in the memory, before responding to the display.

The following sections of the literature review will focus on four main areas. First the evidence related to the comparison of alphanumeric versus graphic displays will be discussed. This will be followed by a discussion of the overall effects of color-coding as it is related to graphic and alphanumeric presentation. The overall effects of color-coding will be further analyzed by discussing those situations where color-coding is an effective coding method and those situations where color-coding has proven ineffective.

GRAPHICS VS ALPHANUMERICS

The literature that focuses on the empirical evidence directly related to graphic vs. alphanumeric displays is somewhat limited. Nawrocki (1972) found no significant advantage to either graphics or alphanumerics when subjects were required to remember previously presented information. In a study of computer printout formats, Grace (1966) found that two alphanumeric formats ("Verbal" and "Data Block") resulted in significantly better interpretation scores than did a pseudographic format. From a training aspect, Rigney and Lutz (1976) found that students trained using graphic representations of electro-chemical processes performed better on a post-test than did students trained using a text presentation.

A study comparing graphic versus alphanumeric displays was conducted by Vicino and Ringel (1966). They evaluated the decision-making ability of subjects when tactical information was presented in alphanumeric and graphic forms. A series of slides depicting three enemy sectors was presented to the subjects and they were asked to decide which of the enemy forces was preparing to attack. The battlefield information was presented alphanumerically and graphically. The findings of the study were that no differences in (a) quality or (b) timeliness of decision or in confidence that a decision was correct were found between alphanumeric and graphic presentation. Vicino and Ringel concluded that since alphanumeric and graphical presentation of information results in equally efficient decision-making behavior for certain tasks, some question is raised concerning the utility of introducing elaborate symbol generation and display devices in future information processing systems. If the utilization of graphic representation is deemed necessary for some fairly specific tasks, it can be plotted manually without the problems of supporting automated symbol generation devices.

Tullis (1981) evaluated operator performance with graphic and alphanumeric display formats in a computer-based telephone line testing system. Bell System employees evaluated four types of CRT display formats. The narrative format used complete words and phrases. The structured format used a tabular format to present display information. The black-and-white graphic format used a schematic of the telephone line. Color graphics used a schematic but added color-coding. The subjects were measured in terms of speed and accuracy of response to interpretation of telephone malfunctions. Analysis of their results indicated that accuracy did not significantly vary with format. There was a significant effect of format on response time. It was found that response times for the two graphic conditions were significantly shorter than for the narrative conditions. The only results that did not reflect this advantage was the accuracy data. Another consistent finding was the lack of a significant difference between color and black-and-white graphic formats. The overall conclusion reached by Tullis was that graphic formats can enhance performance when applied to this specific task, but that color-coding and shape coding were equally beneficial in their effects on performance. Color-coding was just as beneficial to performance as was shape coding in this experimental application.

The relative advantage of graphic or alphanumeric display formats again appears to be task-oriented. Graphic formats were subjectively chosen as the most advantageous and color-coding was considered valuable for its aesthetic advantages, but objective performance results did not appear to support these findings. The literature pertaining to the advantages and disadvantages of color-coding compared to other coding methods will be explored in the next section.

COLOR-CODING

The effects of color-coding display formats has been studied more extensively. Reising and Calhoun (1982) and Krebs and Wolf (1979) have stated that the designer of a multicolor display should explicitly define the rationale behind the decision to use color. There are two basic reasons that apply to most situations: (1) increasing the esthetic appeal of the final product; and (2) improving the display functionally through the use of color-coding. Increasing "eye appeal" is certainly a valid criterion but not one that is necessarily functional in nature. In fact, multicolor symbology "coded" in a way that does not relate to operator information might not show a performance change or might actually be distracting. The basic reason for this dependence on color as a redundant coding method is to prevent information overload to the human operator. Christ (1975), in his survey of studies investigating the effects of color-coding on visual search and identification, found that the effectiveness of color depends upon experimental conditions, with search tasks generally being enhanced by color and identification tasks sometimes showing enhancement and sometimes degraded performance. Christ (1977) undertook a series of studies utilizing more complex tasks and highly practiced subjects. His subjects were required to monitor a display console and to respond as requested to one of three or four different tasks (choice reaction, search and locate, and identification-memory). It was concluded that the design engineer should not be concerned with _color qua color_, but that he should be aware that color can be used as another dimension along which information can be presented. Whether color should be used for that purpose depends upon how it effects human performance for any particular task or purpose.

Evidence of Effective Uses of Color-Coding. One of the earlier studies conducted to compare the effects of color versus black-and-white coding was accomplished by Smith (1963). The subjects in this experiment were required to conduct search and count tasks on displays containing 20, 60, or 100 items consisting of vectors, letters and three-digit numbers. Half of the displays were in color and half in black-and-white. The results of this study showed that the independent variables of search and counting time, as well as counting errors, increased with increasing display density, and that the addition of color as a redundant code resulted in an average time reduction of 65 percent in the visual search task; counting time was decreased by 69 percent, on the average; with an overall reduction of 76 percent in counting errors. In the color displays, all the symbols in an item were displayed in a particular color, with the particular color code chosen to be redundant with a specific letter, i.e., "F" was always green. Search and locate questions were used to evaluate the search and counting tasks. The value of the display color-coding in the counting task was not limited to its effect in reducing time required since there was also a sizable reduction in counting errors. Smith concluded by saying that the effectiveness of color-coding was not surprising under the circumstances of this particular experiment since it was designed to show a greater absolute difference for color-coded items.

Smith and Thomas (1964) extended Smith's (1963) earlier work by examining the usefulness of color as a nonredundant code, and comparing it with other possible visual coding dimensions, in particular with shape coding. Coding based on shape or symbology has always been a most versatile means of presenting information on visual displays because of the large "alphabet" of discriminable symbols that can be used. Subjects were required to count objects of a specified color or shape on displays of increasing item density. Results again confirmed that as the display item density increased, counting time increased linearly. The results also confirmed that despite differences in experimental procedures and the use of different Ss, the average color counting time results, and error frequency results, are identical to the Smith (1963) study. The overall results of this study explicitly confirm the effectiveness of color-coding for a counting task and presents data to provide a quantitative measure of the relative superiority of color over various shape codes.

Christ (1975) conducted a study to analyze unidimensional and bidimensional displays using relatively simple single tasks (choice reaction, search and locate, and multiple target identification). The experiment was designed to investigate the effectiveness of color-coding relative to coding with letters, digits, and familiar geometric shapes. Christ has always supported the view that the advantages of color-coding appear to be task specific.

The use of color over achromatic or monochromatic displays must take into account the purpose of the display and the conditions in which it will be used. Christ has also pointed out that objective measures of the relative effects of color on operator performance are much less consistent than the subjective reports of the operator. This research was limited to examining the effects of color on objective measures of human performance. The study consisted of a multiple display-multiple task system designed to provide a revised and expanded table of gains and losses associated with the use of color in visual displays relative to achromatic coding variables.

Results of this study concluded that when a subject is to identify a single target as rapidly as possible, color produced relative losses in choice reaction time as large as 16 percent and relative gains as great as 36 percent. These percent difference scores varied as a function of achromatic code use and display item density. The use of color in search and locate tasks generally leads to a relative decrease in search/locate time. The greater gains are more likely to occur for more dense displays. When the subject is required to identify multiple targets from a briefly exposed display, color is less effective as a target code relative to achromatic stimuli if the primary objective is to maximize the accuracy of responses. However, if the average correct response times are of primary importance, color-coding leads to superior performance relative to letters, digits, or shapes, but as Christ points out, the effects in either case are never very large. In conclusion, it appears that color-coding will benefit performance in any task that must deal with more complex, multiple stimulus formats and when the subject must distinguish one class of stimuli from another. Christ does point out that even though there were relative differences in performance attributable to color, it is not certain that color was the only coding variable or the best coding variable that could produce these results.

Silverstein (1982) presented a seminar on human factors for color CRT displays. In the operator performance section of his presentation, he stressed that the nature and complexity of the operator's task, the manner in which color is functionally related to the task, and the operating environment are all major determinants of color-coding effectiveness. He felt that color-coded information displays offer the most potential for enhancing performance in certain operational situations.

In a review of a compilation of a large number of studies that differed considerably in their purposes and methods, Silverstein concluded that: (1) color is superior to size, brightness, and shape as unidimensional target features but inferior to alphanumeric symbols; (2) color is superior to size and shape within nonredundant, multidimensional displays and equivocal with respect to alphanumerics; (3) adding completely redundant color to an achromatic, multidimensional display facilitates identification performance, and (4) partially redundant color and natural color representation have little effect on identification accuracy.

