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"Metaphoric Displays for Dynamic Tasks"

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The Contractor, Klein Associates Inc., hereby certifies that, to the best of its knowledge and belief, the technical data delivered herewith under Contract No. F33615-86-C-0544 is complete, accurate, and complies with all requirements of the contract.

Date

Paula G. John, Director
Finance and Administration

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Introduction

What effect are computer generated displays having on dynamic tasks such as piloting an aircraft or controlling critical stages of process manufacturing? Operators have been accustomed to mechanical analogue displays; will display designers be able to format a CRT screen as effectively? What guidelines are available to designers who want to be sure that there is not too much information on a screen and that the operator will retain orientation even during emergencies? One possible source of guidelines is the use of metaphors, and this report examines the potential value of metaphoric displays.

The emphasis of this report is on dynamic tasks, where the situation changes, unexpected events occur, and operators are under time pressure to react. Although we are not so concerned about such relatively static tasks as text editing or library information retrieval, many of the issues discussed will have relevance to static tasks as well.

The Organizing Value of Metaphor

Although the concept of metaphor in design has been recognized (Carroll, 1983), there have been no guidelines for its application. We see metaphor as potentially useful in two ways: (a) to the designer as a source of organization and a decision guide about how to portray information, and (b) to the user as an attention guide to important information needed for skilled action under time pressure. This report concentrates on the ways that designers use metaphor and the ways metaphor might be used more systematically and effectively. We do not examine the effect of metaphor on the user, which remains an important consideration in designing displays.

People who operate complex machines such as jet planes and nuclear power plants require detailed and complex information about the current situation in order to perform their tasks. Because the situations of process control and flight are dynamic and complicated they pose a challenge to designers who construct the instruments and displays that allow operators to perform their tasks. At its best, a display presents dynamic information that specifies the world so that operators can use it to guide their adaptive action in complex, dynamic, and often time-limited situations. Metaphor can focus attention in an immediate way (Verbrugge, 1980), for use in situations where action is highly skilled and requires close attention to key information in the environment. For example, metaphor can guide attention to the resources available, provide a framework for viewing a situation, and provide a focus of interpretation. The word-processor-as-typewriter metaphor leads the user to notice the resources for creating text, aids the user in seeing the task in terms of an activity that is well known, and provides a focus for interpreting the effects of different commands. One major question of the present study is whether metaphors exist that could serve as resources for display designers who work on operator and crew station displays. Such metaphors would provide guidance on what to display, how to display it, and how different displays could be organized.

The coupling of current computer technology with advances in cathode-ray tube (CRT), liquid crystal (LC), and charge-coupled display (CDD) technology radically altered the work station design task. Pictorial or graphic information displayed on a CRT can be used to support many types of tasks or activities, and may have distinct advantages over isolated alphanumeric displays (Adam, Dillard, Velten, & Guenther, 1963; Furness, 1986; MacGregor & Slovic, in press). These new display devices are inherently flexible, allowing one screen to be reconfigured for different tasks and scenarios. And, perhaps more important, CRTs can be used to display dynamic changing situations in rich detail. Rather than designing isolated dedicated instruments such as fuel gauges and pressure gauges, designers now have the option of displaying pictorial information and of fusing many types of information into one display. In fact, in many ways the CRT and other display surfaces present the designer with a "blank slate," for they allow completely new kinds of displays. These new displays can present in a much more direct way the layout of surfaces and the organization of events in the real world; information is present in the organization of the display and does not have to be coded into letters, numbers, and conventional symbols and then decoded by the user. The importance of organization in display design has been recognized (Easterby, 1967), and new display technologies make systems of organization even more important. Thus, the presence of so many possibilities for the display suggests the need for guidelines and methods of organization that designers can use efficiently to create and test such new kinds of designs. There is some evidence that simply adding relevant information about a task can distract from designated relevant dimensions as much as adding irrelevant information does (Edgell & Castellan, 1986). It is precisely for this reason that it is so important for designers to understand just what to display. The purpose of this study is to explore the value of metaphors for effective displays for either operator or crew stations.

Metaphor is a potentially powerful tool for guiding attention by referring to what is well known and familiar in order to comment on or to depict what is less well known. With an increase in the use of pictorial displays come more opportunities for visual metaphor. Indeed, metaphors are pervasive in designs for interfaces in the areas of word processing and animation (Carroll & Mack, 1985). Organizing metaphors (which structure a whole display or set of displays) and visual metaphors (which can appear in iconic displays) seem to be important tools for designers of word-processing software and interfaces. An example of an organizing metaphor is thinking of a word processor as a desktop. The word processor can be talked about and depicted as involving desktop objects and activities. Creating a "file" in a computer is not the same kind of activity as putting paper in a file drawer, but it does bear an actual resemblance to that activity. Written texts are saved and can be recovered. In addition, metaphor has been powerful in training and teaching skilled action in order to aid learners in smooth performance (Klein, 1978). For example, in playing tennis, hitting a forehand at the net can be described as like "shoving a pie in someone's face." The metaphor organizes a set of actions the learner already knows and can bring to bear smoothly in the new task. The resemblance between different domains supports the transfer of skilled action known well in one domain to action in another domain, and supports, also, the transfer of knowledge as the basis for inferences and reasoning about new domains (Klein, 1987).

Are designers of CRT display formats taking advantage of metaphor as a tool? In what ways might metaphor be useful in designing display formats, for what tasks, and with what degree of effectiveness in aiding the user of the display? In order to investigate these questions a definition of metaphor is required along with a theoretical foundation for the use of metaphor as part of a visual representation.

