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Aircraft Multifunction Display and Control Systems: A New Quantitative Human Factors Design Method for Organizing Functions and Display Contents

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The objectives of this study were to review the current state of aircraft multifunction display and control system (MFDCS) design methods and develop a quantitative method of designing MFDCSs that incorporate important human factors issues. Reports in the literature indicate that MFDCS design can influence flight performance. However, current design methods rely primarily on the designer's intuition and experience. MFDCSs in aircraft cockpits use computer-generated graphics and symbology that have integrated and largely replaced the myriad discrete electromechanical flight instruments found in older aircraft. While much is known about the physical and visual properties of MFDCSs, less is known about which human factors are important for their design and use. MFDCSs may result in greater workload if the distribution of virtual instruments, graphical and text data, and control functions in an n-dimensional structure of display pages places excessive cognitive and psychomotor demands on pilots during either routine or emergency situations. A quantitative method was developed, involving the derivation of a weighted sum of separate cost functions, each of which incorporates the effects of an arbitrary number of human factors and MFDCS design guidelines. The method models, using a high level of

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abstraction, a pilot's search for specific information or functions among alternative hierarchies of MFDCS display pages. An annealing algorithm was proposed as an effective numerical method for finding the display page hierarchy that minimizes the composite cost function. Further research is needed to determine whether the set of constituent cost functions is sufficient or needs to be expanded. Studies also are needed to determine specific values for cost function coefficients and to validate the overall model. The quantitative method delineated in this report for designing optimal hierarchies of MFDCS content pages and functions may become useful for engineers as a design tool during development of MFDCSs that will maximize pilot performance and minimize errors and excessive in-flight workload.

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Introduction

Everyone, at least occasionally, has probably experienced frustration with poorly designed interactive, computer-based, information display interfaces. Modern automated telephony systems, for example, have had notoriously problematic user interface designs. Users often have had to listen to lengthy, complicated instructions and navigate their way through numerous levels of option menus to eventually reach or input the information they desired. Likewise, the typically poor interface designs for many bank automatic teller machines (ATMs) have prevented individuals from learning to use them (Rogers et al., 1996). This has frustrated new ATM users and, undoubtedly, has been costly to providers of these types of services since they probably lost a portion of these customers to competitors offering alternative, easier to use systems. In aviation contexts, the quality of an interface design for electronic display and control systems can obviously have greater impact than mere inconvenience and frustration.

Military and civilian aircraft designed in the 1960's and 1970's had so many separate gauges, dials, lights, switches, buttons, circuit breakers, control wheels, and levers in compact aircraft cockpits that crewmembers necessarily had to spend a significant amount of time heads-down scanning instrument panels to find the information and functions required to maintain safe flight. At that time, display, monitoring, and control functions were still largely dependent on the use of loosely interconnected analog systems. With such technology, maintaining continuous, complete, and accurate awareness of aircraft status imposed a heavy psychomotor workload. It required explicit mental effort to continuously integrate the dynamic information from the many scattered dials, gauges, and advisory or caution lights. Furthermore, an early or subtle emergency situation probably took longer to clearly identify, and more steps to correct, than is usually the case in current generation aircraft. Because of high pilot workloads associated with early generation cockpits, most transport aircraft required a flight engineer in addition to the pilot and copilot.

The development of increasingly capable microcomputers, software tools for implementing real-time digital data acquisition systems, and advances in the design and manufacture of small video displays provided the technology for the evolution of computerized multifunction display and control units for both military and civilian aircraft. Technological advances gradually permitted replacing the multitude of separate electromechanical status, warning, and control devices with integrated multifunction display control systems (MFDCSs). From their inception, MFDCSs were often similar in appearance and usage to ATMs in that crewmembers pushed buttons to move through a hierarchy of display pages containing instructions, information, or lists of user-activated functions (e.g., data entry). MFDCSs gained increasing acceptance among aviators and were generally credited with reducing cockpit instrument "clutter" as well as reducing the time crewmembers spent searching for, and mentally integrating aircraft status information. The reduction in pilot workload due to the introduction of increasingly capable MFDCSs in the cockpit was a primary factor in eliminating the need for flight engineers in most current generation transport aircraft.

The initial impressions of MFDCSs were that they reduced pilot workload during routine flight. However, with time, any reductions in workload were gradually offset by the ability of these computer-based cockpit systems to encapsulate an increasing number of additional features, functions, and capabilities not feasible with the analog systems they replaced. This progressive increase in functionality has become particularly apparent in military aircraft. For example, military combat and electronic warfare aircraft have been using computer-based display systems since the 1970's and, although today's versions of these systems have much greater computational speeds and memory capacity, the number of functions available to users seems to have expanded proportionately. Most of the expanding array of functions require substantial crewmember involvement (e.g., monitoring a large amount of additional, previously unavailable, information; selecting from an expanded array of options and system configurations; multisensor-based decision making; and troubleshooting complex software-dominated systems). Therefore, crewmember workloads with current state-of-the-art aircraft MFDCSs in some circumstances may actually be greater than that experienced in older aircraft with less sophisticated systems.

The use of MFDCSs in U.S. Army helicopters is just beginning to become prevalent. Currently, for example, only the OH-58D scout helicopters and versions of the UH-60 utility transport for special operations have more than one MFDCS in the cockpit instrument panel. Other Army helicopters are primarily equipped with the more traditional arrays of discrete electromechanical gauges, dials and switches. However, helicopter upgrades and entirely new helicopter designs for the U.S. Army, such as the Comanche scout/attack and the TiltRotor transport helicopters, will include multiple, highly integrated cockpit MFDCSs and retain only a few critical backup analog gauges to maintain basic flight capability in case of complete electronic systems failure.

Figure 1 is a schematic of the aft (copilot/gunner) cockpit layout of the AH-1W SuperCobra attack helicopter as proposed for the British Army (Holley and Busbridge, 1995). This is a modern version of the AH-1 Cobra gunship, which originally was designed for, and effectively used in the Viet Nam War. SuperCobra prototypes incorporate an advanced technology mission equipment package called the SuperCockpit which includes two large color MFDCSs with 26 push-buttons integrated into the surrounding bevels. Eight of the push-buttons are hard-key switches which activate critical or frequently used high-level functions or display modes. The other 18 push-buttons are soft-keys, meaning that their functions and labels may change across different MFDCS display pages.

Figure 2 depicts two MFDCS display pages for the SuperCockpit (Holley and Busbridge, 1995). The left display shows real-time status information from the aircraft engines and other aircraft systems (SYS). The push-buttons on the right side of the panel are associated with software-generated display labels indicating jumps to additional display pages containing related information. Pressing a soft-key causes the MFDCS to display a new page containing the information or functions indicated by the key's label.

MFDCSs typically contain a wide range of single and multistep functions. The type of objects and information displayed on the MFDCS, the data acquisition channels that are represented by the

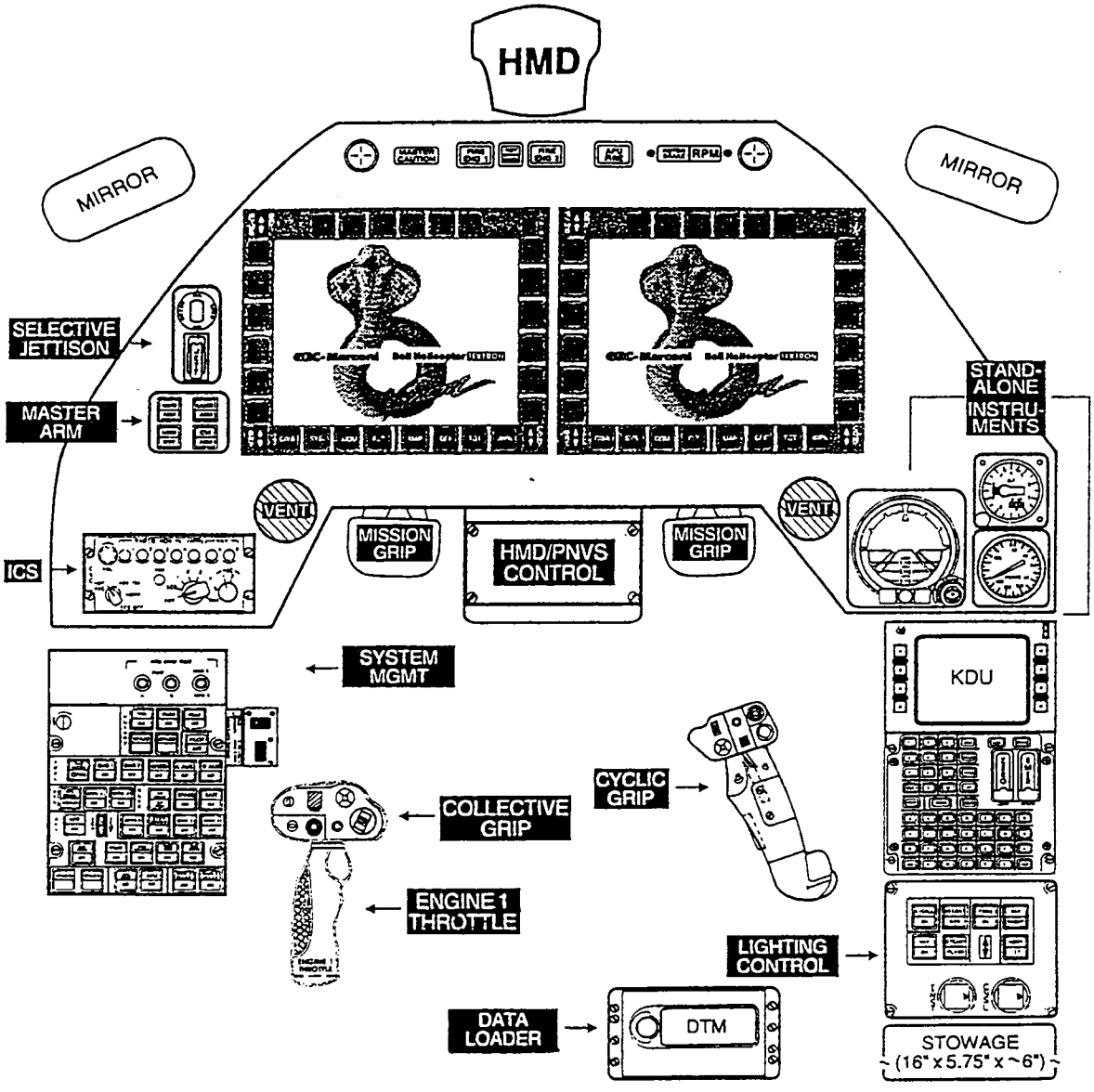
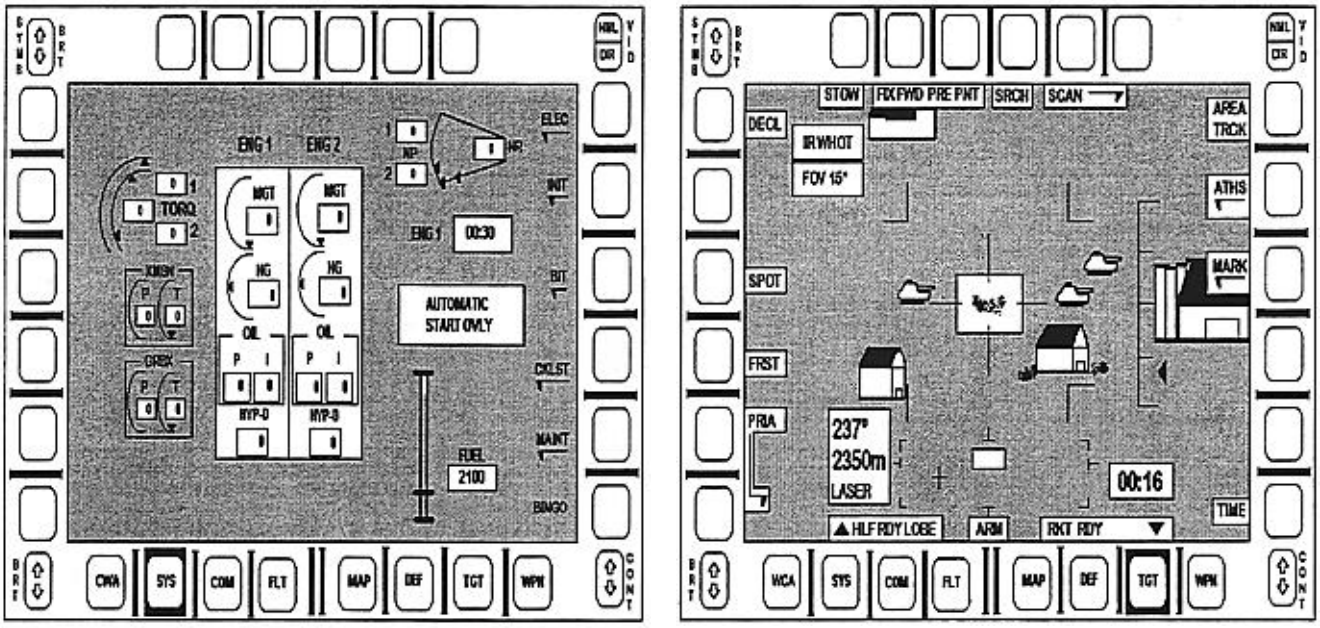