The conclusions reached by Silverstein have been addressed by several other researchers. Teichner (1979) did extensive research in the areas of color and visual information coding. His conclusion was that color could be useful in visual coding in three ways: (1) to provide pictorial or scenic realism, (2) to overcome the effects of image degradation or of masking effects due to clutter or other visual noise, and (3) to code informational events in visual displays that are used to represent specific meanings. The distinction between the second and third possible use of color is one between sensory processing of visual data to the point of image acquisition and a perceptual-cognitive processing of the acquired image. Teichner then developed a list of 10 principles that are useful in the formulation of complex color formats which blend different levels of coding. To summarize the advantages, Teichner found color to be useful as an information chunking unit and for the storage of information in the memory. Color was found to interfere as a coding method when it was irrelevant or partially redundant. Color was also not a useful indicator of detail when display sets of items were greater than six.

The overall conclusion to be reached from these studies is that color can be a useful coding device that will improve operator performance if properly applied to a given format. These studies also stress that color-coding is very task specific and that research should be conducted with specific tasks and visual display formats in mind. Silverstein gives an excellent summary of Krebs (1978) list of situations where color-coding can be most beneficial:

1. Unformatted displays
2. High symbol density
3. Operator must search for relevant information
4. Symbol legibility may become degraded
5. Color code is logically related to operator's task
6. Information requirements and/or operator work load are high

Evidence of Ineffective Uses of Color-Coding. As previously mentioned, the use of color-coding can actually be detrimental to operator performance. Again it appears that the specific task to be accomplished by the operator is the determinate factor in determining which coding method is most suitable to the situation.

Calhoun and Herron (1981) conducted an experiment to evaluate whether pilot performance, while identifying aircraft engine parameter failures, is better when engine information is integrated onto a single electro-optical display compared to electro-mechanical instruments. A secondary purpose was to determine the effectiveness of color-coding the engine display information. Calhoun and Herron used a single-place cockpit simulator to test aircraft engine display formats as they might appear in the actual aircraft. Results indicated that response times to emergency situations with both the monochromatic and color CRT formats were significantly shorter than those with conventional electro-mechanical instruments. Concerning the comparison of the monochrome and color CRT engine formats, there were no significant performance differences noted. This study also confirmed the fact that subjective responses to color versus monochrome formats vary significantly from objective performance measures. Color was chosen as the best display format by 82% of the subject pilots. Overall, the subjects felt that the effectiveness of the formats was equal and that color-coding is not worth the additional expense. This study is significant because it took an application's approach in evaluating the effectiveness of color formats. This allowed an actual performance measurement of pilots under simulated flight conditions. Calhoun and Herron concluded that designers should take into account the full graphics capability afforded by computer driven displays and that they should carefully evaluate the benefits of the application of color. These results concur with Krebs (1978) study in which he concluded that color-coding is not beneficial when the display format is relatively static, symbol density is low, and symbol legibility is not degraded.

In a previously described study, Tullis (1981) failed to find a benefit from the use of color graphics compared to monochrome graphics for presenting diagnostic data. For the four displays used in the study there were no significant benefits to human performance from the use of color graphics over black and white graphics. Subjects did express a clear preference for color graphics but Tullis makes a generalization that color is only beneficial if the complexity of the display or the number of dimensions to be coded make it impractical to convey information.

Christ (1977) conducted a research program to evaluate the empirical basis of possible design recommendations for or against the use of color in aircraft displays. The first phase of the experimental research program used highly practiced subjects to investigate the effectiveness of color-coding relative to coding with letters, digits, and geometric shapes. The results of this phase of the program were equivocal; the direction and magnitude of the effects of color vary as a function of task variables. The second phase of the program used more complex multiple task conditions. The subjects were required to monitor a display console and to respond as requested to one of three or four different tasks. Of the results that dealt with color, it was found that task uncertainty and variations in exposure time had no effect on the relative effectiveness of color-coding. The third phase of the program investigated the realistic application of color-coding to an operational situation. Subjects assumed the role of an air traffic controller and were in control of aircraft flight parameters on a CRT display. The overall conclusion of phase three was that practice on the task, to the point where the subjects were operating the air traffic control task proficiently, produced no differences in performance on the air traffic control task that could be related to a difference between the effects of shape or color-coding.

The results of the previous studies and investigations provide no basis for concluding that color has any peculiar advantage or disadvantage to task performance that makes it different from achromatic codes used for comparison. Whether color-coding should be used for the application of adding one more dimension along which information can be presented, depends upon how it compares in its effects on human performance for a particular purpose. The question in any specific case derived from this literature should be one of how to best encode the display; the best way may or may not involve the use of color-coding.

SUMMARY

The overall purpose of any visual display is to transmit specific information about the status of a particular system to an operator of that system. The question of whether to use color in this regard is whether or not it may be employed to increase the rate of information transmission and improve operator performance. Several key considerations have emerged from the review of the current literature in this area.

(1) Subjective preference ratings and questionnaire responses to the use of color-coding indicated that color

coding is preferred to other coding methods, but objective performance results do not tend to support this preference.

(2) The bulk of the data available from the cited literature reviews is derived from subjects with minimal experience.

(3) There is also some suggestion that the characteristics of display density and exposure duration interact in their joint effects on identification accuracy. This tends to be a critical consideration for display design.

(4) The effectiveness of color-coding is highly dependent upon the specific task to be accomplished by the operator.

(5) The last consideration is one of realism. Since color-coding is task oriented, it is essential that performance measures be made in realistic or quasi-realistic environments to get an accurate account of actual operator performance levels using a given format.

THE HYPOTHESES

With these considerations in mind, the purpose of this study will be to investigate and compare the effectiveness of color pictorial displays, black-and-white displays, and alphanumeric displays by systematically manipulating several variables. Experiment one will investigate reaction times to the different display formats. In experiments two and three, the first variable to be manipulated will be the exposure duration to the display format. This should force one of the displays formats to be superior to the others under short exposure durations. The next variable to be manipulated will be the type of question the pilot will be required to answer when viewing a display format. There will be a simple question type that will require only one piece of data to be retrieved from the format or a complex question type that will require two pieces of information to be retrieved. The complex question type should cause an additional processing load on the subject and the display format that best aids the information processing load should prove superior to the other formats. A question before and question after condition will also be evaluated to study the effects of format type on recognition and recall performance. The study will use highly experienced pilots, viewing fixed information display formats in a realistic attempt to monitor and recall weapons status information as it might appear in a CRT equipped aircraft.

The research was designed to investigate the following hypotheses.

1. a. The first hypothesis is that pilot response time will increase significantly when the pilot is required to obtain several pieces of information from a display (complex question) versus only one piece of information (simple question). When several pieces of information are required, the task becomes similar to a visual search and count

task in which color has shown superior results (Christ, 1977; Smith, 1963).

b. Since color can be a redundant coding method when used in conjunction with shape coding, it should follow that color pictorial formats will have shorter response times when compared to black-and-white pictorial and alphanumeric formats for both complex and simple questions. The addition of a redundant coding method should allow more rapid processing of information especially if used in conjunction with the advantages that can occur with the use of pictorial displays (Biederman, 1970; Nelson, et al., 1976).

2. a. The second hypothesis is that color pictorial formats are superior to black-and-white pictorial and alphanumeric displays when exposure duration is very short but will not be superior at longer exposure durations. Given ample time to view any format should allow equal response accuracies. Under more difficult, limited exposure conditions, the display format that most effectively presents the data should prove superior to other format types (Biederman, 1974; Christ, 1975; Silverstein, 1982).

3. a. The third hypothesis is that there will be more errors with the question presented after the format presentation than if the question is

presented before the format presentation but that the error difference between before and after question presentation should decrease as exposure duration is increased.

b. Since rehearsal will be allowed in the question "after" exposure, color pictorial formats should produce a smaller error rate over black-and-white and alphanumeric because it provides the subject with an additional cueing aid to help recall the requested information. The application of a question before presentation and question after presentation compare the effects of format type on recognition and recall processing capabilities. Recall events normally take longer to respond to and are not as accurate as recognition tasks (Christ, 1977).

III. METHOD

SUBJECTS

Twenty-four operationally qualified pilots with a mean flying time of 850 hours served as subjects in this experiment. These pilots have flown fighter and attack aircraft such as the A-7, F-4, and F-105 that had as a primary or secondary mission ground attack or close-air support. Experienced fighter pilots were used to ensure familiarity with weapons terminology, weapons switchology, and weapons delivery procedures. All pilots had been current at one time in the delivery of MK-82 bombs on conventional or tactical bombing ranges.

All subjects satisfied the color vision requirements established by the U.S. Air Force by scoring at least 9 out of 14 correct on the VTA-CU (Vision Testing Apparatus - Color Vision) color differential chart or at least 50 points on the VTA-CTT (Vision Testing Apparatus - Color Threshold Test) color test.