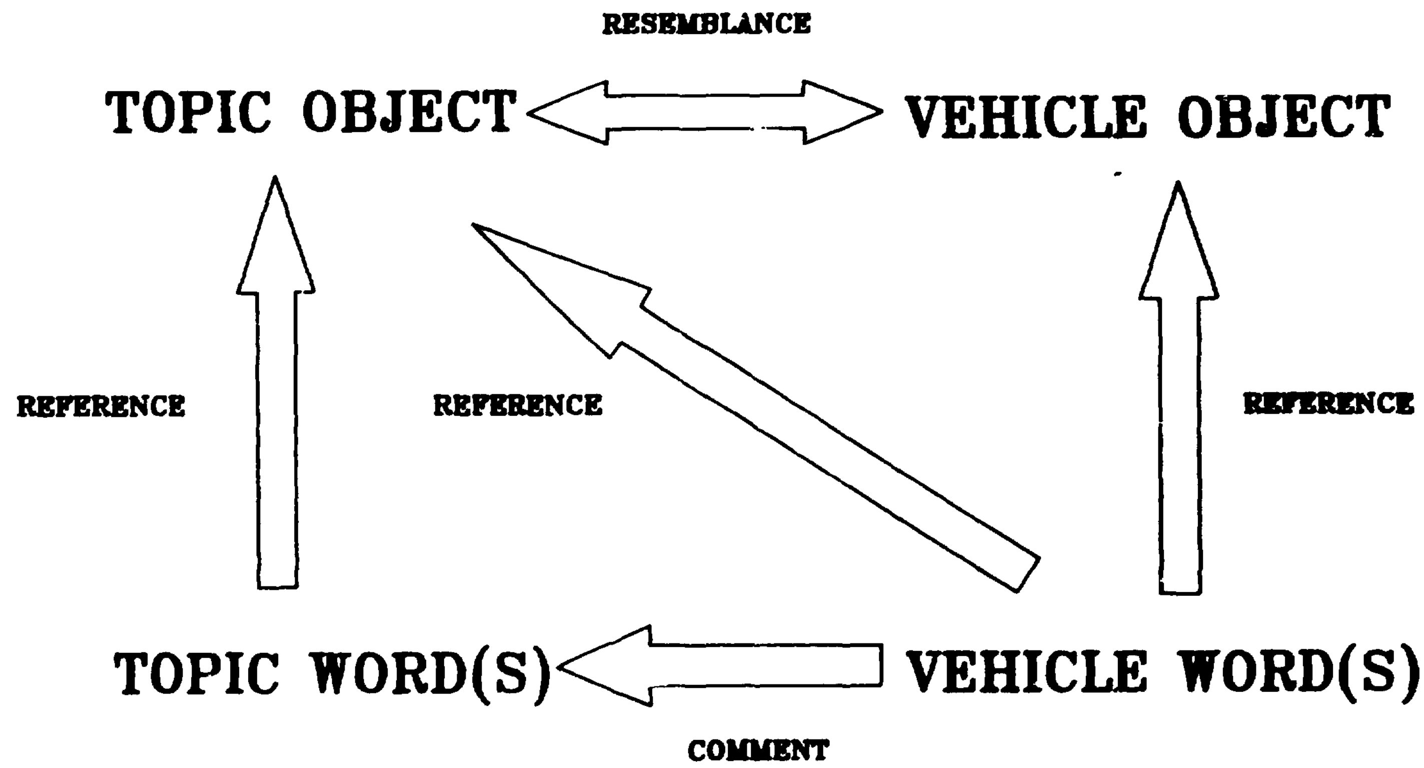
Definition of Metaphor

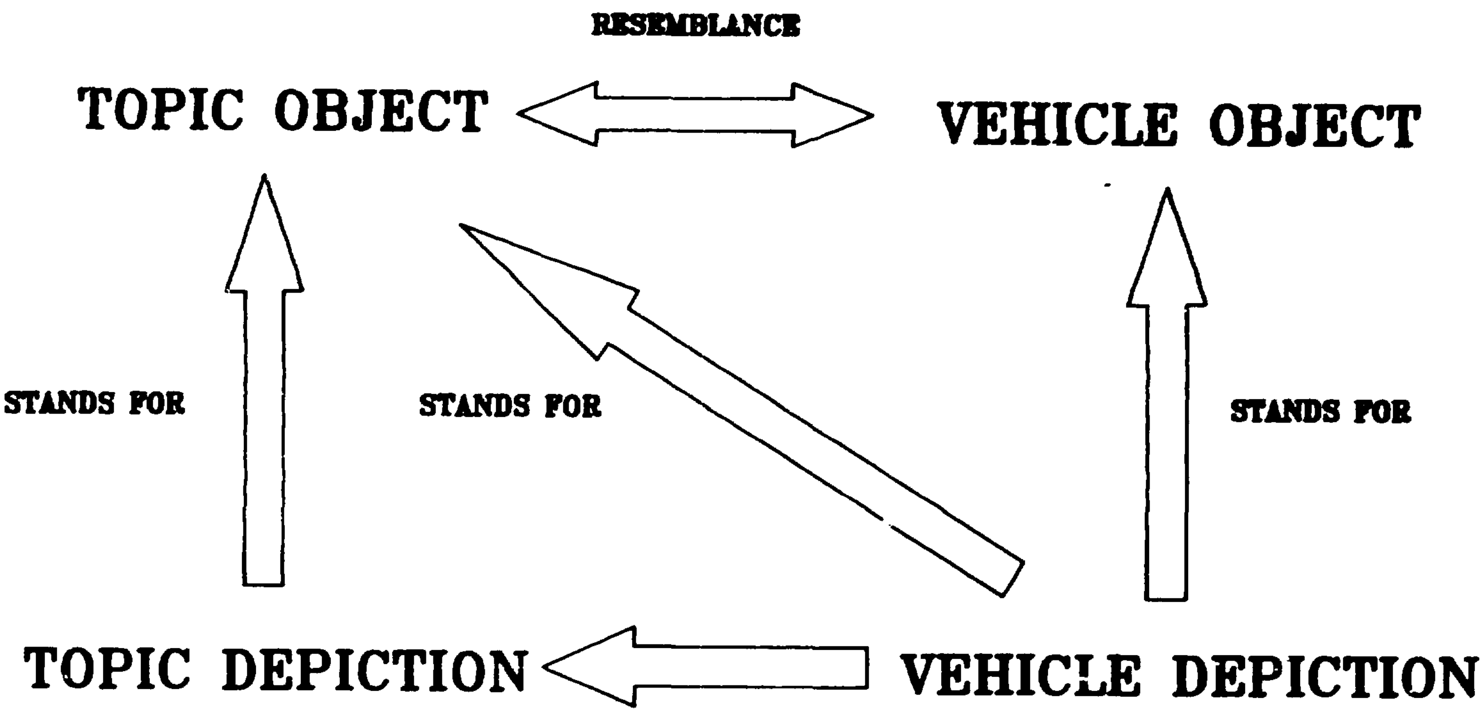
It may be useful to present some tutorial material on metaphor, and a brief review is now offered.

Carroll and Mack (1985) distinguish between theories of operational metaphor that concentrate on metaphoric thought, theories of structural metaphors that are more formal theories aimed at the mechanism of using metaphor in thought and language, and pragmatic theories of metaphor, those that analyze metaphors used in the course of attaining a goal. This latter category is most relevant to the present study. In order to examine this further we must look at the relationship between verbal and nonverbal metaphor.

In a novel verbal metaphor one thing is said to be or be like another different kind of thing to which it bears an actual resemblance. In using a metaphor a speaker is using one thing to talk about another and the hypothesized mental activity is thinking of one thing in terms of another. An example would be the observation that a biological cell is like a city. The topic, or what the metaphor is about, is "seen in the light of" or "seen through the filter of" the vehicle, or the word being used figuratively. These word and object relationships are diagrammed in Figure 1 in which the simultaneous reference of the figurative word or phrase to both its literal referent and its temporary figurative referent is made clear.

Similarly, in pictorial metaphor one thing is <u>depicted</u> in terms of another thing which is different in kind, but bears a real resemblance to the first object. An example would be a text-editing system that uses a symbol of a wastebasket for handling the deletion of files. Some properties of the vehicle object must be present in the depiction of the topic object in order for the depiction to be metaphoric. These relationships are illustrated in Figure 2 which shows that the structure of pictorial or visual metaphor is the same as


RESEMBLANCE
TOPIC OBJECT
VEHICLE OBJECT
REFERENCE
REFERENCE
REFERENCE
TOPIC WORD(S)
VEHICLE WORD(S)
COMMENT


RESEMBLANCE
TOPIC OBJECT
VEHICLE OBJECT
STANDS FOR
STANDS FOR
STANDS FOR
TOPIC DEPICTION
VEHICLE DEPICTION

that of verbal metaphor although no words are used in the case of pictorial metaphor.[1]

We would point out that metaphor and analogy are not synonymous. Analogies draw on parallels in relations, such as kittens are to cats as puppies are to dogs, but the two sets of relations can be either in the same domain or not. When they are in the same domain, as in the cats and dogs example, the analogy is literal. It is only when the relationships are not in the same domain, as in "using interactive software is to the computer as conversing is to people," that the analogy is metaphoric. In this paper our interest is in metaphors because we want to use the transfer of a set of relationships from one domain to another. The reader is challenged to identify other concepts and principles that would meaningfully organize displays and provide an orienting structure for actions.