Figure 1. A schematic of the aft cockpit layout in the AH-1W SuperCobra, Venom. Two MFDCSs display the bulk the information.



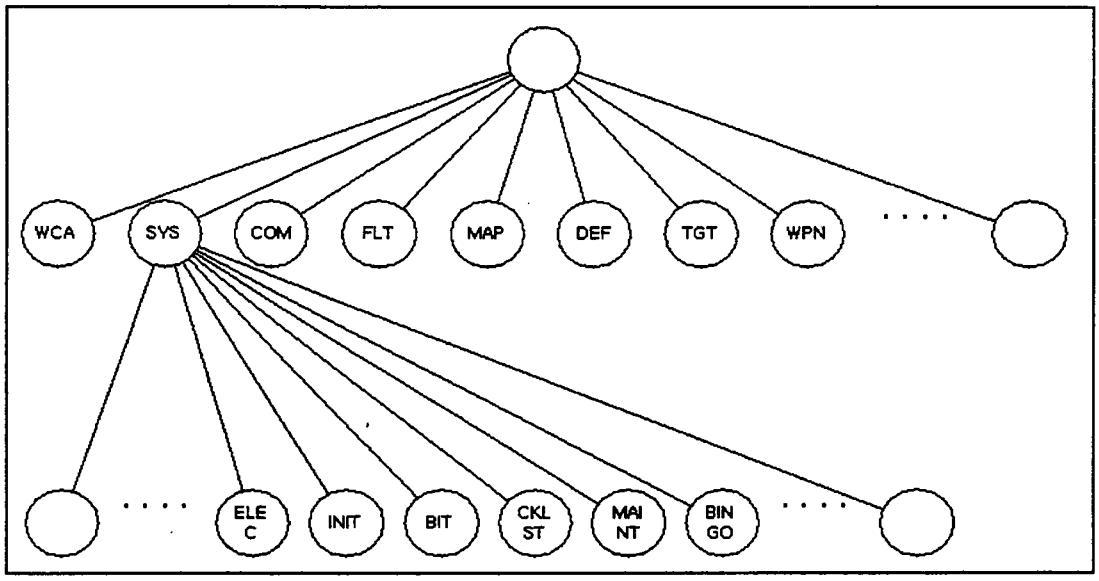


Figure 2. Simulated pages for the proposed Venom SuperCockpit. The systems page (top left) shows information on engines and includes legends along the right to indicate that pressing the associated button will cause the display to present the requested information. Targeting information is shown in the top right figure. The hierarchical structure corresponding to some of the MFDCS is presented at the bottom.

displayed objects, the set of active database links, as well as the functions that soft-keys can activate are commonly grouped together logically on one or more interconnected display pages forming a specific MFDCS mode. Flight crews can cycle through the numerous MFDCS functional modes with one or more of the surrounding push-buttons. Typical MFDCS modes include those for attitude reference and navigation, communications, moving map display, systems control and status, targeting and weapons selection and status, as well as situational awareness displays based on multisensor datafusion. Some MFDCS modes may have display pages containing clusters of related virtual instruments such as attitude, altitude, and airspeed indicators, fuel gauges, moving maps, etc., with or without symbology overlays for navigation or weapons selection and targeting. Display screens are designed to present, for any selected mode, only a subset of the total information from the monitored aircraft systems. Pilots dynamically select display modes based on the information and functionality desired to accomplish constantly changing flight management or combat tasks such as situational awareness, navigation, communications, systems monitoring, battlefield and threat monitoring, and targeting.

An MFDCS can be conceptualized as a relatively small two-dimensional window for viewing a single page of information selected from a much larger number of pages of static and dynamic data arranged in a multidimensional hierarchy. The information accessible via an MFDCS and its hard- or soft-key option selection buttons has a virtual structure that can be represented descriptively, graphically, symbolically, or as mathematical models. For crewmembers to efficiently use complex and extensive MFDCS data and function hierarchies, they must acquire an accurate mental image and conceptual understanding of how all the data and functions encapsulated in the available display modes are grouped and interrelated and how this structure can be efficiently and rapidly traversed using the available dedicated and software defined buttons. If the display page hierarchy and navigable paths between functionally related clusters of display pages are not well understood, MFDCS users are likely to become lost in the MFDCS's information space or become confused with regard to the location of immediately needed information or functions.

Obviously, becoming lost in the information space of a poorly designed MFDCS would only add to a pilot's sense of danger and confusion during in-flight emergencies involving spatial disorientation, serious system failures, or sudden unusual attitudes. During critical in-flight situations where composure, clarity of thought, and efficient use of time are essential, getting "lost" in the page space of an MFDCS is likely to precipitate panic and prevent identification and resolution of the problem. In such situations, MFDCS users might begin entering essentially random MFDCS page navigation selections. Similarly, during combat operations, gunners in Army attack or scout helicopters, despite danger and fear, must be able to rapidly and accurately traverse the information (MFDCS mode) subspace relevant to their specialized tasks. Gunners in high threat scenarios must be able to cycle very rapidly through various MFDCS modes to accomplish such tasks as target detection, recognition, hand-off, ranging, prioritization, weapon selection, target designation (e.g. lasing), weapons firing, and effect assessment. Becoming confused at any point during these complex processes, with respect to how to transfer between modes on the MFDCSs utilized to perform the tasks, could result in target escape or, of more

immediate consequence, give the adversary sufficient time to detect, close in, and fire first, with potentially lethal effect.

Modern MFDCSs are truly impressive and seem functionally and esthetically well designed as depicted in advertisements and during demonstrations in circumstances of little or no stress. But, while the modern cockpit relies on MFDCSs, little has been published regarding how unusual, critical, or dangerous circumstances affect user-MFDCS performance and mission effectiveness. Furthermore, there has not yet been a systematic evaluation of MFDCSs to enumerate and define a taxonomy of the cognitive and psychomotor human factor issues that should be considered during their design. In this report, we offer what we believe to be a new quantitative method for designing MFDCS display page hierarchies that optimizes the distribution of content and functions using a set of weighted priorities representing human factors and design guidelines thought to be important influencers of user-MFDCS interactions.

MFDCSs trade the workload associated with visually searching cockpit instruments for a cognitive workload associated with a cognitive search through mental images of a multi-dimensional database of pages of information and functions. Physically searching for a display page containing necessary functions can be time consuming and often has the additional drawback of requiring the coordinated use of buttons, cursor controls, and data entry keypads. These activities can distract crewmembers and temporarily reduce their situational awareness. The SuperCobra and the AH-64D Longbow Apache cockpit include numerous MFDCS mode select buttons and menu scroll toggles located not only along the borders of the MFDCS, but also on the flight controls (Hannen and Cloud, 1995). Studies indicate that time spent accessing information from a MFDCS influences performance. Sirevaag, et al. (1993) had five U.S. Army helicopter pilots fly simulated nap-of-the-earth (NOE) reconnaissance missions and report information at specific waypoints. Reporting this information required paging through an MFDCS. Although the pilots also had a head-up display (HUD) on their helmet that provided aircraft situational awareness information (speed, altitude, etc.), flight performance was adversely affected as the communication load increased. In particular, under high communication loads, pilots spent, on average, 8 more seconds per minute above the specified NOE altitude. That study illustrated that the time spent accessing information from MFDCSs can adversely affect flight performance.