APPARATUS

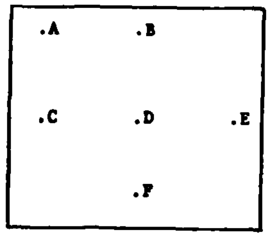
Each pilot was tested in a static mockup of a single-place F-16 cockpit. This cockpit contained a 5 x 5 inch display screen mounted at eye level to display weapons status information to the pilots. Information pertaining to weapons onboard the aircraft was back-projected onto the display screen using a Kodak Ektagraphic RA-960 random access projector controlled by a Kodak Ektagraphic RA-960 Remote Control Unit. Exposure duration was controlled by a Uniblitz shutter attachment on the projector. Activation of the lens shutter attachment and elapsed times/exposure durations were controlled and recorded by an APPLE II Computer using a Mountain Computer Apple Clock Board. The subject manually initiated each slide presentation via a button located on top of the F-16 "joystick." In experiment one, the shutter was opened when the subject depressed the joystick button and was closed when the subject released it. In experiments two and three, the subject initiated the slide presentation by depressing the button but the termination of the presentation was controlled by the APPLE II computer as determined by a predetermined exposure duration. Slides (2 x 2) were used to display sixteen different weapons status options (see Appendix C). Subjects were seated 36 inches from the 5 x 5 inch display screen. These dimensions subtended approximately 3° of arc. The 5 x 5 inch display format was chosen because of its current use in McDonnel Douglas F-15 and F/A-18 and General Dynamics F-16 fighter aircraft.

DISPLAY LUMINANCE CHARACTERISTICS

A variable aperture was attached to the Uniblitz shutter control in order to maintain luminance at a comfortable level on the display screen. A Prichard Model 1980 CDB-PL Photometer with a Standard OL-7 objective lens was used to measure luminance levels in foot lamberts at several locations on the display screen without any slides present. The luminance levels are listed in Table 1.

Table 1

Display Screen Luminance Levels



Location	Foot Lamberts
A	102 FL
B	164 FL
C	152 FL
D	271 FL
E	105 FL
F	137 FL

All location points, except location "D", were measured ½ inch from the edges of the screen. Location "D" was measured at the center of the display. With the projector bulb off and the display screen in the normal experimental position, the luminance was measured at an average of 7.3 FL.

Ambient illuminance was measured using a Spectra Photometer, Model FC-200, and was found to be 16 foot candles (FC) incident normal to the display surface with the display screen in the luminance test position. The illuminance measured with the display screen in the normal experimental position was measured at 0.5 FC.

Color measurements using the 1931 C.I.E. xy chromaticity scale were made using the Macbeth Corporation TRIAD II Colorimeter, Model KCS-14.

Three xy measurements were taken on each of the five colors used in the color pictorial formats. The average of the three measurements are listed in Table 2.

Table 2.

Chromaticity xy Coordinates

Color	XY Coordinates	
Red	.514	.402
White	.483	.424
Blue/Violet	.436	.392
Green	.478	.427
Yellow	.504	.431

Due to the narrow construction of the bomb shapes, the yellow and green color measurements reflect some desasturation because of the white background that interfered with the measurement.

EXPERIMENTER'S CONSOLE

The experimenter's console was located directly behind the subject's station allowing the experimenter to view all subject activities while not interfering with the subject's field of view. The console consisted of the Kodak Remote Control Unit to allow the experimenter to individually select a particular slide for each given presentation.

Exposure duration for each slide trial was selected through the APPLE Computer. Each subject also had a subject data sheet that listed all format presentation orders (Appendix B), slide orders, duration and question orders per trial, and an answer sheet designed for each trial.

FORMAT DESIGNS

The three display formats, color pictorial, black-and-white pictorial, and alphanumeric were presented on 2 x 2 slides. All three display formats contained identical weapons status information. For example, slide one in the color format contained the same weapons status information as slide one in the black-and-white and alphanumeric formats (Figures 4, 5, and 6, Appendix D). There were sixteen individual weapons status display slides within each specific format. One slide tray was used to hold all of the slides for each of the display formats. The slides were arranged in numerical order and were selectible through the Kodak Remote Control Unit. The weapons status information contained on each slide consisted of seven different levels of the following factors:

1. Bomb Quantity: The total number of bombs on board in the following levels; 6, 8 10, 12 bombs.
2. Interval Setting: Will apply interval settings between bombs in the following levels; 030 ft., 040 ft., 060 ft., and 075 ft.
3. Fuzing: Determines fuzing on bombs as either nose, tail, or nose and tail fuzing.

4. Master Arm: Refers to Master Arm switch position as either ON or OFF.

5. Stations: Refers to the actual weapons stations on the aircraft's wings being used to store the bombs and are listed as Stations 2, 3, 6, and 7.

6. Mode: Determines what delivery mode has been selected by the pilot and are labeled as SINGLES, PAIRS, or SALVO.

7. Bombs Armed: Refers to the number of bombs that have been armed by the pilot and consist of the following quantities: 2, 4, 6, 8, 10, and 12 bombs.

Color Formats. Weapons information in the color format will be represented in the following manner (Figure 6, Appendix D).

1. Quantity: Bomb shapes were color-coded in yellow with a solid black outline. Green bombs are armed and are considered part of the total quantity.

2. Interval Setting: This information was indicated by the word INTERVAL followed by the actual setting and will be located in the tail section of the aircraft silhouette.

3. Fuzing: The nose section of the bomb was color-coded black for NOSE fuzing and the tail section of the bomb was color-coded black to indicated TAIL fuzing.

4. Master Arm: Master Arm ON was indicated by the centerline tank being color-coded red. A black centerline tank outline only indicated Master Arm switch OFF.

5. Stations: Stations were indicated by the location of the bombs on-board each wing, i.e., two clusters of bombs on the left wing indicated stations 2 and 3 in use, two clusters on the right wing indicated stations 6 and 7 are in use.

6. Mode: Mode selected was indicated by arrows pointing to particular bombs to represent the mode, i.e., one arrow on the format represented SINGLES, two arrows only would represent PAIRS, and arrows pointing to all the bombs would indicated SALVO release. The use of arrows is an individual coding method and therefore does not point at a particular bomb to be released.

7. Bombs Armed: The center section of the bomb shapes were color-coded in green and could have either NOSE or TAIL fuzing included, or no selected fuzing at all.

Black and White Format. Weapons information in the black-and-white format will be represented as follows (see Figure 5, Appendix D):

1. Quantity: Bomb shapes were outlined in black dashed lines. Black armed bombs are part of the total quantity.

2. Interval Setting: Interval settings were indicated in an identical manner to the color format.

3. Fuzing: The nose section of the bomb was outlined in a solid black line for NOSE fuzing and the tail section of the bomb was outlined in a solid black line for TAIL fuzing.

4. Master Arm: Master Arm ON was indicated by the centerline tank being color-coded solid black. A black centerline tank outline only indicated Master Arm switch OFF.

5. Stations: Stations were indicated in an identical manner to the color format.

6. Mode: Mode selections were indicated in an identical manner to the color format.

7. Bombs Armed: The center section of the bomb shapes were color-coded solid black and could have either NOSE or TAIL fuzing included, or no selected fuzing at all.

Alphanumeric Format. Weapons information in the Alphanumeric format were represented in black alphanumeric letters and numbers and were displayed in the following order (see Figure 4, Appendix D).

1. Quantity
2. Interval Setting
3. Fuzing
4. Stations

5. Bombs Armed

6. Mode

7. Master Arm: The ON or OFF response will be blocked in a solid black line box.

Trial Questions. Experiments one, two, and three used two levels of questions to task the subject's ability to obtain information from a given display format. The questions will be labeled "simple" and "complex" and will relate to the weapons information contained on each format (Appendix B).

Exposure Durations. In experiment one, the APPLE clock recorded reaction times from switch activation to switch release and provided a print-out of reaction time in seconds to nine decimal places. In experiments two and three, the APPLE clock was programmed for exposure durations at predetermined levels of 50 msec., 100 msec., 250 msec., and 750 msec. Actual exposure levels were measured at 63 msec., 111 msec., 252 msec., and 750 msec. with each level being a mean of five trial exposures. The ranges extended to 2 or 3 msec. above and below the mean. The discrepancy between the APPLE clock durations and the actual exposure durations was due to the hardware interface between the APPLE computer and the Uniblitz shutter control and because the Uniblitz shutter control would "hang-up" if the exposure durations were made shorter than 50 msec.

EXPERIMENTAL DESIGN

The experimental design for this study consisted of post-test only, repeated measures factorial design. Three experiments were conducted using different combinations of the following independent variables.

1. Question types at two levels: simple and complex.
2. Display formats at three levels: color, black-and-white, and alphanumeric.
3. Exposure duration at four levels: 63 msec., 111 msec., 252 msec., and 750 msec.
4. Question presentation at two conditions: before and after display presentation.

The specific combination of independent and dependent variables including the order for each treatment, will be discussed in each experiment description.

Experiment One. This experiment was a 2 x 3 factorial design and was conducted to determine a baseline performance for each subject on each format type. The independent variables were:

(a) Question Type: simple and complex

(b) Display Format: color pictorial, black-and-white pictorial, and alphanumeric.