Representation in Displays

In order to show how to identify metaphors in displays it is necessary to discuss the different types of signs or representations displays may contain and then to show which of these is metaphoric and which not. As with defining metaphor, defining and classifying signs and representations is an ongoing process. C. S. Peirce (1960) has provided a systematic theory of signs which

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[1]We must also be careful to distinguish "frozen" metaphors from novel or "live" metaphors. Frozen metaphors are basically idioms such as "the leg of the table" or "wedded to work" in which one term does have two meanings (leg as limb and leg as part of furniture) but only one meaning is used at a time. Calling a cursor a "hook" is an example of a frozen metaphor because no aspects of hooking or catching are used in the display. An example of the analogue to verbal frozen metaphors in the pictorial mode is the color red used for "in operation or hot" in the nuclear power station displays. Red has another meaning of "stop" (at traffic lights) or "warning of emergency" (red lights on ambulances), that are not intended by the designers of the power station operator displays. Therefore, frozen metaphors are not interesting to us because they lack the interplay of structures between two domains.

explicitly treats the relationships of sign to what it stands for, of sign to the perceiver of the sign, and of perceiver to the object the sign stands for. Because this model relates verbal and nonverbal as well as pragmatic aspects of signs, it provides the best basis for analyzing computer-generated displays. Research on aural aspects of computer interfaces has made use of a simplified version of Peirce's system (Gaver, 1986), but the more detailed version described below fits metaphor into the overall pattern of types of signs more accurately.

There are several ways in which an object can stand for something, that is, be a sign for that thing: it can exhibit a likeness to the thing it stands for; or it can indicate something about its object because of a causal connection between them; or it can express a conventional social rule. In the first case, in which a sign has a likeness to the thing it stands for, the sign is <u>iconic</u>. The horizon line in a cockpit CRT display is iconic. The second type are signs that indicate something about their object because of a causal connection; these are <u>indexical</u> signs. A fuel gauge indicates the level of fuel, and is causally connected with it. Finally, some signs have <u>conventional</u> aspects. For example, a gauge with zero at the left and some positive amount on the right exemplifies a convention, for it is conventional to place zero on the left and positive amounts on the right.

As metaphor is a type of iconic sign, it is necessary to examine that type of sign in detail. There are three types of iconic signs. The first functions based on simple qualities such as color and one-to-one correspondence of points and is called <u>image</u>; colors and photographs are examples. The second represents the parts of one thing by analogous relations in its own parts and is called <u>diagrams</u>; a flow diagram of electric circuits is an example. The third involves the icon being a sign of something and in addition representing something else because of a parallelism between the two things being represented; this third case is metaphor.

Therefore, in a metaphor, whether verbal or pictorial, the vehicle is a sign of one thing independently of its role in the metaphor and it is also a sign of a second thing in its role as a vehicle. For example, the corridor in a flight display is a sign of a real corridor (or highway) and it is simultaneously a sign of the flight path of the plane in the sky. Therefore, it is functioning as a pictorial metaphor. It can function in this way because there is a parallelism between corridors or highways and flight paths. It is important to note that parallelism implies two critical factors: the two things that the vehicle is a sign of are from different domains (or they could not be parallel), and there is some resemblance between them (the aspects that are parallel).

Given that metaphor can organize a pictorial representation to provide immediate awareness of some aspect of the world, and given the above specifications of metaphor and pictorial representation, actual display designs can be analyzed for the presence of metaphor. The goals of this analysis are to document whether and how metaphor is used in designing displays, and to make recommendations for its more effective use. We have also sought to lay the groundwork for development of design guidelines, and for empirical studies of the effects, on both designers' efficiency and operators' use, of displays incorporating metaphor.

Approach

The general approach was to (a) identify and study actual cases of display designs, (b) identify examples of metaphor use, and (c) make recommendations about metaphoric displays.

Participants

Identifying actual cases of display designs was done through interviews with twenty display designers who worked on display formats (primarily pictorial) for control stations and crew stations. Some of the designers had been involved in revisions of existing designs, some were working on designs for future stations. Their design experience ranged from 5 to 26 years with an average of 14 years, and the number of designs they had worked on ranged from 6 to 48 with an average of 24. Their degrees were primarily in engineering and psychology. Eleven were employed by the military; 9 were working in private industry on military contracts.

Next, the review of the designs was done by four metaphor researchers, two linguists, and two psychologists. The analysis of metaphoric display principles was done by three metaphor researchers--specialists in perception, cognition, and psycholinguistics.

The designers were interviewed using an adaptation of the Critical Decision Interview (Klein, Calderwood, & Clinton-Cirocco, 1986; Flanagan, 1980). In order to elicit information about the form and function of designs, as well as the process of developing designs, designers were asked to report on displays they had found to be particularly challenging. The interviews were typically conducted by two people, usually the Principal Investigator and a second person who was responsible for audio taping and note taking.

Procedures

The study was conducted in three phases. The first phase involved interviewing the 20 design engineers and writing up the information obtained in the interviews. In the second phase, the four metaphor researchers were asked to read these and to analyze the designs and the design processes for the use of metaphor. The Principal Investigator also performed this analysis independent of the consultants. In the third phase, three other metaphor specialists read both the interviews and the analyses of the consultants, with instructions to synthesize the different approaches to metaphor and design and to make recommendations for future research.

Phase I

We began the interview by telling the designer of our interests in display formats that present information about the real world that an operator needs in order to act and/or make decisions, and that we were particularly interested in cases where a real-world object was depicted that was not literally in the situation. The example used was the flight path of a plane depicted as a corridor or highway. Corridors and highways exist, but not in the sky; yet the depiction helps the pilot or the designer (see text of interview in Appendix A). The next step in the interview was to ask the designer to pick a design that had been particularly challenging or unique in some way and explain that design and its development. From there the interview followed the topics introduced by the designers, with the interviewers probing for detailed information about the design itself, the ideas behind it, and the history of different elements in the design. In addition, the tasks that the design was made to support were discussed in detail. The interviewers also probed for designs that had been considered, or tried but not used, and for reasons why these alternative designs were not optimal.

Phase 2

The second phase of the project consisted of analyzing the designs for whether they were metaphoric and/or whether any organizing metaphors were being used by the designers. The four metaphor researchers were sent copies of design materials with interview summaries, and were asked to analyze the interviews and designs for any "root" or organizing metaphors (exemplified by the desktop metaphor used in word-processing display design, and for any parts of the designs that were metaphoric. They were told that our overall goals were to arrive at a clear and concise definition of metaphor, a delineation of how metaphoric processes might be in use in present designs, and a statement of how metaphor might be useful in guiding designers to develop better displays.