Such findings are consistent with concerns about the workload required in continuously balancing flight and aircraft systems-management duties. The capabilities of an increasing number of aircraft require careful attention to, and skilled use of, many MFDCSs. For example, Dohme (1995) observed that OH-58D Aeroscout and AH-64 Attack helicopters both use the airborne target hand-off system (ATHS), accessed through an MFDCS unit. The database for the ATHS functions alone consists of approximately 180 different pages of menus, input fields, and information (ATHS is also one of the options in figure 2, top right). Dohme estimated that about 300 pages of information supported the entire set of functions in the MFDCS. He suggested that learning all the MFDCS modes and developing the ability to quickly and efficiently access the relevant information for all potential tasks was a formidable challenge for trainees.

There are concerns about excessive aircrew workload adversely affecting flight performance during complicated or stressful missions. During high workload mission segments, crewmembers may begin to selectively ignore elements of information which may actually be quite important. The next section discusses methods of improving overall information acquisition in the cockpit, and then focuses on how to incorporate cognitive and psychomotor human factor issues, as well as design guidelines, into the MFDCS design process. Subsequent sections propose a new method for including human factor issues in determining an optimal distribution of MFDCS content and functions, discuss how to apply the quantitative methods, and recommend directions for further research.

Reducing information workload in the cockpit

As military aircraft complexity and functional capabilities increased, concern arose that crewmembers could become more easily overwhelmed with information and task overload. In response to this concern, there developed a strong interest in simplifying cockpit system-user interfaces and assisting pilots in coping with the proliferation of flight and mission related functions. A general goal for new aircraft designs was to make it as easy as possible for crew-members to access, understand, and efficiently take action on cockpit and systems-related data. This section reviews various proposed methods for improving information transfer to crew-members to improve flight and mission performance and capabilities.

Integration

The introduction of computer-driven display and control systems into aircraft cockpits allowed MFDCS designers to create new and dynamic methods of combining and presenting information from systems and sensors. A single cockpit display became capable of simultaneously integrating many different sources of information, thus reducing the workload required to scan a multitude of separate instruments. Work in this area led to novel methods of integrating and portraying flight information (reviewed by Stokes and Wickens, 1988). In support of these efforts, a wide variety of new symbology was developed, but often it was only applicable to specific aircraft (e.g., Newman, 1995, Appendix).

Integrating information from multiple sources into an MFDCS can greatly reduce the time needed for crewmembers to access information. Additional improvement could be gained by refining the criteria for selecting which display objects and soft-key functions should be collated together into functionally related groups of display pages. The proper strategy in designing the contents, menus, and branching scheme for MFDCS pages has the potential for reducing the total number of display pages or modes. Combining related information and functionality into relatively few coherent display modes can give crewmembers a better understanding of the entire information structure and allow faster and more efficient use of MFDCS capabilities. As a result, automated flight systems information integration can achieve large savings in crew effort.

On the other hand, integrating unrelated information sources and soft-key functions into single display pages can hinder, rather than help, crewmember's understanding of systems status (Stokes and Wickens, 1988). Likewise, including an excessive number of menu options or soft-key functions in a single display page or MFDCS mode can produce display clutter and complicate a crewmember's search for a particular function. Deciding which functions and information objects to integrate together into a single or related group of display pages requires a thorough understanding of the interrelationship between aircraft systems and subsystems, as well as the information and functions required for performing cockpit procedures and mission tasks. However, data and function integration based on these factors alone usually will not solve all MFDCS-user interface problems. The MFDCS content database must also be designed to incorporate display pages in a way that maximizes the user's ability to efficiently search and locate the desired MFDCS functions, options, and pages or modes.

HUDS

HUDs project (via application of advanced video technologies) flight information directly into the crewperson's line of sight, thereby reducing the need for head-down scanning of cockpit panel displays or instruments. HUD systems allow pilots to continuously track relevant flight performance parameters via computer generated symbology and data superimposed on the direct line-of-sight imagery. Numerous studies have demonstrated improved flight performance with HUDs (see Newman, 1995 for a comprehensive review). Currently, however, HUDs cannot display as much or as wide a range of different types of data and display objects as MFDCSs. This is partly because excessive information or display objects projected on a HUD can lead to severe visual clutter, thereby deteriorating a pilot's external view. Therefore, HUDs do not supersede the need for MFDCSs. Increasingly sophisticated MFDCSs will continue to be the primary flight and systems monitoring and management interface for civilian and military pilots for many decades into the future. HUD and MFDCSs, however, will undoubtedly become increasingly integrated and complementary.

Pilot's associate

A pilot's associate is an advanced concept for assisting pilots with a software-based system that uses data fusion techniques and automatically analyzes complex multisensor data, recommends actions, and implements pilot's commands to perform certain tasks. Part of the pilot-associate interface will consist of an advanced highly integrated MFDCS utilizing a large flatpanel screen as part of the user interface. It will incorporate artificial intelligence methods to adaptively integrate multisensor information and dynamically advise and alert crews about potential problems, solutions, threats, and opportunities (McBryan and Hall, 1995). It will also be capable of autonomous decision making for constrained and predefined circumstances. The pilot's associate will automatically track and anticipate necessary changes in flight modes and adaptively organize and display the appropriate task-oriented information and functions. The development of such a system has the potential to greatly reduce the need for pilots to search for and integrate information and functions scattered among the many display pages or modes in an MFDCS.

While potentially valuable, a pilot's associate for advanced military rotary-wing aircraft is still an emerging technology. Moreover, similar but less complex types of automation in commercial aircraft have occasionally led to serious problems with "mode awareness," whereby crews have experienced difficulty determining what the automation was doing (Sarter and Woods, 1995). Currently, mode identification often requires paging up and down through different layers of the MFDCS modes to enable the user to identify the most current settings for system and control variables as well as to reorient with respect to location in the MFDCS mode or page hierarchy.

Alternative MFDCS interfaces

Research suggests that using an MFDCS function select interface other than push-buttons can reduce the difficulty of navigating through MFDCSs' information and function space. Speech recognition devices and pilot electroencephalograghic (EEG) signals are potential means of hands-off interfacing with an MFDCS. Such methods eventually could replace or complement the use of hard and soft-keys for controlling MFDCS displays, selecting modes, and activating various functions. These alternative input interfaces would have the advantage of freeing the pilots' hands for other tasks. However, they will not necessarily lead to improved performance searching an MFDCS database. Reising and Curry (1987) found no difference in flight performance for a speech recognition interface compared to a well-designed push-button interface. Whatever the interface, limitations in the design of the MFDCS still will likely impact a flight crew's ability to fully exploit the many complex capabilities of the aircraft. Indeed, it may be necessary to entirely restructure the MFDCS database to obtain optimal performance with a new interface method. How to do this rationally is not clear and requires additional MFDCS human factors research.

Expanded use of visual and auditory senses

Another alternative to the MFDCS interface is presenting flight and aircraft systems information to crewmembers through peripheral rather than foveal vision. Stokes and Wickens (1988) provide a review of studies that evaluated auditory and peripheral visual displays. Information delivered via a peripheral display is designed to be noticeable in the pilots' peripheral vision. Although potentially useful, the benefits of such displays have not yet been verified in aircraft. Additional research is needed to define how they can be effectively adapted to enhance pilot performance, information processing, situational awareness, and decision making.

Simple auditory signals are commonly incorporated into cockpit warning systems. However, more complex warning and advisory auditory systems, to include three-dimensional auditory "displays" to assist crews with situational awareness and threat localization, are being researched. Major drawbacks for extensive use of auditory systems are their potential for interfering with crew communication, the time needed for listening to and interpreting long messages, and their transient nature, which may require pilots to rapidly refocus attention from other tasks to mentally register the auditory message. These are some reasons why auditory pilot information systems are unlikely to completely supersede visually oriented MFDCS panels.

MFDCS content and interface design

MFDCS systems are typically composed of hardware and software components. The hardware components include aviation capable computer boards, cockpit display panels, surrounding bevels with push-buttons, and alphanumeric keypads. Software components include real-time operating systems, routines for generating dynamic symbology, map databases, aircraft systems information, as well as databases for graphic display objects, soft-key function mappings, object interaction rules, performance limits, procedures, and various checklists. A governing event-oriented software program keeps the system continuously active and responsive to pilot inputs and changes in aircraft status. The design of this software, and the databases that it can dynamically and adaptively draw objects and information from, is the focus of our concern. MFDCS software and associated databases can be conceptualized as a multi-dimensional space of interconnected pages of information, menus, and functions. The high-level design problem is how to organize an optimal structure and pattern of interconnections for the information and functionality assigned to an MFDCS. Because of the complexity of these systems, it is usually necessary to define optimality with respect to constraints and desired performance criteria or goals. One of the essential design goals for an MFDCS is that users be able to efficiently search through its information space to find necessary data and control functions in urgent situations.

Careful design and distribution of display objects, data, and functions across MFDCS pages and modes can minimize the time and effort required to locate necessary information. For example, Reising and Curry (1987) used a realistic F-15 simulator game which projected the out-the-window view on a display in a cockpit mockup and required nonpilot test subjects to access flight, navigational, and systems information through a simulated MFDCS. They compared flight performance for two hierarchical designs of the MFDCS display pages. They found substantial improvement in flight performance when they organized the contents of the pages according to the different phases of the flights, compared to a fixed organization that clustered the information according to data source characteristics. Their results indicated that different types of MFDCS page hierarchies could significantly influence simulated flight performance.

Assigning functions to pages and switches is a difficult task because the human-computer interactions involved in accessing information from an MFDCS are complicated and not entirely understood. Unfortunately, the frequency and pattern of MFDCS mode or page switching and function selections during actual flight have not been well documented. Also, the large number of possible combinations of pages, functions, and soft-switches quickly leads to combinatorial explosion when attempting to consider all possible layouts. The next section describes current approaches to MFDCS design.

MFDCS design issues

Studies of human-computer interaction have investigated many important characteristics of displays and human information processing. The displays must operate within constraints imposed by the human visual system (e.g., contrast, resolution, brightness, etc.) and the properties of the

interface (e.g., size of knobs, button sizes, and resistance) must mesh with pilot abilities and anthropomorphic characteristics. Studies of biophysical interface variables have lead to military standards for MFDCS design (e.g., military standard (MIL-STD) -1472D). In particular, a great deal is known about the responses of the aviator visual system under various conditions in helicopter cockpits (e.g., Frezell, Hofmann, and Oliver, 1973; Frezell et al., 1975; Holly and Rogers, 1982; Behar, Bachman, and Egenmaier, 1988; Kotulak and Rash, 1992; Rabin, 1995, 1996; Rabin and Wiley, 1996) and about the electro-optical and physical properties of electronic display devices (e.g., Rash, Monroe, and Verona, 1981; Cote, Krueger, and Simmons, 1982; Rash and Becher, 1982; Rash and Verona, 1989; Kotulak, Morse, and McLean, 1994; Rabin, 1994, 1996). This knowledge is clearly important because it helps ensure that the various components in modern aircraft cockpit instrument panels have properties consistent with crewmembers' biophysical capabilities.