The dependent variable was time response measured to 0.01 seconds from pilot activation of the presentation to termination of the presentation initiated by the joystick button. Question type was assigned in a random order and the display formats were determined by using a 3 x 3 latin square. Slide presentation within a given format was determined in a random order. All 16 slides within a given display format were observed before going to the next display format as determined by the latin square.

Experiment Two. This experiment was a 4 x 3 x 2 factorial design and was conducted to control the time duration that the display was presented to the subject. The independent variables were:

(a) Exposure duration: 63 msec., 111 msec., 252 msec., and 750 msec.

(b) Display Format: color pictorial, black-and-white pictorial, and alphanumeric.

(c) Question Type: simple and complex.

The dependent variable was the number of errors in response to the questions presented in each of the experimental conditions. Each subject received eight examples of the combination of each of the independent variables, therefore, the errors could range form 0 to 8.

Display formats were determined by using a 3 x 3 latin square. Exposure duration was determined by using a 4 x 4 latin square. Question type and slide presentation order were assigned in random order.

Experiment Three. This experiment was a 4 x 3 x 2 factorial design in which a simple question was asked either before or after the display presentation. The independent variables were:

(a) Exposure duration: 63 msec., 111 msec., 252 msec., and 750 msec.

(b) Display Format: color pictorial, black-and-white pictorial, and alphanumeric.

(c) Question Presentation: before or after.

The dependent variable and experimental design was the same as experiment two. The question before and question after conditions were assigned in a random order.

PROCEDURE

Each subject was required to attend two experimental sessions to complete the study. Session one took approximately 45 minutes to complete and consisted of the initial overall briefing and experiment one. Session two occurred seven to ten days later and took approximately 90 minutes to complete. Session two consisted of a refresher briefing and experiments two and three. The subjects were scheduled according to their individual availability.

Briefing/Familiarization. Each subject received a briefing on how the Weapons Status information was displayed on each of the display formats (Appendix C). He then viewed four samples from each display format for 20 seconds to familiarize himself with the formats used and with the information contained on each display. The subject was exposed to each of the 8 simple and 8 complex questions and how they could be answered by using each of the display formats. The subject used the joystick activation button to initiate each sample presentation. Subject questions were answered at this time.

Experiment One. On each trial, the following sequence of events occurred. First the proper slide was selected by dialing it into the remote control unit, which dropped it into the slide projector. The subject was asked if he was ready to begin. The subject pressed the joystick button to illuminate the display and released it when he felt that the could answer the question. The subject answered the question after slide termination. The search was made as rapidly as possible consistent with an errorless report to the question asked. The amount of time the subject took to press the button was recorded as response time, measured to 0.01 seconds. Slides on which incorrect answers were given were retested at the end of the experiment one trials. Each subject viewed 32 trial conditions for each format in this experiment, 16 using simple questions and 16 using complex questions.

Experiment Two. The initial set-up for experiment two was identical to experiment one except that the subject viewed the format presentations at four predetermined exposure durations controlled by the APPLE clock. The subject was asked the question before the slide presentation. Slides were exposed when the subject depressed the joystick button. Subjects attempted to answer the question following termination of the display presentation. Subjects were allowed to omit answers.

Omitted answers were counted as incorrect responses. Each subject viewed 64 trial conditions for each display format.

Experiment Three. The initial set-up and procedure for this experiment was identical to experiment two except that subjects only had to answer simple questions. On one half of the trials, the subjects were asked the simple question before the exposure while on the other half of the trials they were asked the question after the exposure. These two types of trials were randomly intermixed. Each subject viewed 64 trial conditions for each display format type in this experiment. Again, omitted answers were counted as incorrect responses.

IV. RESULTS

EXPERIMENT ONE

The experimental design was a 2 x 3 factorial with subjects treated as a random effect and all other variables considered as fixed. The time needed to respond did not depend upon display format. The format effect was not statistically significant, $F\ (2,46) = 0.41$, $p > 0.05$. The response times did depend upon type of question asked (simple vs. complex) and was statistically significant, $F\ (1,23) = 134$, $p < 0.001$. Complex questions took an average of 0.56 seconds longer to answer than the simple questions did. The interaction of format and question type was not statistically significant $F\ (2,46) = 0.25$, $p > 0.05$. Figure 1 shows the effects of the three display formats on the mean response times of the subjects. The percentage errors in the alphanumeric format was 4 percent for the simple questions and 5 percent for the complex questions. The percentage error in the black-and-white format was 4 percent for the simple questions and 5 percent for the complex questions. The percentage error for the color format was 4 percent for the simple questions and 5 percent for the complex questions. The complex question type required longer to answer than the simple question type suggesting that the technique was sensitive to the need for additional

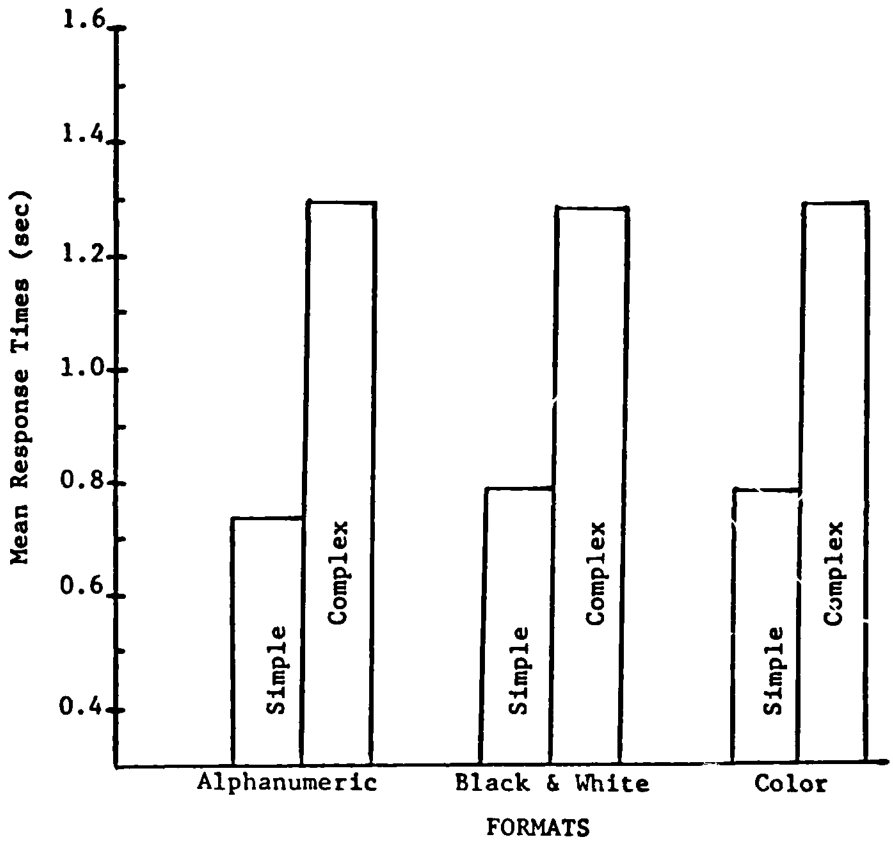


Figure 1. Mean response times for display formats as a function of question type.

processing to handle the complex questions. Format, however did not influence time to respond. The pictorial formats took as long as the alphanumeric formats.

EXPERIMENT TWO

The 2 x 3 x 4 ANOVA conducted on the variables of format type, exposure duration, and question type revealed that all main effects and all interactions were statistically significant. The subjects were given eight exposures to each format condition. Therefore the number of errors in each experimental condition could range from 0 to 8 for each subject.

The mean percent correct responses for the subjects was affected by display format type, exposure duration, and question type. Format type was statistically significant, F (2,46) = 22.1, $p < 0.001$, as was exposure duration, F (3,69) = 247, $p < 0.001$, and question type, F (1,23) = 669, $p < 0.001$. The interaction of format and exposure duration, format and question type, and exposure duration and question type all significantly affected the mean percent correct responses. Format and exposure duration was statistically significant, F (6,138) = 6.08, $p < 0.001$, as was format and question type, F (2,46) = 41.3, $p < 0.001$, and exposure duration and question type, F (3,69) = 65.8, $p < 0.001$. The three-way interaction of format type, exposure duration, and question type was also significant, F (6, 138) = 7.11, $p < 0.001$.

A comparison of the mean percent correct responses for the simple question condition and complex question condition reveal that the three format types had similar mean percent correct responses at each of the four exposure durations for the simple question condition. Under the complex question condition, the color format was superior to the alphanumeric and black-and-white formats at the three shorter exposure durations with all format types appearing equal at the 750 msec. duration (Figure 2).