Phase 3

The third phase consisted of synthesizing the consultants' reports and clarifying empirical questions as well as discussing methods for investigating these questions. In this phase the four consultant reports obtained in Phase 2 were sent to three experts along with the same interview materials. These experts were asked to synthesize the separate analyses of metaphor use in the designs; to make suggestions about possible organizing metaphors that might be useful to designers; and to develop a theoretical perspective or foundation for applying metaphor concepts to display design, with the advice that organizing metaphors were probably the best focus. They were told that our goal was to develop a set of testable hypotheses that could be studied empirically to see which classes of design problems match which class of organizing metaphors. We then had on-site meetings to receive their reports.

Results and Discussion

The 17 interviews resulted in detailed descriptions of 32 designs. These designs are described along with information on the design problem, the task the design was constructed to support, and an indication of the language used to describe the designs, in Appendix A; each design is numbered for reference to Appendix A. The designs were categorized into four types based on the general context in which the display occurred:

A. control station:

chemical process plants (2, one planned but not executed)

missile warning station (2)

nuclear power plant (1)

B. flight training:

instructor operator station (1)

simulator designs (4)

C. flight:

18 for jets (one planned but not executed)

3 for helicopters

and surveillance: 1 for a patrol plane.

The first ten interviews were scored for verbal, visual, and organizing metaphors by two independent judges; agreement was 94%.

<u>Metaphors in displays</u>. Our interview data indicate that designers use metaphor in four ways: verbal descriptive metaphors, pictorial metaphors in the displays, organizing metaphors, and verbal metaphors about the process of designing. Frequencies for the different types of metaphor are given in Table 1.

Table 1

Frequencies of different types of metaphor used by designers.

Type of Display:	Control Station	Simulator	Flight	Surveillance	Total
Type of Metaphor					
Descriptive	8	6	48	2	64
Pictorial	4	4	19	0	27
Organizing	1	0	2	0	3
Process	0	0	2	0	2

Verbal metaphors are used in referring to and describing the displays and how the displays function. Examples of this are: a cursor is called a "tadpole", text is said to "scroll", masking radar fields are called "shells". These are descriptive metaphors. Some of these metaphors were accurate descriptions of the depiction in the display and of the function of what was depicted. Thus, for example, masking radar was referred to as a "shell," drawing on the protective function and the shape of the field; the limits of a gun fired from one plane at another were described as like "squirting a hose" at the enemy plane (#8). In contrast, other verbal metaphors were a good deal less descriptive and did not seem related to the function. Thus, a cursor that was a circle with a vector was called a "tadpole"; "fans" was used for the probable path of missiles, "scrolling" for the movement of text. All but one designer used verbal metaphor (the exception was the description of color used in displays for the Instructor Operator Stations [#6]).

In addition, metaphors were used in the display depiction itself, that is, pictorial metaphor was used. The two major uses of pictorial metaphor were in depicting the flight path of aircraft as a corridor or highway and depicting electromagnetic radar fields as surfaces. In addition, in one suggested design (#20), safe areas for flight that were close to the terrain were depicted as ponds of varying depth. These are pictorial or visual metaphors. These metaphors are important because they demonstrate how metaphor is being used in display depictions. In crew station displays, pictorial metaphors are used to show both safe areas, (e.g., the highway or ponds), and areas of danger, (e.g., the radar fields of ground-based weapons and the tracking radar of other aircraft). In the latter case, lines and color are used in the depiction to stand simultaneously for solid surfaces and for radar fields which are not solid surfaces. In the operator stations, generalized paths, as opposed to a specific type of path like the highway or corridor, are used as pictorial metaphors for missile vectors and chemical processes.

Third, we found that designers occasionally think and describe some aspect of the plane or of the mission in metaphoric terms. An example is describing the functioning of the plane in terms of "health", with the hydraulic system parallel to the circulatory system, monitoring status as examination and diagnosis, responses to emergencies as remedies, etc. This thinking was not used in the design of the formats themselves, but in designing possible organizations of status display formats. This is an example of an organizing metaphor; such metaphors function to structure a whole set of decisions about what should be portrayed and how it should be portrayed. Organizing metaphors function to guide decisions within individual displays and across associated sets of displays. A second example which illustrates these aspects of organizing metaphors is the display designed by the Navy (#14) based on thinking of flying solo as flying in formation. That is, the display depicts a "phantom plane" that the pilot treats as a wing leader with that plane showing acceleration, turning, deceleration, landing gear, etc. This thinking directly affected the display in that a depiction of a plane is used as the sign to guide flying. The depiction of the plane is not metaphoric because it only stands for one thing, another plane. However, the activity of the pilot is not really flying in formation so the depiction of the plane is evoking an organization for the pilot. Thus, in addition to structuring design decisions, organizing metaphors provide structure for the user. An organizing metaphor can show the user where to look for certain variables, and the user will know how variables will be depicted because the different components are inherent in the metaphor, for example in "following a flight path as flying in formation". Organizing metaphors may result in pictorial metaphors (but not necessarily), and always result in descriptive metaphors. The health-of-the-plane metaphor affected what displays were used and how the set of displays was organized, that is, around circulation systems, nervous systems, etc., but did not affect the actual formats. The hydraulic system was not depicted with any aspects of human circulatory systems. Organizing metaphors always result in verbal metaphors when designs are described; the metaphor organizes talk about designs as well as the designs themselves. This is similar to the notion that metaphors structure our thinking about social activities such as arguing or aspects of the world such as time (Lakoff & Johnson, 1980).

Lastly, metaphor was use to describe the design process itself. One designer said designing a display is like trying to paint the Mona Lisa, you can try but the final product won't be anywhere close to what you had in mind. A second designer said the process is like putting together Chinese puzzles, you fit many pieces together, then add one more piece and the whole thing falls apart. These metaphors highlight the need for organization and guidelines to aid designers.

Pictorial and organizing metaphors in different types of displays. Operator station displays (Appendix A) showed a minimal use of pictorial metaphor and organizing metaphor. These displays were either primarily diagrams of the tanks or containers, valves, flows, etc. or primarily indexical displays, that is grids, graphs, or rows of numbers. All made use of color (i.e., image likenesses or based on conventions). One pictorial metaphor that was used portrayed a chemical change as a path on which temperatures "march" as the reaction takes place; a second portrayed the path of missiles as a surface along which the missiles progress (#3). Yet another pictorial metaphor portrayed a radar field of satellites and ground-based detectors using lines, that is, portrayed them as surfaces (#4). Pathways and other types of surfaces used metaphorically will be discussed below in more detail in relation to the designs for future cockpits. The interactive display for the missile warning station was described in terms of the "geography" of placing displays on the screen and in terms of the operator having a "dialogue" with the display. However, neither of these potential organizing metaphors was used systematically. To have done so, the designers would have had to use maps, quadrants, boundaries, etc. for the geography metaphor and rules of conversation for the dialogue metaphor. Thus, these organizing metaphors were used to structure the talk about the displays, but not to structure or format the displays themselves.