On the other hand, few research results are available that define and quantitate the cognitive dimensions and problems relating to pilots acquiring and maintaining a clear mental picture of the distribution of information, display objects, menus, data entry fields, and functions across hundreds of MFDCS display pages; the n-dimensional interrelationships between pages; or the most efficient set of actions to take to navigate to different display pages or functions. This must become better understood so that MFDCS design criteria can be developed in a truly rational manner.

Surprisingly, development of present and past generations of MFDCSs have generally been ad hoc, relying on the experience and judgment of MFDCS design experts. Most MFDCS designers organize the information content into a hierarchical structure and then deviate from that structure when intuition, experience, or testing suggests that it will be beneficial. The design of an MFDCS is difficult because even a small content database can generate an immense number of different hierarchical structures. Searching through all the possibilities to find the best hierarchy can be very difficult, resource intensive, and time consuming.

Discussions with members of current MFDCS design staffs (e.g., at Honeywell, Sikorsky, Army Research Institute, U.S. Army Aeromedical Research Laboratory) indicate that MFDCS design has primarily relied on quasi-systematic, nonquantitative techniques learned through experience and validated with trial-and-error. For example, Graf and Holley (1988) described the steps taken to design the MFDCS in the cockpit of the V-22 Osprey. Figure 3 is a schematic of the development process. The designers started with a mission analysis to determine crewmember duties for the aircraft and specified range of missions. The designers determined how much time crewmembers had to carry out various tasks during missions. With this information, the designers created a cockpit design (including MFDCSs). They analyzed the cockpit in two ways. First, they used a computerized workload and performance analysis tool to predict whether the current design was acceptable for the aircraft's mission profiles. Second, crewmembers tested the cockpit design in simulated flights. These man-in-the-loop simulator flights provided data for determining problem areas in the design and allowed crewmembers to make comments on positive and negative aspects of the new cockpit design. The designers modified the cockpit systems accordingly and iterated the process until cockpit instrumentation capabilities matched mission and usability requirements. As

can be imagined, this was a lengthy process. Repeatedly measuring pilot-MFDCS interaction in simulators is both time consuming and expensive. Moreover, ad hoc changes to the MFDCS (or other parts of the cockpit), that help solve one problem, may inadvertently introduce new ones.

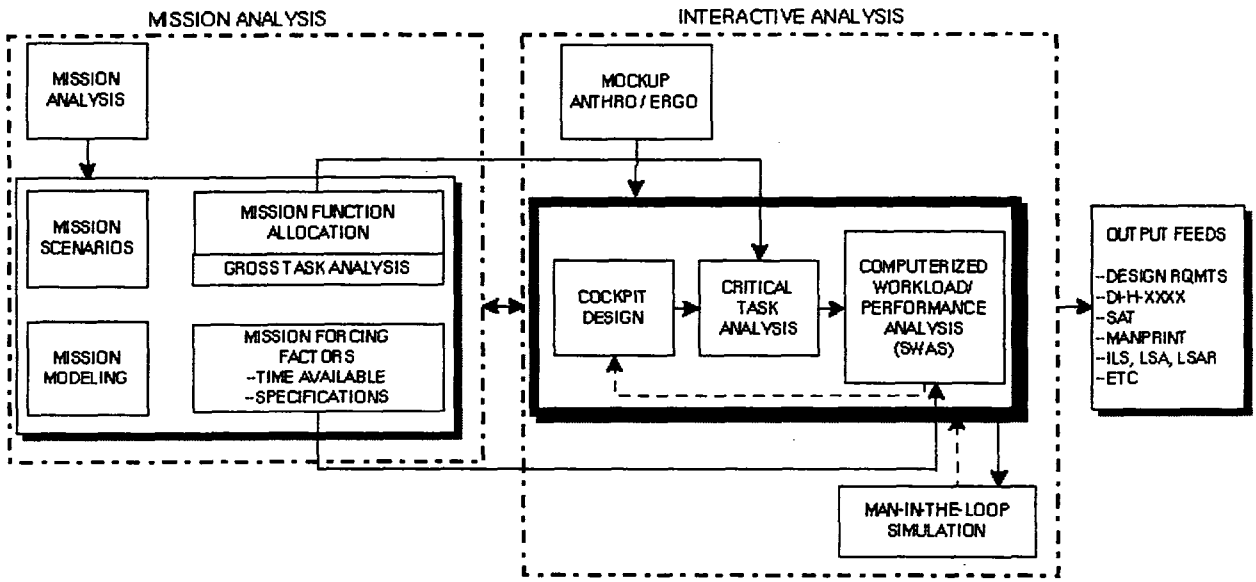


Figure 3. The design process for the development of the V-22 Osprey cockpit and MFDCS. Designers identify constraints imposed by mission analysis and then iteratively build a cockpit that satisfies those constraints (modified from Graf and Holley, 1988). The box with the thick edge indicates where the proposed quantitative method will influence the design process.

Published descriptions of MFDCS design techniques emphasize that the layout of functions and pages should follow general guidelines, but they do not explain practical methods for satisfying the guidelines (Calhoun, 1978; Lind, 1981; Spiger and Farrell, 1982; MIL-STD-1472D; Williges, Williges, and Fainter, 1988; Holley and Busbridge, 1995). Some of these guidelines are:

1. Frequently used functions should be the most accessible.
2. Time critical functions should be the most accessible.
3. Frequently used and time critical functions should be activated by the buttons that feel "ideally located" (e.g., top of a column of buttons).
4. Program repeated selection of the same button. For example, locate the most commonly selected function of a menu on the same button that called up that menu. Failing that, program common functions to adjacent buttons.

5. The number of levels in the hierarchy should be as small as possible.
6. The overall time to reach functions should be minimized.
7. Functions that are used together should be grouped on the same or adjacent pages.
8. Related functions on separate pages should be in a consistent location.
9. Related functions should be listed next to each other when on a single page.
10. Consider the types of errors crewmembers might make and place functions accordingly to minimize the effect of those errors.
11. In some cases, frequently used and time critical functions should be removed from the hierarchical structure and be given dedicated displays.

Many of these general MFDCS design guidelines are the same as those for structuring the layout of physical controls (Sanders and McCormick, 1987), while others (4, 5, 8, 9, and 11) appear to be unique to the design of software generated function selection switches for computer-driven display units. Some of these guidelines have been investigated experimentally. For example, Snowberry, Parkinson, and Sisson (1983) showed that search speed and accuracy increased as the number of levels in a hierarchy of user-activated functions decreased (5). Likewise, Teitlebaum and Granda (1983) demonstrated that placing related functions in inconsistent positions resulted in a 73 percent increase in search time (8). A literature search found no reports documenting the degree of effectiveness of the remaining guidelines, although they seem reasonable and have face validity.

MFDCS designers select the guidelines they consider to be most important. For example, in the development of the MFDCSs for the SuperCobra attack helicopter, Holly and Busbridge (1995) focused on guidelines 1, 2, 5, 7, and 8. The designers grouped related functions into one of eight subsystems (which were assigned to the buttons along the bottom of the MFDCS as in figure 2). These were further organized into two major subgroups. Related information on the same display page was functionally grouped, and the same information on different pages was presented in the same position across the pages. The designers also emphasized a minimum-depth approach and ensured that all critical information was no more than two levels from the top of the MFDCS page hierarchy. The most critical information needed to fly and fight was no further than one level from the top of the hierarchy.

However, application of these general MFDCS design criteria is problematic because they often conflict with each other. For example, should a frequently used function be placed by itself near the top of the hierarchy of the MFDCS pages (1) or should it be placed in a submenu on a secondary page with its related, but infrequently used, functions (7)? Likewise, should criteria 3, 4 or 7 dominate selection of a soft-key for a specific function? Currently, there does not appear to be a quantitative method of deducing the optimal trade-offs so designers try out different options until the entire system "feels" good. This is a time consuming task because movement of a single function can require a cascade of related changes throughout the MFDCS.

With an ad hoc, intuitive, or trial-and-error approach to the design of MFDCS data content and functionality, operational tests must be used to judge the performance of an MFDCS. However, it

often requires a great deal of effort both to build new MFDCS layouts and to measure their performance experimentally. Designers, therefore, may not have sufficient time or resources to generate and validate many alternative designs. Indeed, in the design of the SuperCobra's MFDCSs, Holley and Busbridge (1995) conclude, "A rapid prototyping capability for control-display formats is such an important tool that the design of a 'glass cockpit' should not be undertaken without one." Those designers had access to simulators and graphics workstations, and so could quickly try different MFDCS configurations. However, there is no indication that they had a quantitative optimization method for assigning functions to MFDCS pages and buttons. In figure 3, the bold box suggests where a quantitative method for building a MFDCS hierarchy would contribute to the overall cockpit design process. A quantitative method of design might also help clarify the relative importance and interrelationships of the design guidelines listed above.

Quantitative MFDCS design methods

Navigating through a hierarchy of display pages containing functions mapped to hard or soft keys is a commonly required task for many familiar applications (e.g., automated tellers, computer program menus, telephone answering systems). This section summarizes some previously developed generic formulas for analysis and design of hierarchical data structures. Because, to date, these methods have not been fully developed or validated, they are generally unsuitable for complex practical applications like the design of MFDCSs. This section also introduces notation for use in subsequent sections.

Most MFDCSs incorporate hierarchical structures that define organization of content and navigational paths between display pages or modes. Navigation through the hierarchy is accomplished via the use of navigational objects such as menus, lists, and soft or hard-keys. In a simple branching hierarchy, each screen contains information, display objects (e.g., virtual instruments, gauges, and warning lights, symbology, and text) and soft keys for various functions. Activating soft-keys on the display or hard-key buttons on the MFDCS bezel are used to navigate through the hierarchy to the desired display pages having the desired information and/or further selections. The top of the hierarchy is the one page that is not a selection from any other page. From the top page, the user navigates through a sequence of screens that is unique for each target page. Each page in the hierarchy is at a level which indicates how many screens the user must go through to reach the page.