Because the three-way interaction was significant, the relationship between format type and exposure duration was further explored by using a separate 3 x 4 ANOVA on the data from the simple questions and again on the data from the complex questions. For the simple question type, format did not significantly affect mean percent correct responses, $\underline{F}$ (2,46) = 0.50, $\underline{p} > 0.05$, but exposure duration did have a significant effect, $\underline{F}$ (3,69) = 50.2, $\underline{p} < 0.001$. The interaction of format and duration for the simple question type was also not statistically significant, $\underline{F}$ (6,138) = 0.28, $\underline{p} > 0.05$. As Figure 2 shows, the percent correct responses increased from 79% at the 63 msec. duration to 95% at the 750 msec. exposure duration.

For the complex question type, format did significantly affect mean percent correct responses, $\underline{F}$ (2,46) = 40.4, $\underline{p} < 0.001$, and exposure duration still had a significant effect, $\underline{F}$ (3,69) = 186, $\underline{p} < 0.001$. The interaction of format and duration for the complex question type was

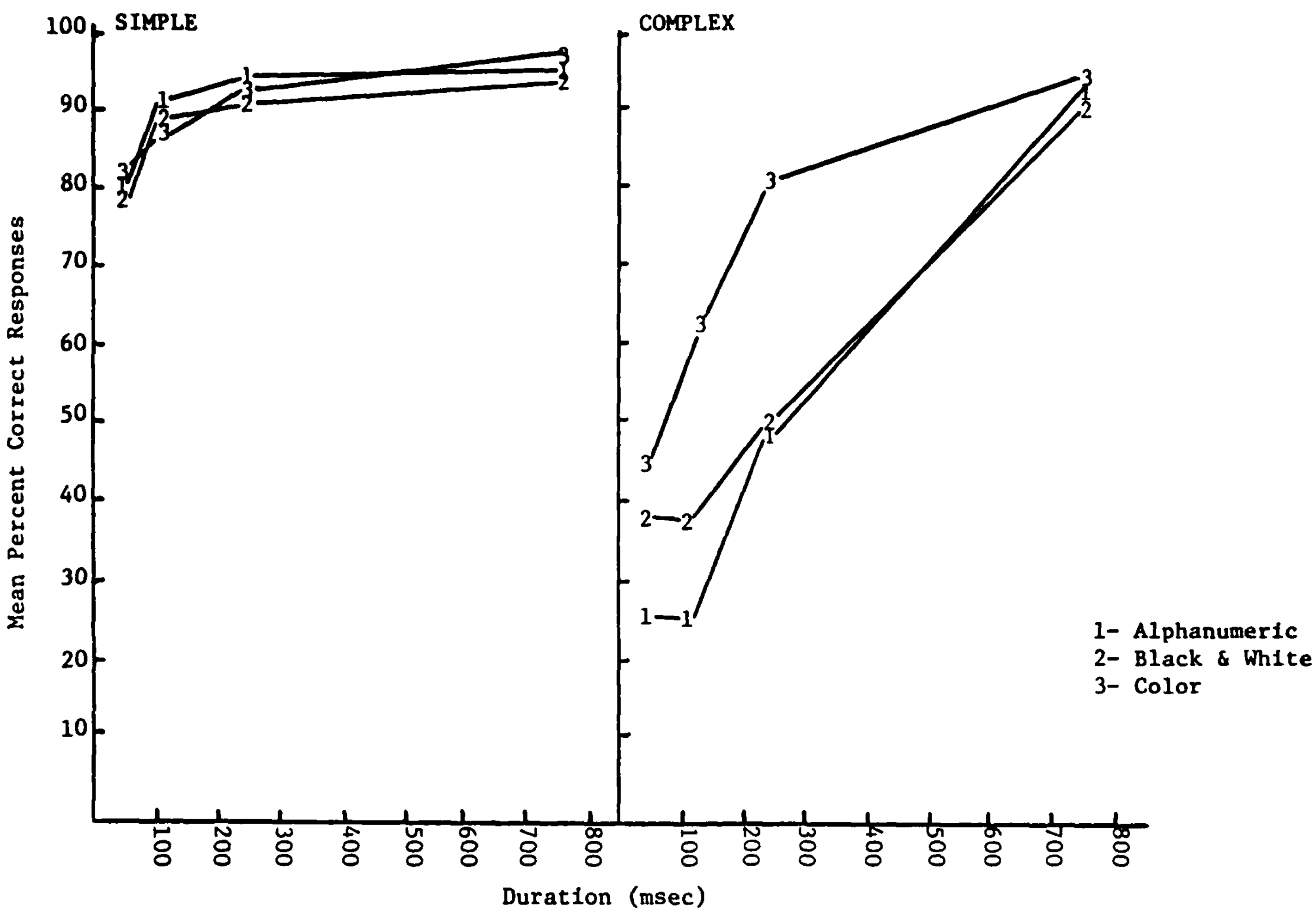


Figure 2. Comparison of format type for simple and complex questions.

significant, F (6,138) = 11.1, $p < 0.001$. The range of percent correct responses for the complex question type was 26% at the 63 msec. exposure duration and 95% at the 750 msec. duration. The advantages of the color pictorial format occurred at the shorter exposure durations, and at 750 msec., no significant differences existed between the formats.

EXPERIMENT THREE

The 2 x 3 x 4 ANOVA conducted on the variables of format type, exposure duration, and question presentation revealed that all main effects and all interaction effects were statistically significant. The subjects were given eight exposures to each format condition. Therefore the number of errors in each experimental condition could range from 0 to 8 for each subject.

The mean percent correct responses for the subjects depended on display format type (F (2,46) = 81.8, $p < 0.001$), exposure duration (F (3,69) = 173, $p < 0.001$), and question presentation ($F(1,23)=139$, $p < 0.001$). The interaction of format and duration, format and question presentation and duration and question presentation, all significantly affected the mean percent correct responses. Format and exposure duration was statistically significant, F (6,138) = 7.46, $p < 0.001$, as was format and question presentation, F (2,46) = 18.0, $p < 0.001$, and exposure duration and question presentation, F (3,69) = 10.5,

$p < 0.001$. The three-way interaction of format type, exposure duration, and question presentation was also significant, $F(6,135) = 2.12$, $p < 0.05$. The results as indicated in Figure 3 show that color pictorial displays have superior response accuracy at exposure durations of 63 msec. and 111 msec., in both the question before and question after conditions. The effects of format type are reduced at the 750 msec. exposure duration indicating that format type is not necessarily a significant factor as long as the pilot has ample time to view the display. Comparison of the mean percent correct responses in the question before and question after condition for each format type show that the alphanumeric format varied from 68 percent to 43 percent at 63 msec., 78 percent to 39 percent at 111 msec., and from 94 percent to 67 percent at the 252 msec. duration. The black-and-white format varied from 70 percent to 48 percent at 63 msec., 64 percent to 48 percent at 111 msec., and from 90 percent to 73 percent at the 252 msec. duration. The color format varied from 88 percent to 70 percent at 63 msec., 88 percent to 73 percent at 111 msec., and from 97 percent to 87 percent at 252 msec. Even though the question after condition consistently produced lower mean average responses, the color format consistently remained superior to the other formats at the three shorter exposure durations.