The primarily pictorial displays for the crewstation, that is #12, 13, 14, 18, 19, 20, 21, 28, 29, 30, 31, had several pictorial metaphors. One type of pictorial or visual metaphor employed was the depiction of radar fields as spheres (called "shells") or columns (called "search lights"); in these cases, lines that are typically used to depict surfaces were used metaphorically to depict electromagnetic fields which are not solid surfaces. In a different type of pictorial metaphor, flight paths are depicted as corridors, highways (with lines across the "road" and posts beside it), or tunnels. In a third type of metaphor, safe areas were depicted as ponds with shape and depth, corresponding to safe areas that allowed a pilot to fly close to the surface in order to use terrain masking. There were no organizing metaphors that united the different elements of the displays, or made the different pictorial metaphors consistent with each other. Specifically, different kinds of radar fields, the plane's masking radar, ground weapon radar, other planes' tracking radar, were all portrayed in the same way except that color sometimes varied. To be systematic, if these fields are to be portrayed as surfaces, then different types of radar should correspond to different types of surfaces. The highway metaphor was used more systematically in that cross lines and width and height of path were all portrayed as they would be on real highways and corridors. However, no other aspects of the displays were consistent with the underlying metaphor of "flying as driving". That is, driving was not used as an organizing metaphor.

There were two organizing metaphors used in crewstation designs (#13, 14). One was "health" as an organizing metaphor in thinking about status displays, but it was not used in the actual depictions. As discussed above, the health metaphor may have been used to group and order the presentation of displays, e.g., those based on hydraulics ("circulation"), electronics ("nervous system"), etc., but was not used in the depictions of the status of the aircraft. In contrast, the flying-in-formation metaphor did directly affect the display and did organize one part of the pilot's task (flying at a certain altitude and speed). In addition, this metaphor organized a whole set of decisions for the designer, including how to depict critical information on altitude, speed, orientation, etc., so that the "phantom plane" in that depiction was shown accelerating, turning, etc. The flying-in-formation metaphor did not, however, serve to organize the whole display or the whole mission. This metaphor is appropriate for take-off, ingress, egress, and landing, but not for air-to-air or air-to-ground modes.

The displays that were somewhat iconic, but not to the extent of the primarily pictorial displays, were those described for current or currently-in-revision heads up displays (HUD). While several aspects of these displays were described metaphorically, including "accordion" for the action of a pitch ladder in fast maneuvers (#23), and symbols as "pegged" or "caged" if they corresponded to variables out of the field of view, often the metaphors were not relevant to the activity of the operator or crew and were not used in the depiction. There is a HUD symbol being used in designs for the LHX helicopter helmet-mounted displays that corresponds to the nose of the helicopter, and one designer said it "becomes like the nose on your face"; but that metaphor was not expressed pictorially -- nothing about the display was face-like. This may be because current HUD displays are primarily indexical rather than iconic, so that the opportunities for pictorial metaphors are. Whether HUD displays would work better if they were more iconic and more metaphoric is an open question; two pilot/designers thought HUD displays would work better if they were more pictorial.

Summary of Observations

Verbal metaphors were used in relation to all but one of the designs, either as descriptors or as organizing metaphors. Pictorial metaphors were used primarily in the displays for future cockpits and somewhat in missile warning displays. Pictorial metaphors can occur only in iconic displays, and many older designs are not iconic. Newer designs take advantage of the new hardware and software tools that allow pictorial formats and, consequently, there is more potential for pictorial metaphors. Both pictorial and organizing metaphors were based on activities that are very familiar to both designer and user, that is, locomoting on and interacting with surfaces, and driving or flying in formation. Two metaphors that were based on less well known activities were the safe-areas-as-water metaphor, (diving-and-moving a vehicle in water is known by fewer people than is driving), and the health metaphor. Medical diagnosis is not well known by either pilots or designers.

Types of Tasks the Displays Support

There were 7 distinct types of tasks or activities that the displays were designed to support; sometimes multiple tasks are performed using one complex display or set of displays. Therefore, one display may support several different tasks. The types of tasks are:

1. Current state. Obtaining information that specifies the current real world situation, for example, knowing the terrain beneath the plane, where other planes are, where radar fields are, where safe areas are;

2. Dynamic state. Assessing how the situation is likely to change, for example, seeing where other planes are going or whether a chemical reaction is proceeding as it should;

3. Sensor control. Controlling sensing mechanisms to control the information available. For example, controlling the range of radar or choosing information on temperatures in a reactor;

4. Key process. Identifying and locating objects or processes in the world, for example, finding other aircraft and identifying them as friend or enemy or identifying whether a chemical process is in reaction or regeneration;

5. Actions. Controlling mechanisms of the vehicle or plant to act on the objects or processes that have been located; in the case of flight the object can be another plane controlled by a person, so the pilot must interact with the object located;

6. Routine control. Controlling the mechanisms of the vehicle to control its course. For aircraft, this involves controlling the throttle and wings;

7. Distributed decision making. Coordinating activities with others who are on the same mission or working in the same control room. Surveillance displays support monitoring which subsumes tasks 1 through 4 above. Objects must be identified, located, monitored, and reported on, but not acted on. Designs #3, 4 and 32 fall into this category. Process control station displays support this set of tasks as well as the task of acting on the process. In a sense, displays for pilot Instructor Operator stations fall into this category, too, as the instructor must monitor the pilot's actions and also control the scenario presented to the pilot. Flight involves all the tasks listed above so displays for crewstations must support all these types of activities. Displays for simulators designed to train pilots must support these activities with the added consideration that the displays are modified to help pilots learn the tasks.

Iconic displays could be used to support all the activities listed above, and, therefore, visual metaphor could be used. Metaphor guides both awareness of the situation and what to do in the situation. The corridor or highway shows where a safe path is and what to do to stay on it; a path for a reaction shows where the reaction is in time and whether any intervention is necessary. Metaphor may be more effective for tasks where action rather than just monitoring is required, but that is an empirical question. As outlined above, we found that visual metaphor has occasionally been incorporated into designs, primarily in the case of designs for future cockpits. As designs have become more iconic or pictorial, more visual metaphor has been incorporated. Thus, research on the use of metaphor in designing displays that guide complex action is in advance of the technology now available in working cockpits and control stations. As part of this study we explored ways that current metaphors could be extended and used more systematically.

Extending current visual metaphors. Metaphors that have either already been used in designs or have been suggested for designs can be extended in two ways. First, variables included in the design but not depicted metaphorically could be depicted in ways consistent with the metaphor. Second, new information not in the displays could be added, with the display information structured by the metaphor. In this section of the report we will first discuss control station displays and then crewstation displays for training simulators and aircraft.

Chemical processes can be thought of metaphorically as on a "path", that is, as starting at a certain point and progressing to another point (Johnson, 1987). This metaphor suggests to the designer a pathway along which objects or numbers progress, or a moving point that creates a pathway as it progresses, or a pathway ahead of a point indicating how the process should proceed. In the latter case deviations could be portrayed so operators could easily detect whether the process was normal. This metaphor could be used to portray many of the variables currently contained in schematic diagrams of pipes, tanks, and valves. A metaphoric pathway has been used, also, for missile warning displays to show the progress of a missile on a fan-shaped path that corresponds to the probability of the endpoint. This pathway design could be made more systematic if the type of "surface path" and the depiction of the missile corresponded to the type of missile that has been detected.