Figure 2 (bottom) shows part of the hierarchical structure in the SuperCockpit MFDCS. The top of the hierarchy is a dummy page, as it contains no information except choices to jump to other pages. Many of the buttons at this top-level page (and other pages) are not used, but are included in the hierarchical structure to represent button locations. The SYS page presents some information (not indicated in the hierarchy) and options to jump to other pages, which are indicated by links to pages at the next level. These pages will present some information and (may) provide options for additional pages at the next level. Thus, reaching the MAINT page from the top page requires two button pushes, one to access the SYS page and another to access the MAINT page.

Hierarchical data structures also are used in computer science applications for database sorting. By arranging the contents of an ordered database into hierarchical trees, a computer can more quickly search the database. A number of algorithms exist to optimize the layout of a database (e.g., Knuth, 1973; Lorin, 1975). Unfortunately, these algorithms were developed exclusively to satisfy requirements for efficiently searching through structured databases. These early algorithms, however, did not include mechanisms for optimizing database structures with respect to the numerous and complex details of human-computer interactions. The database layout algorithms for efficient automated searching for simple information do not appear to be generalizable to the more difficult problem of human searches. Nevertheless, the notation for describing a hierarchy is useful in both situations.

Consider the hierarchy in figure 4a. It consists of $n = 3$ page levels, {0,1,2} with $m = 3$ menu options (represented graphically as the lines emanating from nodes) possible from each page (represented as the circular nodes). Each page, or node, in the hierarchy is indexed as (j,k) which indicates the level, $0 \le j < n$, of each page and position, $0 \le k < m^j$, in that level (n.b., k=0 for the first page or node at each level). The numbers in the hierarchy schematized in figure 4a suggest this coding scheme. Note that the total number of pages in this type of hierarchy is: $\sum_{j=0}^{n} m^j$.

It will be helpful to discuss how this notation corresponds to movement in the hierarchy. The "parent" menu, if it exists, of page (j,k) is at position $(j-1,\lfloor k/m \rfloor)$, where $\lfloor x \rfloor$ is the largest integer less than x (i.e., round x downward). Likewise, the "children" of page (j,k), if they exist, are found at positions $(j+1,km)$ to $(j+1,km+m-1)$. Figures 4b and 4c demonstrate how the notation corresponds to the positions in the hierarchical structure. This notation only describes the positions of pages in the hierarchy, it does not require that a page actually contains a function or jump selection.

Some pages in this hierarchy may contain information, virtual instruments, or other display objects, in addition to mechanisms (e.g., menu section or soft-keys) to jump to other pages as constrained by the interconnections. Other pages also contain specific functions that can be activated. These functions allow the user to interact with aircraft systems to perform necessary tasks.

Suppose there are v functions in a database. Let i=0, 1,...,v-1 index the functions and let $q(i) = (j,k)$ indicate the position of the function in the hierarchy. Define $Q = \bigcup_{i=0}^{v-1} q(i)$ as the set of page indices containing functions.

With this notation in hand, we can describe a simple model of the human-computer interaction and show how to minimize expected function access time within a restricted class of hierarchies. If

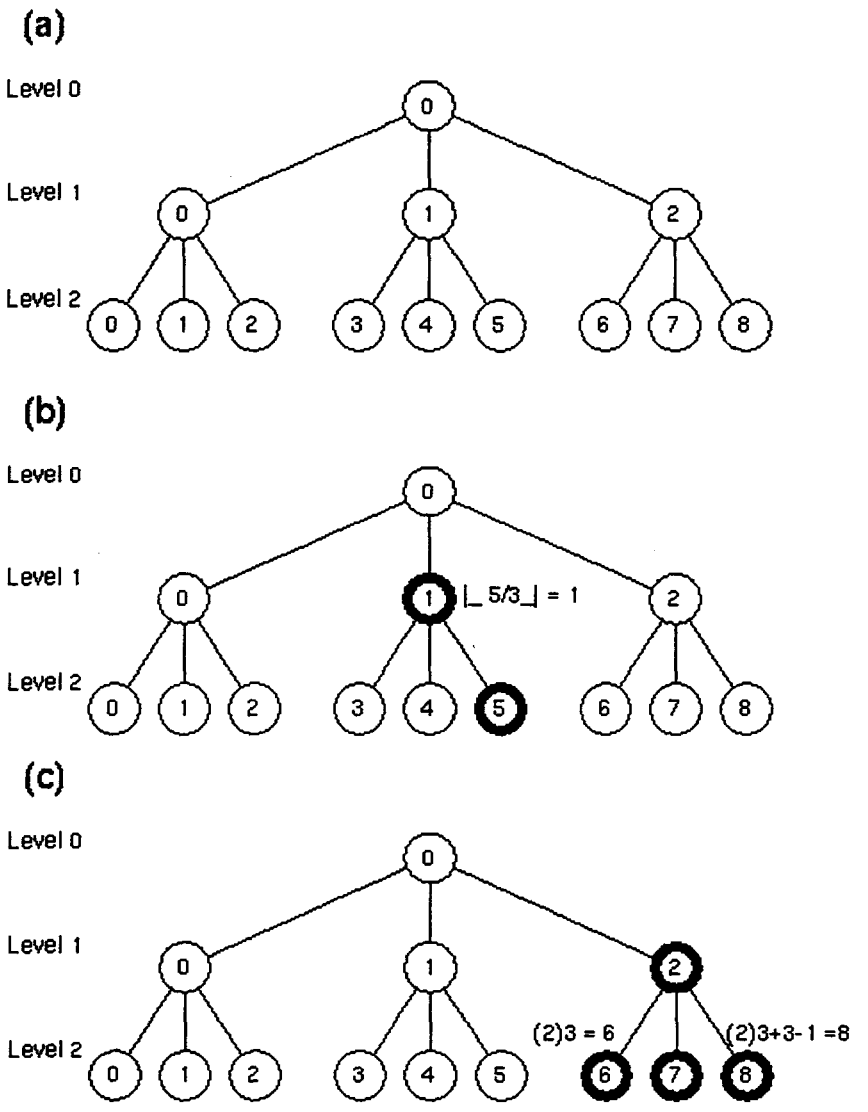


Figure 4. (a) A hierarchical structure with three levels and three possible options at each choice point. The numbers indicate a coding scheme that identifies the position of each option at each level. Each position can be identified as a coordinate pair (j,k), where the first number indicates the level and the second number indicates the position within the level. (b) The notation identifying the position of the parent to page (2,5). (c) The notation identifying the positions of the children of page (1,2).

each function, i, is assigned to a unique page in a hierarchy and has a probability of being needed, p_i, and $T_{q(i)}$ is the time needed to reach page $q(i)$, then the expected (average) time that it will take to navigate to a desired page containing any randomly selected series of the functions is:

$$E(T) = \sum_{i=0}^{v-1} T_{q(i)} p_i .$$

Accurately estimating $T_{q(i)}$ requires detailed knowledge about the interaction between computer and human systems. Lee and MacGregor (1985) proposed the following model. Let c indicate the time needed for a user to read, mentally interpret, and categorize one option on a display page. Let s indicate the time needed to strike a key to select an option once the user knows which option to select. Let r indicate the time needed by the computer to produce the next display. Let m_{jk} indicate the number of options at page position (j,k) that the user must categorize before making a choice. Then, assuming that c, s, and r are constant across pages, the time needed to reach page (j,k) is:

$$T_{jk} = j(s+r) + c\sum_{l=1}^{j} m_{(j-l)\lfloor k/m^l \rfloor},$$

where the summation is across all the levels that the user must navigate, and the sum identifies how many hierarchy locations the user must categorize between the top page and page (j,k).

Lee and MacGregor (1985) considered the situation where the user accesses each function equally often, $p_i = 1/v$; each page has the same number of options, m; and the user must go through a constant number of pages, n; to reach a function. Then, assuming that searching through m options requires (on average) categorizing $(m+1)/2$ options before finding the desired item, the expected access time boils down to

$$E(T) = n\left[s + r + \frac{c(m+1)}{2}\right].$$

Given this analysis, one can determine whether it is better to have a broad design (with many options per page) or a deep design (with many levels in the hierarchy). With all the functions at the bottom level of the hierarchy, it is easy to see that one needs only

$$n = \frac{\ln v}{\ln m}$$

levels in the hierarchy. Substituting the right side of this equation for n above and setting the derivative of $E(T)$ with respect to m equal to zero produces:

$$\frac{\partial E(T)}{\partial m} = \ln v \left[\frac{s + r + c(m+1)/2}{m(\ln m)^2} + \frac{1}{\ln m} \frac{c}{2} \right] = 0 .$$

A bit of algebra shows that this means:

$$m(\ln m - 1) = 1 + \frac{2(s+r)}{c} .$$

Lee and MacGregor (1985) showed that if a designer measures the terms c, s, and r, then the expected response time can be minimized by selecting the number of navigation or function options per MFDCS page, m, that satisfy the above equation. Techniques such as Newton's method can be used to estimate the value of m. For reasonable values of c, s, and r, Lee and MacGregor found that m rarely goes above eight.

Paap and Roske-Hofstrand (1986) considered a variation on the Lee and MacGregor analysis by hypothesizing that the manner in which the navigational or function options are grouped on a display could affect the time required to select an option on a menu page. When navigation or function options on a display page are grouped, the effective number of categorizations for each menu page decreases. This can reduce the overall selection decision time or conversely allow a larger number of options while maintaining the same decision time. For instance, with $c = 0.25$, $s = 0.5$, and $r = 0.5$ (seconds), Lee and MacGregor's analysis, that does not incorporate grouping, suggests setting $m = 8$. On the other hand, Paap and Roske-Hofstrand's analysis that incorporates the improved efficiencies due to grouping options gives $m = 38$.

Unfortunately, these analytic design results are often of tangential relevance to many practical situations because of current limitations in the design models. For example, physical factors such as the size of soft-keys and bezel buttons as well as display size and resolution typically limits the maximum number of option selections per page. Additionally, function search strategies at each page will likely vary between users based upon organization of the content and previous experience (Vandierendonck, et al.,1988). The line of analysis discussed above also restricts itself to very specific types of hierarchies: ones that use all available key positions on each page (compare to figure 2) and where all the functions are on the lowest level. Thus, even optimality from Lee and MacGregor's approach may not lead to the best information display overall. Fisher, et al. (1990) proposed an expanded scheme for optimizing the search for specific functions in an information display system with a larger class of hierarchies. Unfortunately, their scheme is still too limited in scope for most applications.