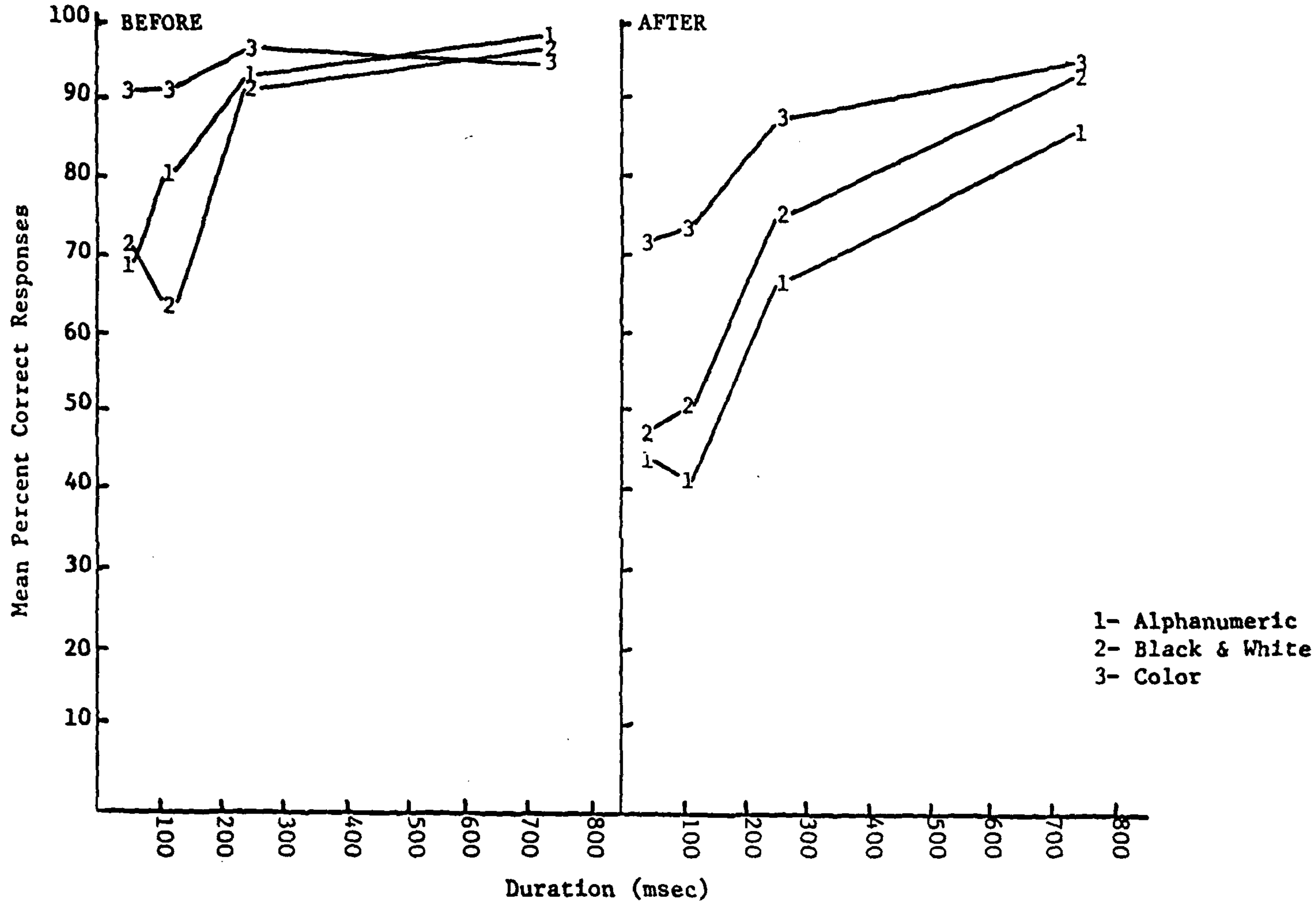


Figure 3. Comparison of format type for the question before and question after conditions for a simple question type.

Because the three-way interaction was significant a separate 3 x 4 ANOVA was conducted on the question before presentation and question after presentation. Unlike the results of the simple question condition of experiment two, both format and format X duration were statistically significant in the question before condition. Display format had a significant effect on mean percent correct responses, F (2,46) = 32.0, $p < 0.001$, as did exposure duration, F (3, 69) = 91.9, $p < 0.001$. The interaction of format and duration for the question before condition was also significant, F (6, 138) = 6.82, $p < 0.001$. Response accuracy in the question before condition ranged from a low of 64 percent at the 111 msec. duration to a high of 99 percent at the 750 msec. duration as shown in Figure 3.

For the question after condition, display format had a significant effect on mean percent correct responses, F (2,46) = 57.7, $p < 0.001$, as did exposure duration F (3,69) = 82.6, $p < 0.001$. The interaction of format type and exposure duration for the question after condition was also significant, F (6, 138) = 4.08, $p < 0.001$. As Figure 3 shows, response accuracy in the question after condition ranged from a low of 39 percent at the 111 msec. duration to a high of 94 percent at the 750 msec. duration. Again, the advantages of the color pictorial format occurred at the shorter durations, and at the 750 msec. duration, no significant differences exist between the formats.

V. DISCUSSION

One of the most important findings of the present study was that color graphic display formats showed superior results for response accuracy over alphanumeric and black-and-white formats when exposure durations were extremely short. There are several reasons why this finding is particularly important. First, the finding suggests that for the specific task of monitoring weapons status information, color-coding and pictorial representations appear to improve the information processing capability of the pilot under extremely short exposure durations. Second, color-coding appears to have a more pronounced effect on response accuracy when the pilot is required to identify and process more than one piece of information at a time (complex question type). Third, the finding strongly implies that recommendations given to design engineers concerning the design of visual displays must be based on a thorough knowledge of the tasks to be accomplished by the pilot under all possible situations. These tasks usually consist of the acquisition and identification of pertinent information from a display that will have direct consequences on the specific mission segment being flown. Weapons displays are unique in that their value as an information display system usually occurs in situations where the pilot is under heavy workload. The extremely high delivery speeds used by today's jet fighters coupled with low altitude penetration and enemy threat arrays can very often only afford the pilot a brief glance at his weapons status to confirm or reconfigure his delivery options. Any coding method that will enhance the pilot's acquisition and analysis of information pertaining to the status of a monitored system is extremely important.

Under normal less demanding flight conditions, such as navigation at high altitudes, pilot workload is minimal and as much time as necessary can be devoted to the acquisition of information from a given display system. Experiment one shows that when a pilot is not restricted by short exposure durations or short eye fixations, color graphic, black-and-white graphic, and alphanumeric formats were equally effective in presenting the requested information. Since the pilot's reaction time to a given format was not forced by low exposure durations, the strategy used to answer the simple and complex questions ensured that the answer was correct before extinguishing the display. The strategies used produced an average reaction time of approximately 800 msec. for the simple question type and 1300 msec. for the complex question type. These results are consistent with the results of experiments two and three which show that the three format types did not differ significantly at exposure durations approaching 750 msec. Although not required in this study, in order to force a difference to emerge between display formats, subjects must be forced to respond faster by using feedback or direct answering via switch closures or voice-activated switches, or by using deadline procedures. Reaction time appears to measure the time required by the pilot to use multiple strategies that will insure error free performance. The use of a deadline design will force the pilot to use only the most efficient strategy he can develop to find the requested information and this approach should allow any differences in format type to emerge. Format type was not significant under the reaction time conditions of this study. Therefore, at longer exposure durations, the findings of experiments one, two, and three, are in agreement with Christ (1977) who concluded that color, while often an effective coding method, offers no significant advantage in respect to human performance over achromatic codes such as shape coding.

The results of experiments two and three point out that the color display format had superior response accuracy compared to the alphanumeric and black-and-white formats at the shorter exposure durations of 63, 111, and 252 msec. There are several considerations to be discussed that impact these results.

The simple question condition of experiment two and the question before condition of experiment three appear to be identical situations but the results of the two experiments are not the same (see Figures 2 and 3). The mean percent correct responses in the question before condition of experiment three are consistently lower than the mean responses of the simple question condition of experiment two at exposure durations of 63 and 111 msec. One possible explanation for these findings is that the design of experiment three (question before and after) did not allow the subject to develop a consistent strategy from trial to trial based on the uncertainty of what the next trial condition might be. This mixed strategy caused a time delay in the processing of information contained in the display causing an increase in error frequency. Experiment two allowed the subject to develop a fixed pattern search strategy for all trials because the questions were always asked before format presentation. Therefore, the subject always knew where to fixate before the format was presented.

The higher mean percent correct responses for simple question type compared to the complex question type for the 63, 111 , and 252 msec. durations in experiment two can be explained by fixation strategies used by the subjects. As previously explained, in the simple question conditions, the subject can fixate at a known location on the display screen. During the complex question condition, the subject can fixate at a known location to answer part of the question but must initiate a search of the display format to answer the remaining part of the question. This additional search requirement causes a time delay that results in an increased number of error responses at duration exposures of

63, 111, and 252 msec. The 750 msec. exposure duration allows sufficient time for several fixations, hence a lower error rate. Eye movements were not measured in this experiment. The advantages of color-coding are therefore more evident with complex questions at the shorter exposure durations and occur because the subject is able to utilize color as an additional aid in the search fixations resulting in a higher mean percent correct responses compared to the other formats. These results support the conclusions of Smith (1963), Christ (1975), and Krebs (1978), that state that color-coding will benefit performance in any task that requires the subject to search for relevant information in a display. Christ (1975) also states that if average correct response times are of primary importance, color-coding leads to superior performance relative to letters, digits, or shapes, and this is again supported by the results of experiment two.

The question after results of experiment three can also be explained by the fixation strategy used by the subject. As in experiment two, the question before conditions allows the subject to fixate at a predetermined location before display presentation. In the question after condition the subject would fixate at a predetermined location and hope he could fixate his eyes at least one additional time to locate the requested information. At exposure durations of 63 msec. and 111 msec., this eye movement was not feasible and correct responses only occurred if the subject's predetermined fixation point was close to the required area on the display. Response accuracy increased at higher exposure durations and started showing consistently better performance at and above the 252 msec. duration (see Figure 3). Color again shows superior performance over alphanumeric and black-and-white formats and therefore appears to aid the pilot's memory in a recall task. These results are in support of the findings of King and Bevan (1979) because there is a high overall recall advantage using pictorial cues and that the addition of color-coding will enhance the processing of pictorial information. These results also support Smith's (1963) findings that the addition of color as a redundant code resulted in an average time reduction of 65 percent in the visual search task and should therefore allow a subject to retain more information from a color display which will enhance the amount of information that can be recalled in the question after conditions.