Metaphors used in crewstation displays that could be extended are the flying-as-driving and radar-field-as-solid-surface metaphors. The flying-as-driving metaphor could be applied to information that is not currently being included in designs for heads up or heads down displays. This could be accomplished by displaying side and rear views as "side- and rear-view mirrors" with the displays inset in the forward view with a size, position, and flow pattern that corresponds to some extent with the positioning of mirrors on a car. Of course the pilot should probably have control over whether these displays are present at any point in time. An analogue to this idea could be used even on the HUD for look-into-turn and look-over-the-horizon radar. This would draw on the pilot's extensive experience and habits with looking for information about side and rear views while operating a vehicle that is traveling forward. The inset in the virtual panorama displays has been termed a "rear-view mirror" (Furness, 1986), but whether the information is displayed in ways consistent with that metaphor is not clear. Another aspect of metaphor that could be extended is the portrayal of a "highway" or "corridor" for the projected safe path for the plane. For example, the surface of the "highway" could be portrayed as smooth vs. pitted corresponding to the degree of safety of the path (safe areas were stressed by one pilot/designer as being important to display, see #22). These are only a few of the extensions that are possible based on the flying-as-driving metaphor.

A second general visual metaphor that we explored in the crewstation designs was the electromagnetic-field-as-solid-surface metaphor. The radar limits of ground weapons, ground stations, and other planes are portrayed in current and future designs (e.g., #12, 19) using lines or lines and color fill. Both lines and color are used conventionally to represent edges and surfaces. In extending the metaphor of "field as surface" one might vary the types of surfaces portrayed in order to indicate something about the strength of the field, or alternatively, the strength of the weapon or plane using the field. Masking radar might be portrayed as armor (cf. the protective "shells" in design #12); ground weapon radar could be portrayed as spiked to indicate the danger of that area, or radar from another plane could be telescoping surfaces that can extend and attach as the range is changed. In general, there are many types of natural surfaces that can be portrayed and the use of this surface information in displays might organize the display in terms of both designer decisions and operators' use.

A third metaphor is the computer-as-conversing-person metaphor that is used to describe the pilot's relationship with onboard computers (the "dialogue" between the pilot and the "pilot's associate" computer, e.g., Furness, 1986). One potential extension of this metaphor is to use rules for conversation as rules for design. One system of rules that conversing people seem to use has been termed conversational postulates (Grice, 1957). This metaphor does not clearly specify as directly how an iconic display would be structured as do the two metaphors described above.

The extensions of metaphors illustrate the general point that metaphor has the power simultaneously to organize designers' decisions on how to display information and the operators' use of the display. These two aspects of metaphor have been documented for word processing (Carroll & Mazur, 1986) and, therefore, should operate also in the area of designing displays that support complex action and decision making. Based on the fact that some visual metaphor has been used in operator and crewstation designs, although not systematically, and on the potential of metaphor to provide organization in displays, we have arrived at a position statement on the importance of metaphor for display design and a set of recommendations for documenting and implementing the organizing potential of metaphor.

Summary

The question driving this research was how to organize displays so that they could be easily used during dynamic task conditions. The use of computer-driven displays has expanded the capabilities of designers but it has also created a potential for information overload and clutter. In periods of time pressure, it is critical that operators be able to quickly locate relevant items of information.

Lakoff and Johnson (1980) have described the value served by metaphors in providing conceptual structure for new domains. We were interested in seeing whether this function could be made explicit for display design. It was felt that metaphors could provide organizing principles to improve a the intelligibility of displays. The current project evaluated existing designs for their use of metaphor.

We found that metaphor is used by designers of software, interfaces, and display formats. However, at present the use of metaphor is ad hoc. There are different metaphors for different parts of displays. Organizing metaphors are rarely used systematically to tie parts of the display together, and principles or rules to guide the use of metaphor are lacking. When used systematically, metaphor can be a powerful tool for organizing both the designer's task and the operator's use of the display; examples are the "flying-in-formation" metaphor that results in a phantom wing leader portrayed for the pilot and the desktop metaphor that organizes commands and icons for word processing.

Analyses of the information collected showed that visual metaphors fell into three classes: descriptive metaphors, pictorial metaphors, and organizing metaphors. It was this last class that we found the most interesting because of its potential for applying skills and reactions learned in one domain to the demands of another. This is the type of payoff we were looking for: ways of enhancing the smoothness and coordination of performance.

We also identified several task types requiring metaphoric displays: presentation of current state, presentation of dynamic and anticipated states, sensor condition/control, monitoring key processes, actions/controls, routine performance, and distributed decision making. It will be important to determine the different requirements for each of these categories, and the types of metaphors best suited for each.

Finally, we described a logic for the use of organizing metaphors. The logic involves identifying the relationship between two domains, and application of reaction patterns from one domain into another.[2] It is worth

[2]It would be interesting to speculate whether this underlies phenomena such as transfer and generalization, but such speculation would take us away from the main interests of this report.

emphasizing that organizing metaphors do not simply map one set of symbols onto another. In the displays we studied, the power of the metaphors was in mapping of responses. It was organization of behavior that mattered, allowing the operators to improve their performance.

The power of metaphor lies in its potential to organize and provide structure for displays and the use of displays. Domains that are well known to both designer and user can be used to coordinate displays and the actions the displays support. This is why the flying-as-driving metaphor and the word-processing-as-typing metaphors work so well. This is also why the health metaphor for the status of an aircraft might not work, because physiology and diagnosis are neither well known nor used often by designers and pilots, and because the metaphor describes a state without have the power to guide the pilot's reactions.

Because two different domains, however, are involved in metaphor, mismatches or areas of dissimilarity will exist, creating the potential to hide certain information. This has several implications. One is that the mismatch can be endured if it is trivial--this is what metaphor buys you, the de-emphasis of irrelevant features. Second, the mismatch can be important and some means may be needed to provide the missing information. Spiro (1987) has discussed the value of using multiple metaphors. Third, the mismatch can serve a learning function (Carroll, 1987, personal communication) by letting the user understand more about the new domain by observing features and relationships that the metaphor cannot cover.

The challenge is to develop guidelines and support materials to maximize effective use of metaphor by designers and minimize the risk that metaphor could mislead the operator. The cost of the misuse of metaphor (in terms of reducing performance efficiency) may be high and can occur whether or not there is a deliberate attempt to use metaphoric displays. Designers unconsciously rely on metaphors and do not have means of assessing the strengths and weaknesses of these metaphors. In addition, there is the cost of not using effective metaphors.

Our conclusion is that metaphors already impact displays, but without any clear awareness of how specific metaphors will affect performance; and opportunities to use more powerful organizing metaphors are too often missed. So the issue is not whether or not to use metaphors in display designs, but whether to use them wisely or poorly.

We recommend that guidelines be developed and tested that would specify how to identify, extend and evaluate, and then apply metaphors in CRT display designs that support skilled action and decision. Systems to aid designers that incorporate guidelines as well as enforcing a human factors-based nominal design process are now being developed (Frey & Wiederholt, 1986; see also Boff, 1987). These systems provide designers with human factors information and restrictions from the beginning of a design throughout the process, they allow evaluation prior to design completion. Following such a model, it should be possible to provide display designers with helpful information on how to identify and extend metaphors, examples already in use, and lessons learned. It is unlikely that there will be guidelines for generating metaphor; that is a creative act. The use of metaphor once generated, however, can be made systematic.