Expected function access time is not the only factor that can be minimized. Roske-Hofstrand and Paap (1986) described a method of building a hierarchical structure consistent with a user's "cognitive map" of the content database. Subjects rated the similarity of all pairs of the 64 pages in

a database. They converted these similarity ratings into distances between pages. These values were then used in an algorithm to solve for a hierarchical structure of pages having minimum access time paths. The resulting structure improved performance relative to an already existing hierarchy.

Roske-Hofstrand and Paap (1986) demonstrated the importance of considering a user's mental model of the relationships between functions, but it is difficult to design hierarchies with this technique because a generally acceptable and validated measure of a user's mental model has not been developed. While a requirement to satisfy a similarity relationship between functions seems to be a useful constraint for designing a hierarchy of displays, other measures of how functions complement each other (e.g., measure of sequential use) could also be formulated into valid design constraints that would act to offset or exploit related cognitive or user interface limitations or advantages. Even if designers could find a consistently accurate measure of cognitive distance between page contents in a database of information displays, it is not clear how one would build an appropriate display page hierarchy to minimize that distance. Seidler and Wickens (1992) showed that cognitive distance interacted with other aspects of a hierarchical structure besides apparent differences and similarities. Thus, design of a hierarchy of display content must take multiple constraints into account. The method used by Roske-Hofstrand and Paap (1986) is too limited in scope to deal with such additional complexity.

Current state of MFDCS design

The literature on human-factors aspects of MFDCS use and design suggests several conclusions. Accessing information from MFDCSs with large databases of display page content and user-selectable functions can contribute significantly to crew workload. The design of MFDCS display page contents and hierarchies by industry leaders in avionics seems to be most frequently performed by applying general "common sense" guidelines that experienced designers implement in an ad hoc fashion. A quantitative method of balancing the previously listed guidelines for MFDCS design could help designers develop MFDCSs that have higher probabilities of having high function search efficiency and would have the potential of reducing MFDCS-associated workloads. Current quantitative design methods for information display systems seem to be inadequate.

An investigation into the design of MFDCS hierarchies of display pages or modes and embedded functions should have at least two principal foci. First, a quantitative method of designing a hierarchy of MFDCS display pages must be elaborated that incorporates as many human factor and user interface constraints and capabilities as possible. Without a quantitative design tool, designers of MFDCS page contents and access hierarchies will continue to rely on intuition, luck, inefficient trial-and-error experience, and reports from the field regarding operational problems with MFDCSs. Substantial amounts of time and resources may be expended generating what quantitative methods might show to be suboptimal hierarchical structures that could be problematic for pilots in certain high-stress circumstances (e.g., in-flight emergencies). Moreover, without a quantitative MFDCS design method, results from related human factor studies will have little

influence because there is no way to ensure that the hierarchy reflects the relative importance of factors found to be relevant to effective use of MFDCSs. The next section describes a quantitative method that is capable of generating a hierarchy of display pages and user functions that will be optimal with respect to designer specified criteria.

The second element needed to advance model-based methods for organizing MFDCS page structures is additional experimental study to identify and quantitate the relevant components of pilot-MFDCS interactions. Future MFDCS research also should investigate rigorously the previously listed MFDCS design guidelines to determine the extent to which they adequately describe and properly weight cognitive factors and important aspects of the user interface. Such studies will be required to identify realistic values (and variances) for the parameters in the optimization equations. The human factor-related parameters also may be parameterized by user characteristics (e.g., age range, gender, experience levels, education, or use of performance enhancing medications). Likewise, values quantitating the characteristics and performance of the physical components of the MFDCS could be stratified by specific manufacturers and display systems.

A new quantitative method for optimizing MFDCS content hierarchies

This section describes what we believe to be a new method of optimizing the hierarchy of content pages and user functions for MFDCSs.

First, in order to quantify the numerous human factor constraints that could be imposed during the design of the display page structure for an MFDCS, define an overall cost for a given hierarchy as a weighted linear combination of an arbitrary number of cost functions developed to satisfy related criteria:

$$C = \sum_{i=1}^{p} \lambda_i C_i .$$

Each constraint, i, imposes a cost (C_i) and weights (λ_i) each cost according to its significance as obtained by the designer from human factor experts familiar with the capabilities and limitations of the aircraft for which the MFDCS will be installed. The following section describes how to efficiently calculate a cost for expected access time. Subsequent sections demonstrate how to select a hierarchy that minimizes the cost function.

Cost as expected access time

Defining a cost function for optimizing an MFDCS page hierarchy design requires knowing which of the many physical and software-related properties of an MFDCS can have significant effects on performance of required in-flight duties. Also, one needs to consider that some

MFDCS pages can show either functions or option menus, but not both. Other MFDCSs (as in figure 2) can simultaneously display both functions and option menus. For the following discussion, it is assumed that the MFDCS is similar to those in figure 2 and portrays functions, which allow data or control inputs by the user, and menus simultaneously (selecting a menu option typically causes a jump to another display page).

As noted above, a designer may want to minimize the expected access time across all pages, so C_1 might be:

$$C_1 = \sum_{i=0}^{v-1} T_{q(i)} p_i$$

where, as before, the time to reach page (j,k) is:

$$T_{jk} = j(s+r) + c\sum_{l=1}^{j} m_{(j-l)\lfloor k/m^l \rfloor}.$$

For a nonhomogeneous probability distribution, calculating T_{jk} requires more effort. To simplify matters, assume that users search the options on a menu page one at a time, and that the pages are searched in the order of their indices. Thus, at page $\left(j-l, \lfloor k/m^l \rfloor\right)$, a user must categorize whichever pages between $\left(j-l+1, \lfloor k/m^l \rfloor m\right)$ and $\left(j-l+1, \lfloor k/m^{l-1} \rfloor\right)$ contain a desired menu option. The last page is the option that the user must select to reach page (j,k). (While this is not likely a valid model of how users search an MFDCS menu page, the following analysis does not depend on the user's search method, only that the designer can identify the method.) It is easy to check for a function at any of these positions by determining if the page in question is in the set of function position indices Q. However, if a page is not in Q, its contents may still need to be scanned and interpreted because it could contain a menu choice whose descendants are function pages. Such a page would have a label that must be categorized. There is a recursive algorithm that considers these possibilities. Define the following function:

$$H_{jk} = \begin{cases} 1 & \text{if } (j,k) \in Q \text{ or } \sum_{h=km}^{km+m-1} H_{(j+1)h} > 0 \\ 0 & \text{otherwise,} \end{cases}$$

which returns a value of one if page (j,k) is either a function or is a menu selection that eventually reaches a function page. The summation simply checks to see if the children of page (j,k) are function pages or have children that are function pages. Calculation of the H term

works its way down to the bottom of the hierarchy and then filters back up to the top in a recursive fashion.

The number of options that must be mentally categorized at menu position $\left(j-l, \lfloor k/m^l \rfloor\right)$ is then:

$$m_{(j-l)\lfloor k/m^l \rfloor} = \sum_{h=\lfloor k/m^l \rfloor m}^{\lfloor k/m^{l-1} \rfloor} H_{(j-l+1)h} \, .$$

Although the notation is rather awkward to look at, it is a relatively simple matter to write a computer program to carry out these calculations.

With these formulas, it is possible to calculate the expected access time for any layout of functions on a given hierarchical structure. In theory, one could consider every possible layout of functions and select the one with the lowest cost. In practice, such an approach will rarely work because the number of possible layouts typically will be astronomical. In the following sections we discuss several numerical techniques for solving cost minimization problems. The hill-climbing technique is discussed first and subsequently simulated annealing which works better for cost functions having numerous local minima.

Hill-climbing

When differentiable equations, from which analytical optimization results can be directly obtained, cannot be formulated, computer scientists often apply a numerical technique called hill-climbing to find a global maximum for large complex systems. After selecting an initial MFDCS page hierarchy, a designer can calculate its cost $C(0)$ using the equations above. If the designer modifies the hierarchy and calculates a new cost $C(1)$ so that $C(1) < C(0)$, then the new hierarchy has a smaller cost and should replace the older hierarchy. Iterating this process will eventually lead to a hierarchy (or set of hierarchies) for which the cost cannot be reduced any further. This approach is called hill-climbing because it is analogous to climbing a hill by moving in whatever direction is up relative to your current position.

An example will demonstrate the procedure. Suppose you want to distribute v=5 functions on the hierarchy framework in figure 4 to minimize C_1. Suppose the probability of accessing each function is:

$$p_i = \frac{i+1}{15},$$

so that functions with higher indices are accessed most often. To apply the hill-climbing method, calculate the cost of an initial random layout of the functions. Pick a function *i* at random and randomly pick a page in the hierarchy structure. Move function *i* to that page (and if a different

function is already at that page, have the functions swap positions). Recalculate the cost and accept the change if the cost decreases. If the cost increases or stays the same, revert the system back to its layout before the move. Continue this process until the system stops changing.

Figure 5 shows the effect of the hill-climbing procedure. Figure 5a shows an initial random layout of functions. The layout is not optimal and has a cost of $C_1 = 0.587$. Figure 5b shows the effect of the first move that decreased the cost. Function 3 moved up a level. This reduces search time for that function without affecting any other function's search time, thereby reducing cost to $C_1 = 0.513$. Figures 5c-f show the effects of subsequent moves leading to decreases in cost. Figure 5f shows the final hierarchy resulting from this procedure. The program stopped after one thousand consecutive moves failed to decrease the cost. The final hierarchy places the most probable function at the top, the next most probable functions at level 1, and the least probable function at level 2. This is an optimal layout for this situation. Figure 5g shows the final hierarchy with non-needed pages removed.

Cost for related functions

The design of an MFDCS may need to consider factors other than expected access time. For example, guideline seven from page 13 suggests that the designer should place related functions on the same page or on adjacent pages (i.e., if not on the same page, one button-press away). The relatedness of two functions i and j, R_{ij}, can be estimated through pilot surveys or by MFDCS design experts.