The advantage of color coding could have been predicted using Kreb's (1978) list of situations where color-coding can be most beneficial in a display format. In the display formats used in this study, symbol density varied but was usually high, color-coding was logically related to the pilot's task, the information requirements and the pilot's workload was high, and the pilot was required to search for relevant information. The results of this study differed with the results of Calhoun and Herron (1981) and Tullis

(1980) who concluded that color-coding was not beneficial to operator performance. The Calhoun and Herron study used relatively simple, static display formats that were low in symbol density which according to Krebs (1978) should not show a beneficial affect for color-coding. The Tullis study also used display formats of simple complexity which had a limited number of dimensions to be coded and again color-coding was not required to convey the information in a more effective manner. The situations listed by Krebs (1978) that result in increased operator performance by the addition of color-coding are supported by this study.

The addition of color-coding as a redundant coding method when used with shape coding, etc., appears to give the pilot an additional cueing aid that allows easier storage and retrieval of the viewed weapons status. The obvious advantage here is that the pilot will not necessarily have to look back into the cockpit during periods of high performance maneuvering when his complete attention is demanded. It is during these periods of intense workload that the pilot must be able to confirm his weapons switchology in the minimum time possible. The color-coded graphic display proved superior to alphanumeric and black-and-white graphic displays during these periods of minimum exposure to the weapons display formats.

VI. CONCLUSIONS

The immediate purpose of this study was to compare the effectiveness of color graphic displays, black-and-white graphic displays, and alphanumeric displays using actual weapons status display format under realistic monitoring conditions. For the specific task of monitoring the weapons system on an aircraft, color-coding was superior to the other coding methods used in the other display formats. The specific conclusions of the study are:

(1) Within the limits of the present study, pictorial display formats are superior to alphanumeric formats at short exposure durations. This superiority diminishes at longer exposure durations.

(2) Color-coding is superior to black-and-white coding for the complexity of the weapons display formats used in this study.

(3) Color-colding was superior to the other coding methods when informational requirements, hence, operator workload were high (complex question). This is probably most representative of the informational requirements a pilot might encounter under actual combat conditions, i.e., he must be sure that the proper fuzing has been selected in

addition to confirming the status of the Master Arm switch.

(4) Color-coding was also superior to black-and-white and alphanumeric coding when the pilot had to recall information from a previously viewed format display. The ability of a display format to allow effective recall of information without the need for continuous monitoring is a valuable aid to the pilot. The ability to keep the pilot's attention outside of the cockpit in high threat environments and during periods of extreme workload demands cannot be over emphasized.

The weapons formats utilized in this study are extremely simplified approaches to the pictorial coding of an aircraft's weapons options. Today's combat aircraft can carry numerous weapons systems that all have unique carriage and arming switchology requirements. Many of today's aircraft have up to 22 stations on board to hold weapons versus the four stations used in this study. Even though each aircraft will have unique requirements in terms of the pictorial and color-coding of its weapons options, this study has confirmed that the use of pictorial representation utilizing color-coding materials is the superior coding method to use during periods of high pilot workload and limited display format viewing opportunities.

APPENDIX A

FORMAT PRESENTATION ORDER

(A) ALPHANUMERIC (B) BLACK-AND-WHITE (C) COLOR FORMAT

SUBJECT	EXPERIMENT #1	EXPERIMENT #2	EXPERIMENT #3
1	ACB	ACB	CBA
2	CBA	BCA	BCA
3	BAC	ACB	ACB
4	BAC	CBA	CAB
5	CBA	BAC	CBA
6	ACB	CBA	BCA
7	ACB	ABC	CBA
8	CBA	BCA	ABC
9	BAC	CAB	CAB
10	CAB	BAC	ACB
11	ABC	ABC	BAC
12	BCA	BAC	ABC
13	CAB	CAB	BCA
14	BCA	BCA	BAC
15	ABC	CBA	ABC
16	BAC	ACB	ACB
17	ACB	ABC	BAC
18	CBA	ACB	CBA
19	BCA	CBA	CAB
20	CAB	CAB	ABC
21	ABC	BAC	CAB
22	ACB	CAB	CAB
23	CBA	ACB	ABC
24	BAC	BAC	ACB

APPENDIX B

Simple Questions

1. How may bombs do you have on board?
2. What is your interval setting?
3. What type of fuzing do you have selected?
4. Is the Master Arm switch ON or OFF?
5. How many stations do you have selected?
6. What delivery mode do you have selected?
7. Do you have any bombs armed?
8. How many bombs do you have armed?

Complex Questions

9. Is the Master Arm switch ON or OFF and what type of fuzing do you have selected?
10. How many bombs are on board and how many are armed?
11. How many stations do you have selected and what is your delivery mode?
12. How many bombs are armed and what is your interval setting?
13. How many bombs are on board and what type of fuzing is selected?

14. Do you have any bombs armed and how many stations do you have selected?
15. What type of delivery mode do you have selected and what is you fuzing?
16. Is the Master Arm switch ON or OFF and what is your interval setting?

APPENDIX C. WEAPON DISPLAY FORMATS

WEAPON DISPLAY FORMATS
OPTIONS (SLIDE NUMBER)

STATUS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
TOTAL QUANTITY	6	12	10	8	6	12	8	6	12	10	10	8	6	12	10	8
INTERVAL SETTING	030	040	075	060	040	075	030	075	060	060	040	075	060	030	030	040
TYPE FUZING	NOSE	TAIL	NOSE	TAIL	TAIL	NOSE	NOSE	NOSE	TAIL	TAIL	TAIL	NOSE	TAIL	NOSE	NOSE	TAIL
NUMBER STATIONS	2	4	4	4	2	4	4	2	4	4	4	4	2	4	4	4
BOMBS ARMED	2	8	10	4	4	12	6	6	6	8	10	8	4	6	6	6
MODE SELECTED	SINGLE	PAIRS	SALVO	SINGLE	PAIRS	SALVO	PAIRS	SALVO	SINGLE	SINGLE	PAIRS	SALVO	PAIRS	SALVO	SALVO	SINGLE
MASTER ARM	ON	OFF	ON	OFF	OFF	ON	ON	ON	OFF	OFF	ON	ON	OFF	ON	OFF	OFF

APPENDIX D.