It is our impression that some of the most interesting work in metaphor is being done in applied settings rather than in academic ones. Microelectronics and Computer Technology Corporation (MCC) is currently developing materials to enable designers to use metaphors to structure the human interface. Carroll and his colleagues at International Business Machines (IBM) are also examining principles of metaphor application. In order to make further progress, additional work is needed to resolve the following questions:

1. How to identify visual metaphors? By learning more about metaphor identification we will be able to help designers evaluate their work. How can designers identify what metaphors a display feature suggests and what it depicts? Examples are a highway for a flight path, a surface for a radar field, a plane for "flying in formation" when the pilot is actually flying alone.

2. How to extend visual metaphors? Once the two domains have been identified (such as flying-as-driving) further correspondence can be explored. Guidelines should specify steps for the designer:

--how to think about the activity or object that is not present in the situation, in this case, driving;

--how to find aspects of the activity that are the same as the one the user is actually doing, in this case, flying a certain mission or part of a mission. In both activities the operator needs views in front, behind, and to the side in order to guide the vehicle; in both there is one best path, etc.

--how to use the way the first domain presents and organizes information, to make decisions about how to present information in the second domain, such as organizing CRT displays in the cockpit to correspond to mirrors in a car.

--how to use terms from the first domain not to label and communicate about the displays, so that, for example, some cockpit displays could be labelled "rear-view mirror" displays.

Guidelines should also specify how to think about ways in which the two domains are not similar. This will lead to identification of aspects of the current domain that are being hidden by use of the first domain. For example, cars usually only move in two planes and cannot maneuver off the road. Airplanes move in three planes and can maneuver equally well on or off the path. Does the path depiction from the first domain lead the pilot to avoid dropping down when he might need to?

Guidelines should show how to maximize the aspects that are similar across the two domains. This will help guide operators attention effectively by using an activity they are highly familiar with projected onto one they are less familiar with. Similarly, guidelines can be formulated to help designers minimize use of aspects that are different so as to minimize misdirecting operators' attention.

3. How to develop the necessary supporting material for metaphor use? In addition to guidelines, there should be a database of examples of display formats for operator and crewstations. The database should include cases that have been analyzed for what is metaphoric, with extensions of the metaphor spelled out, and possible alternative metaphors described along with the corresponding alternative displays. This material would provide examples to make the guidelines clear, and would provide ideas for designers who may not know of designs constructed in other fields and at other institutions. In addition, the database along with the guidelines could be used as a training package for teaching display design.

Recommendations for Research

In order to test the usefulness of metaphor guidelines, and the effectiveness of displays created using those guidelines the following set of research questions should be experimentally investigated.

1. What is the overlap between the metaphors used by designers and operations? A study of the metaphors users might be employing as they read a display to perform a task should be conducted, using methods similar to those of the present study. The resulting data could be employed to determine the degree of overlap between designers' and users' conceptualizations of the display and of the task itself. This work could establish whether the metaphors that designers use in conceptualizing and creating the displays are unnecessarily being incorporated into the final display; it is an empirical question whether communicating the organizing metaphor to the user during training can affect performance. In addition, the data could become a source of metaphors to be incorporated directly into displays. For example, since some designers of crewstation displays see the mission as the critical level of organization for displays, perhaps metaphors for missions could be discovered and used as one source of organization.

2. Can metaphors be deliberately applied to improving designs? A second set of studies should be conducted in which experts on metaphor work with designers as they develop new displays, to identify, highlight, and explore metaphors that occur in the design or in the descriptive language used about the design. Boff (1987) provides a useful description of these activities, which would amount to an intervention that should lead to the systematic use of metaphor in designing new displays. Displays so designed could be compared to others that were created without the metaphor intervention. Two design activities are most likely to benefit from this intervention: those for new

workstations incorporating CRTs to a large extent; and those for which current hardware is not a constraint.

3. Will metaphoric guidelines generate better designs? A similar set of studies could be conducted in which designers work in three conditions on an assigned design task: with the metaphor guidelines, with other guidelines, and without guidelines. The resulting designs could be compared for organization and user effectiveness, as well as for efficiency of the design process. This work could provide data on the fit of different types of metaphor to different types of displays and tasks, the fit of designers' and users' metaphors, the relative effectiveness of displays that contain metaphor or were designed with a guiding metaphor. Two products could also result: a database of designs for many different workstations and tasks, analyzed for metaphoric elements with suggestions for extensions of the metaphor; and a set of guidelines with documentation for using metaphor as a design tool.

These studies could lead to a new design technology for workstations incorporating the systematic use of metaphor, and producing better displays because they are based on metaphor. A database of designs analyzed for the use of metaphor, together with guidelines to the use of metaphor, would assist and train designers in this field. Metaphors such as the "highway" in the sky could provide a path into the future of display design.

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Apprendix A

Descriptions of Display Topics

A. Control Station

1. Problem: Depict temperatures in an oil reactor, so that all sensors can be monitored at once; operator needs to watch for temperature gradients and outlier temperatures.

   Solution: Display a 3 by 8 matrix of numbers that correspond to temperatures in thermocouple wells, each row is a different color.

2. Problem: Same as above.

   Solution: One proposed solution was to depict a spiral "path" that corresponds to the physical layout of thermocouples in the spherical reactor and to display the numbers "marching" along the path.

3. Problem: Design a user interface for a missile warning officer, who must detect, identify, and file reports on enemy missile launches.

   Solution: Create a map display that shows radar fields that can detect enemy missiles drawn as bounded by solid or broken lines on a map, depict missiles as boxes moving along "fan" shaped surface that corresponds to the probability of where the missile would hit.

4. Problem: Same as above.

   Solution: Use a second set of displays on a touch sensitive screen, the user can have a "dialogue", "scroll" text, choose different displays, and give several commands for sending reports or obtaining more information.

5. Problem: Systematize the design of CRT displays for a boiling water nuclear reactor, adding human factors information into the design process.

   Solution: Design a design tool programmed on computer that incorporates guidelines and human factors information to force a nominal design (one meeting human factors specifications) at all steps in the design process. Nuclear power station designs are either graphs, with text giving description or directions, text such as checklists, or diagrams of the tanks and pipes with temperature and pressure indicated with numbers.

B. Simulator

6. Problem: Design a workstation for a pilot trainer, who needs to monitor the pilot's flight simulator, monitor the training session, and control the session. Specific problem: Use color to improve

clarity/performance and for consistency across many different kinds of training sessions.

Solution: Keep color identification and symbolism constant under a variety of conditions; base color coding on historical, conventional, and attentional factors.

7. Problem: Provide cuing displays that help pilot trainees to attend to important information aids in learning how to fly, through exercises in a simulator that presents graphics superimposed over video images of real landscapes.

   Solution: Display a "highway" that is the path the plane should be flying on, to maximize attention the highway is made to resemble real highways in details such as shoulders, crosslines, etc.

8. Problem: Same as above, but also show the limits of the pilot's weapon so he will know when he can use it effectively.

   Solution: The cue is a "cone", with lines and fill that correspond to where the weapon can "reach", where it will be effective.