Define the page-distance, W_{ij}, between two functions, i and j, as the maximum number of levels up one must go from either function to find a menu page that is parent to both functions. Page-distance can be calculated in the following way. Let $q(i) = (l,k)$ and $q(j) = (l+r,h)$ with $r \geq 0$ so that function j is at the same or lower level as function i. Then the page distance is:

$$W_{ij} = r + \left\{ \min u \in [0,l] \text{ such that } \left\lfloor \frac{k}{m^u} \right\rfloor = \left\lfloor \frac{h}{m^{u+r}} \right\rfloor \right\}.$$

As u steps up from 0 to l, the calculation on the right steps up from a child to parent page and checks to see if the pathways of the two functions' pages have converged. The page-distance is the smallest number of levels up for which the two pathways converge. For example, when $W_{ij} = 1$ either the two functions can be reached from the same parent page or one function can be reached by a selection from the other page. Minimization of the following cost term will put related functions as close as possible:

$$C_2 = \sum_{i=0}^{v-1} \sum_{j=0}^{v-1} R_{ij} W_{ij} .$$

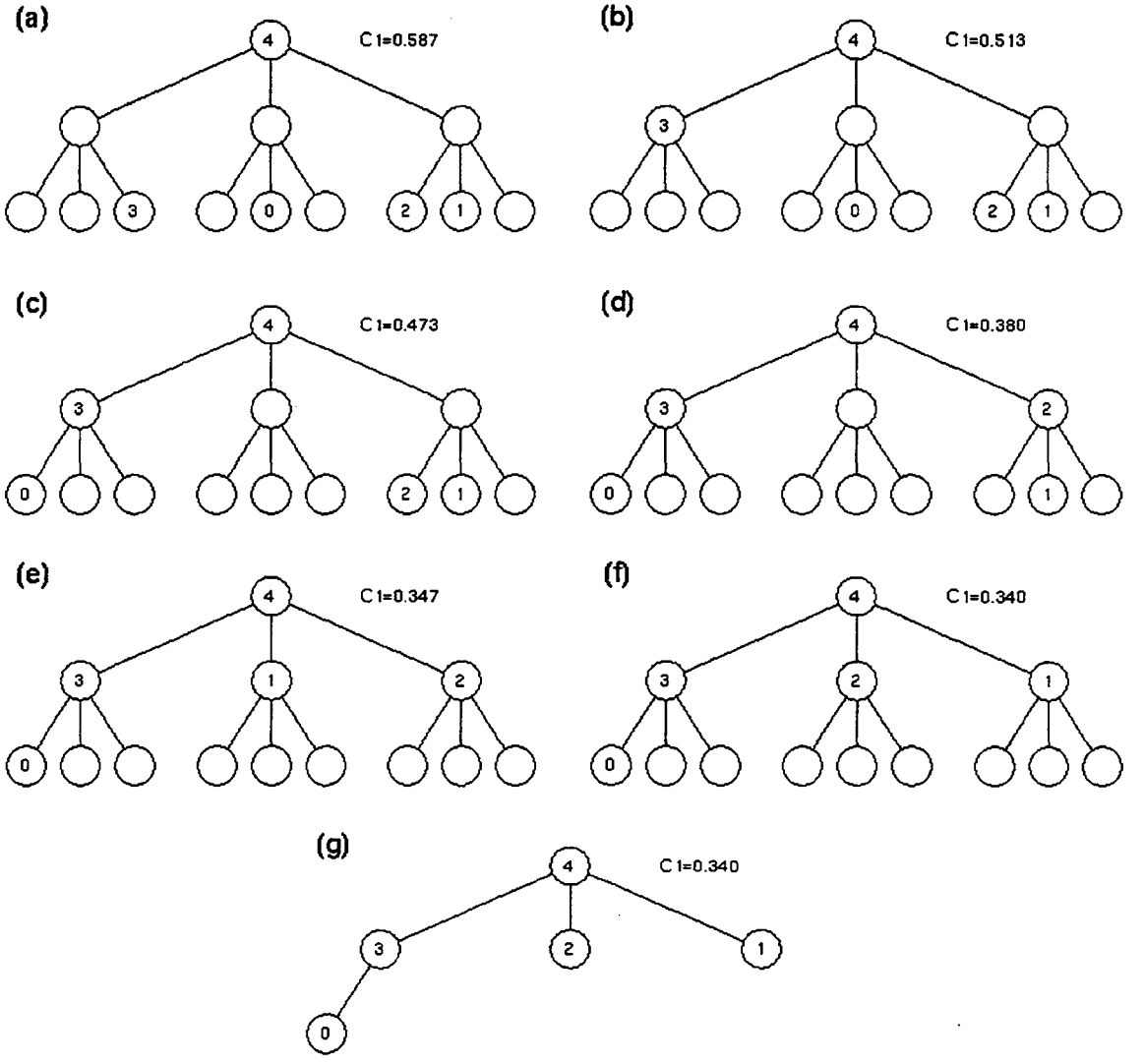


Figure 5. The development of a hierarchy through hill-climbing. (a) The initial layout of functions produces a high cost. (b) Function 3 has moved up a level. This reduces the number of steps needed to reach the function. (c) Function 0 has moved to the left. This frees a menu label at level 1, and reduces categorization time on the way to functions 1 and 2. (d) Function 2 moves up a level. This reduces the number of steps needed to reach the function. (e) Function 1 moves up a level. This reduces the number of steps needed to reach the function. (f) Functions 1 and 2 swap positions. This places the more probable function in a position to be categorized first. Further changes do not reduce cost. (g) The final hierarchy with non-needed pages removed. [The following parameters were use: c=0.1, r=0.1, s=0.2.]

To demonstrate how this cost term works, let relatedness between functions obey the following formula:

$$R_{ij} = \begin{cases} 1 & \text{if } |i-j| < 2 \\ 0 & \text{otherwise.} \end{cases}$$

This means that functions 3 and 4 are related, 2 and 3 are related, but functions 2 and 4 and 1 and 3 are not related. Figure 6 shows how the hill-climbing procedure starts with an initial layout of functions (a) and changes to a hierarchy that places related functions within one button press of each other. For this particular example, the system needed only two moves to reach an optimal layout. In (b) function 1 moved up a level, thereby placing it closer to function 0, while keeping it the same distance to function 2. In (c) function 4 moved to the right, thereby moving it closer to function 3. This optimal layout is not unique; figure 6d shows a very different layout that also minimizes C_2.

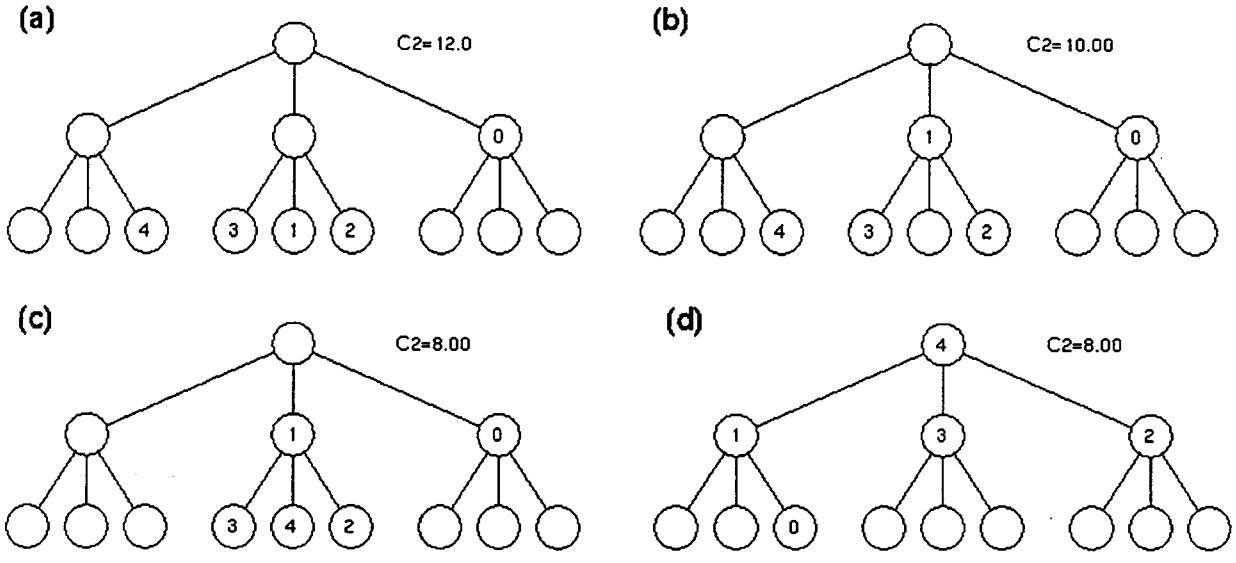


Figure 6. The development of a hierarchy that minimizes distance between related functions. (a) The initial layout of functions produces a high cost. (b) Function 1 moves closer to function 0. (c) Function 4 moves closer to function 3. (d) Another layout of functions that has the same optimal cost.

Cost for expected access time and relatedness

Generally, a designer will want to build an MFDCS that satisfies many different constraints. For example, if the MFDCS hierarchy should minimize both expected access time and put related functions close together, the cost to be minimized would be:

$$C = C_1 + C_2 .$$

Figure 7a shows a hierarchy produced by the hill-climbing method for this cost. The hierarchy does a good job of minimizing both cost terms. Every function is within one page of its related functions, and the most probable functions are located at the highest levels. However, the layout in figure 7a is not optimal. Figure 7b shows an optimal layout, found by the hill-climbing method with different starting conditions. Here, each function is within one page of related functions, and function 1 is placed at level 1, thereby reducing the expected access time.

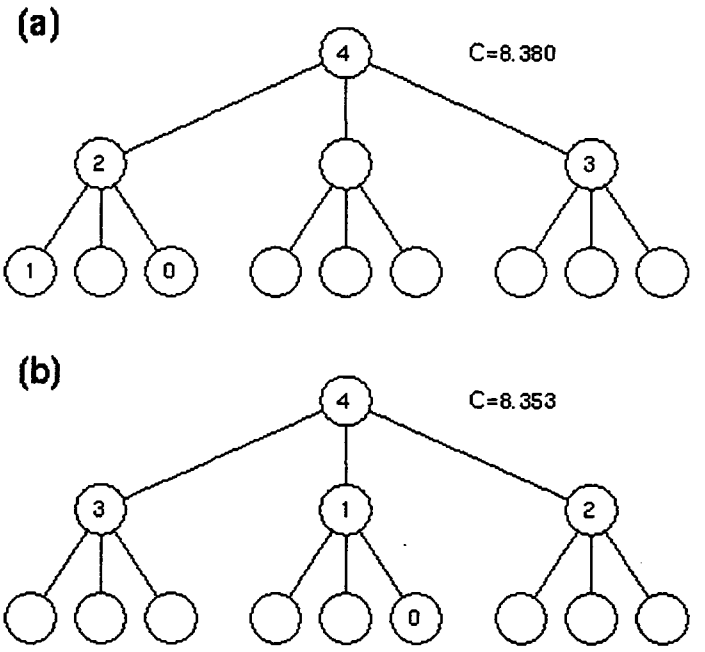


Figure 7. Hierarchies for minimization of expected access time and relatedness. (a) A layout of functions often found with the hill-climbing method. This layout cannot be modified to produce a lower cost. (b) An optimal layout of functions found occasionally with the hill-climbing method.