WEAPONS FORMAT EXAMPLE

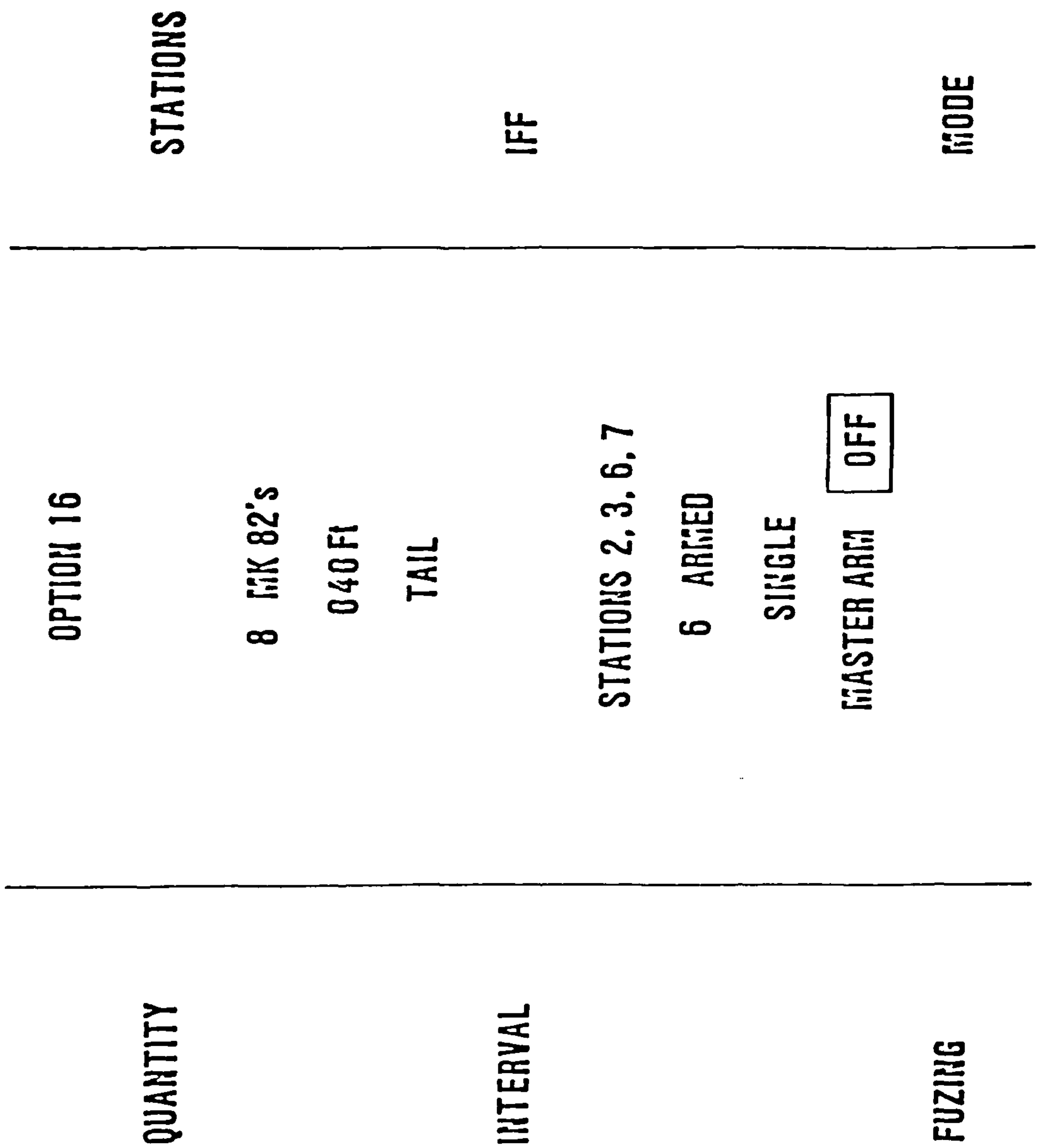


Figure 4. Alphanumeric Format Example

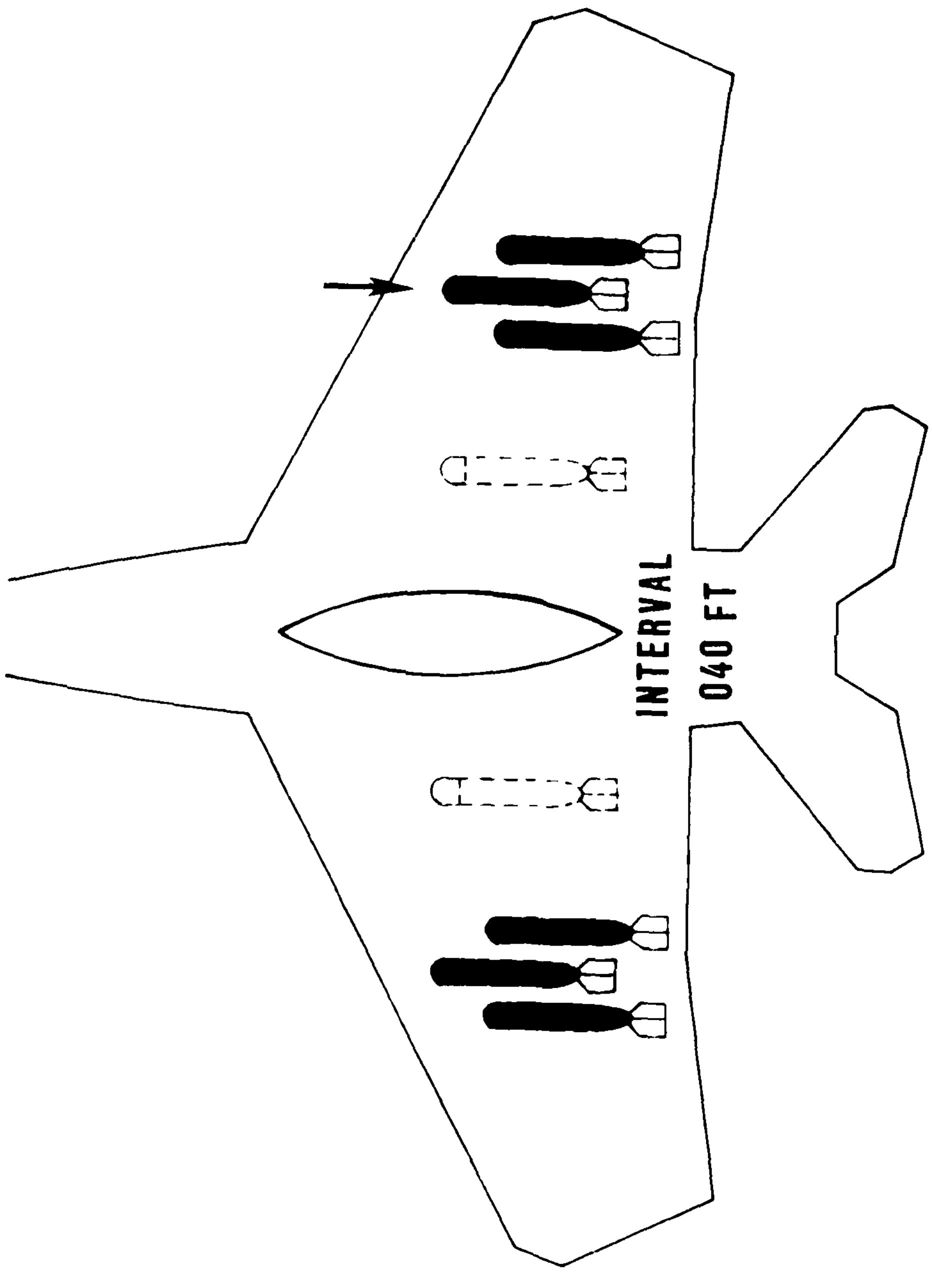


Figure 5. Black-and-White Graphic Format Example

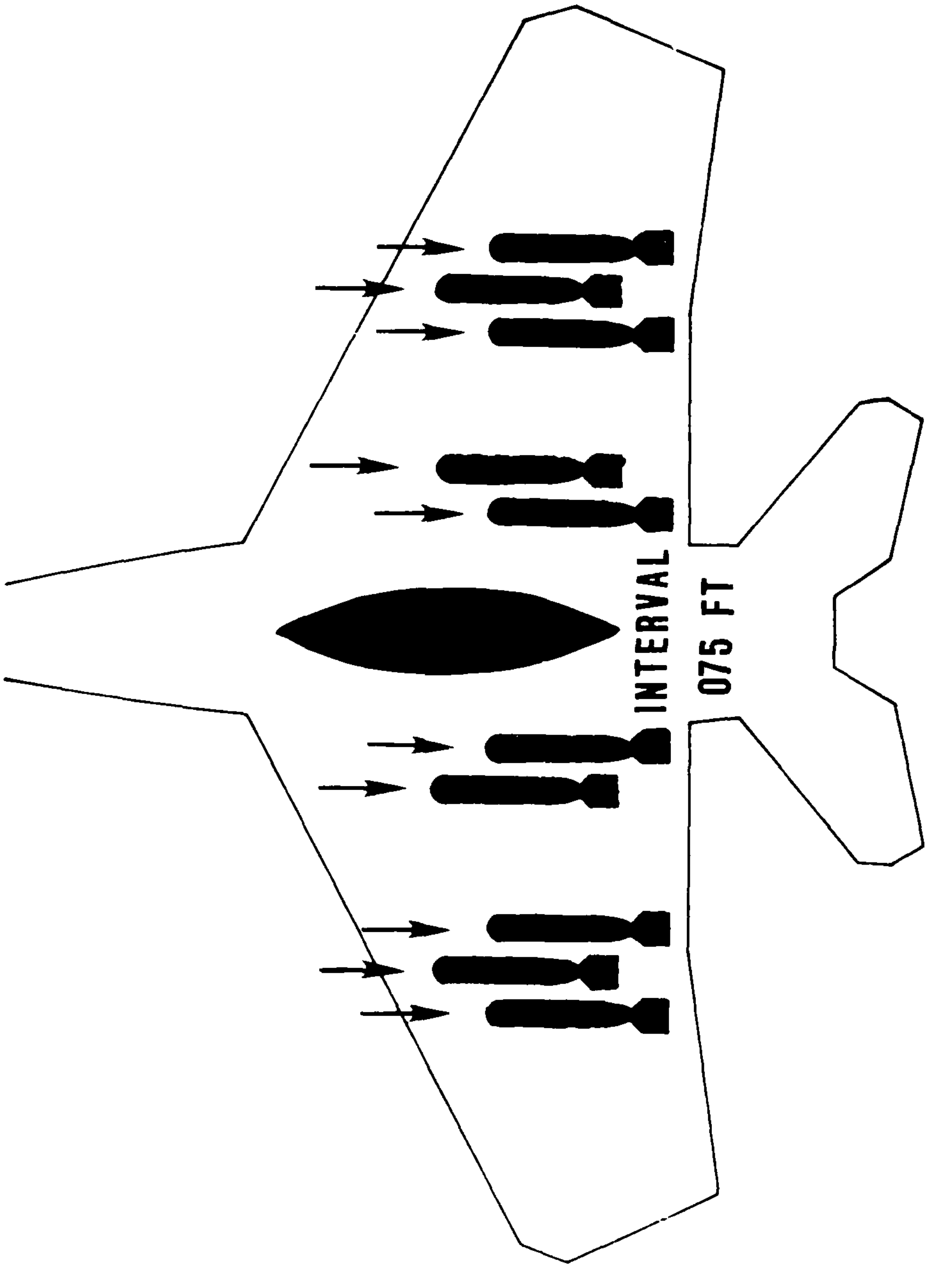


Figure 6. Color Graphic Format Example

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