9. Problem: Same as above, but also depict other planes (enlarged as they are too far away to see) and how they are moving or the limits of their movement so the pilot will know how to engage them.

   Solution: Depict the limits or "envelope" of the other plane by showing two vectors coming from the plane, one vertical and one horizontal, length corresponding to speed in that direction.

10. Problem: Same as above.

    Solution: Cue the pilot's attention to the behavior of the other plane by showing the "cone" or limits within in which the plane can move.

C. Flight

11. Problem: Represent the terrain and planned flight path for a pilot in terrain-following flight; use a heads up isplay (HUD) rather than a heads down graph showing progress along t..e ground line.

    Solution: Display a box that is based on predicted best altitude; when the flight path vector indicator is in the box the plane is on the predicted best path.

12. Problem: Display the current situation to the pilot, using a heads down display.

    Solution: Represent a god's-eye-view, above and behind the position of own plane, plane symbol is in the display. The display is in color, ground terrain, sky, and plane are shown. In addition, there is a "highway" or projected safe path for the plane, "shells" of masking radar around own plane, "tractor beams" of tracking radar from other planes, and "search lights" i.e., radar fields of ground-based weapons, color coded for degree of danger.

13. Problem: Display for the pilot the status of the plane, especially any malfunctions, with directions for remediation.

    Solution: Displays show fuel level, avionics, electrical system, pictorially, with some labels and text. The designer thought of these displays as showing the "health" of the aircraft.

14. Problem: Provide information that allows pilots to fly on the projected best path.

    Solution: Display a "phantom" plane ahead and to the left, i.e., wing leader position, that portrays correct speed, turns, deceleration, etc. slightly in advance of what the pilot should do; the pilot flies as "wingman".

15. Problem: Design a heads up display (HUD) to depict targets and flight path during nighttime infrared navigation.

    Solution: Depict targets as conventional symbols with numbers inside (indicating priority) and superimpose this depiction over the place on the infrared display that corresponds to the target.

16. Problem: Display information about the region to the side of the plane on the HUD base on look-into-turn-radar.

    Solution: Use the same symbols as when looking forward, but they are available only by holding down a switch and they are presented as dashed lines so that the pilot does not start flying by those symbols.

17. Problem: Redesign the F-16 cockpit displays, using multifunction CRTs. Determine placement, controls, format, and symbols for the new displays.

    Solution: Locate mode controls just below the window, locate display controls on the left hand side, organize displays according to mode, i.e., take-off, navigation, air-to-air, air-to-ground, landing. Use conventional symbols for HUD and heads down displays (geometric forms, vector lines, letters, and numbers).

18. Problem: Design a helmet-mounted display (HMD) that enables "visually-guided" flight under adverse conditions (night, fog, etc.), and incorporates all critical cockpit data into the same display.

    Solution: Display a "virtual panorama" that shows ground terrain, horizon contour, etc. realistically; include simplified depictions of other planes, ground targets; depict own plane (nose and wings) at the bottom of the display with weapons shown in place, altitude and airspeed shown in numbers; depict a "highway" or "corridor", "fence posts".

19. Problem: Same as above; also depict areas of danger.

Solution: Depict radar fields of ground-based weapons as "domes", the "surface" of the field is depicted as gridlines filled in with color.

20. Problem: Design a display for guiding covert, nighttime, terrain-following flight.

Solution: Provide a HUD superimposed on infrared scene to show with a "side look" the terrain line from left to right, a symbol for where the plane will be in 30 seconds, one for where it will be in 60 seconds, and a symbol for where the pilot should "push over" or start down after climbing to follow a rise such as a hill.

21. Problem: Same as above.

Solution: Display on the HUD a view of the plane from above and behind so there is a symbol for own plane and a line for the horizon showing real contour, and a ridge-crossing symbol showing the lowest point over a ridge so the pilot can fly to that symbol.

22. Problem: Same as above, but in addition, show a display that would facilitate terrain-masking flight, in which the pilot goes behind hills to get terrain between his plane and missiles that are "locked on" to his plane to mask the plane from the missile.

Solution: Depict the ground contour with safe areas behind rises depicted as "ponds" showing depth so the pilot can choose a safe place to go and decide on flying altitude.

23. Problem: Display target information on the HUD to facilitate target selection.

Solution: Display four or five targets with iconic symbols at the bottom of the display, filled to the percentage that corresponds to the likelihood of accurate designation, and ordered by priorities.

24. Problem: Display the pitch information on the HUD (the pitch "ladder" that shows lines above and below the flight path vector indicating if pitch is above or below the horizon) so that the pitch information is not obscured in fast maneuvers and turns.

Solution: Replace horizontal pitch lines with those that form an inverted "V", with the flight path vector at the top of the inverted V" and the angle of the lines corresponding to the angle of the plane, i.e., its pitch.

25. Problem: Revise the cockpit of the two-person attack helicopter to include heads down CRTs (multifunction displays) and a helmet-mounted heads up display.

Solution: Use three CRT screens for heads down displays, mode of flight organization for the displays (modes are take-off, transition, hover, and bob-up); use traditional HUD helicopter flight symbols for the helmet-mounted display.

26. Problem: Organize the radio communication controls and displays for the one-person helicopter so a person who is navigating, targeting, etc. can also communicate with ground personnel.

Solution: Use graphics rather than digital displays of frequencies to identity whom a pilot is communicating with, and automate the codes.

27. Problem: Design a helmet-mounted display for a single-operator attack helicopter; the task of changing modes and using the symbols in each mode must be simplified when there is only one operator. There are four different symbol sets for four modes of flight--hover, bob-up, transition, forward flight.

Solution: Combine symbol sets for three modes, two that are velocity vector oriented (hover and transition) and bob-up that adds only one symbol. Make these symbols all the same sensitivity and combine ones that look alike.

28. Problem: Facilitate pilots' quickly knowing their situation and what to do, especially in low altitude flight.

Solution: Fuse all information into one large CRT display that can show maps, ground terrain, radar information, etc., all on the same scale. The path for the plane is depicted as a "highway" or "corridor". This "big picture" is heads down; sometimes the corridor continues onto heads up display.

29. Problem: Depict threat information for pilots.

Solution: Radar fields of ground weapons and tracking radar are depicted as "solid surfaces" using lines and color that are conventionally used to depict solid surfaces.

30. Problem: Develop displays that "create more realism" and are "not coded" in order to aid pilots in flying and training.

Solution: Develop a heads down display to show the pilot the current situation with the viewpoint above and behind the plane. Depict ground and horizon with realistic contours, other planes, targets, etc. in detailed icons, and flight path as "highway".

31. Problem: Decide when to use displays that show the goal, e.g. the "highway" to follow, vs. displays that just require tracking, e.g., keeping the flight path vector symbol in a box to stay on best path.

Solution: Use goal-oriented displays whenever hardware allows; local errors may not be minimized, but overall performance is maximized.

D. Surveillance

32. Problem: Represent radio emitters to an operator in a surveillance aircraft. New hardware allows about five times the previous number of sources to be detected.

Solution: Display the text associated with a source next to the symbol for the source when the cursor is on the symbol, move other text to bottom of display, outline different areas in the display.