Note too that the optimal layout is not the same as the optimal layout for expected access time. To minimize expected access time, functions 1 and 2 need to switch positions and function 0 needs to move under function 3. The latter is not possible because functions 0 and 1 are related while functions 0 and 3 are not. Thus, placing function 0 beneath function 3 would increase cost. With that constraint, expected access time is shorter when function 1 (and its child 0) is reached through the second position of level 1 rather than through the third position (as in figure 5). This ensures that a user spends less time searching through options while accessing these two functions. Thus, imposing multiple constraints requires structuring the hierarchy quite differently than might be expected from imposing either constraint by itself.

It is important to realize that the hill-climbing method cannot modify the layout of functions in figure 7a to produce an optimal layout. The movement of any function will lead to an increase in cost and will be rejected by the hill-climbing technique. This layout, or state, of the system is called a stable state. No single move will cause the system to modify itself. A non-optimal stable state, where there can be no further decreases in cost, is a local minimum of the cost. The problem with a hill-climbing method is that it can never accept a change that might increase the overall cost. As the above example demonstrates, sometimes the system must tolerate increases in cost to reach one of the global minima. Researchers have devised a number of methods for resolving the problem, and the next section describes one of the most general methods.

Simulated annealing

Simulated annealing is a technique that allows hill-climbing procedures to avoid the local minima of a cost function and search out a global minimum. Intuitively, each possible layout of the functions, or state, corresponds to a position along an axis line (actually it is a position in a higher-dimensional space). The cost function at each position along the axis defines a curve along the line. Changing states (layout of functions) is then like moving along the line. Hill-climbing techniques start at an initial point on the line and move in a direction that goes down the cost curve (figure 8a). As a result, the technique can become trapped in local valleys.

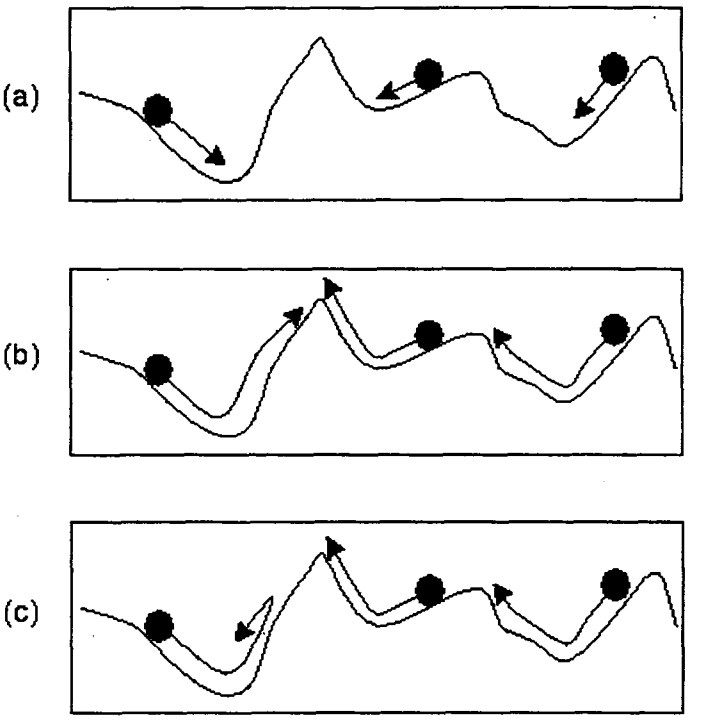


Figure 8. An intuitive description of hill-climbing and simulated annealing. The layout of functions is like a ball on a hill (cost). Movement of the ball down the hill corresponds to changes in the layout that lead to lower costs. (a) A hill-climbing method can become trapped in local minima. (b) With simulated annealing at a high temperature, the ball often travels uphill and out of local (and global) minima. (c) With simulated annealing at an intermediate temperature, the ball can travel out of local minima but not out of the deeper global minima.

Simulated annealing avoids this problem by introducing extra "energy" into the optimization process. With this method, initially, movement along the cost curve can occur in directions that go up or down. Then the probability of moving up the cost curve is gradually reduced as time (or iterations) progresses. As the likelihood of moving up the cost curve decreases, the system is more likely to become stuck in the deepest valley of the curve, a global minimum. It is more likely to climb out of local minima because they are not as deep.

Formally, define a temperature, T, which starts at a large value and gradually decreases. Suppose a random change in the hierarchy at time t produces a cost, $C(t)$. Accept the change with probability:

$$p = \begin{cases} 1 & \text{if } C(t) < C(t-1) \\ \dfrac{\exp(-C(t)/T)}{1+\exp(-C(t)/T)} & \text{otherwise.} \end{cases}$$

Changes that decrease cost are always accepted, and changes that increase cost are accepted with a probability that depends on the cost of the new layout and the current temperature. When T is large, the exponential terms are close to one, and the probability of accepting the change is close to one half, even if such a change leads to an increase in cost. As figure 8b schematizes, this allows the system to move out of local minima, but also allows the system to move out of global minima. As T decreases in size, a large cost tends to make the probability of accepting the change close to zero. By gradually decreasing T, the system goes through a phase where it becomes stuck in a valley of the cost curve that contains the globally minimum cost, but is able to climb out of valleys in the cost curve that contain higher costs (figure 8c). As T decreases further, it remains in the globally minimum cost valley.

Simulated annealing requires a substantial amount of computation. The technique requires starting with a large initial temperature and slowly decreasing it, all while making changes to the hierarchical structure. Selecting the initial temperature and the rate of decrease is important. If the temperature is too small initially or decreases too quickly, the system will become stuck in a local minimum. On the other hand, if the temperature is very large and decreases very slowly, the system will spend much of its time accepting random changes and will take a very long time to produce a final solution. While bounds exist on both the starting temperature and on the rate of annealing, they tend to be impractical for use (Geman and Geman, 1984). For the simulations reported here, the initial temperature was $T(0) = 3900$, and it then decreased with every random move of a function as:

$$T(t) = \frac{T(0)}{1.0 + t}.$$

As with the hill-climbing procedure, the algorithm terminated when one thousand consecutive moves failed to produce a decrease in cost.

Figure 9 compares the cost of solutions found by the hill-climbing method with those found using simulated annealing. One hundred trials were run for each approach. Figure 9a shows the frequency of different costs found with the hill-climbing method. Most of the solutions have a cost of C=8.380, although occasionally the system finds the optimal solution with C=8.353. Figure 9b shows the analogous results for simulated annealing. It finds an optimal layout much more often than any other layout but does occasionally converge to non-optimal hierarchies.

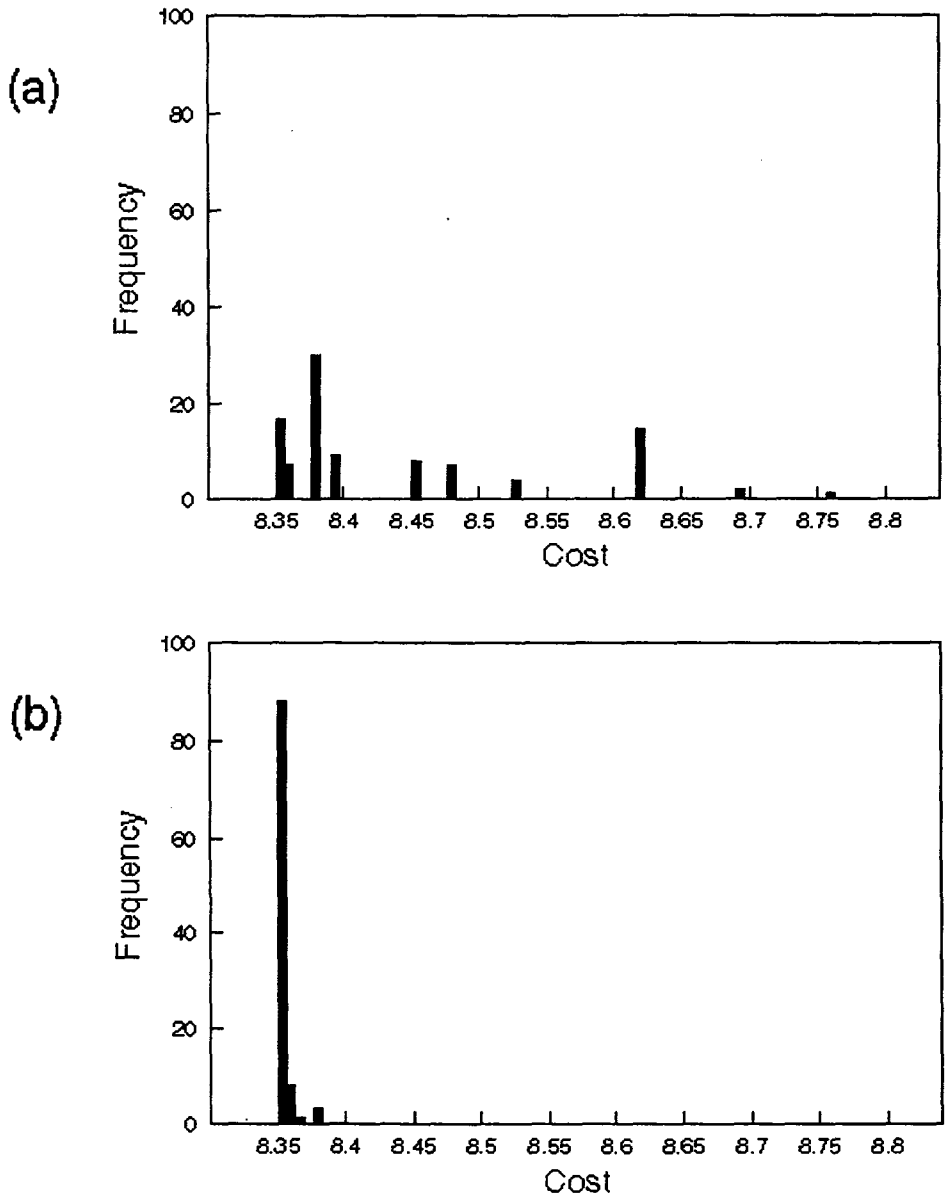


Figure 9. Frequency of final hierarchy costs for hill-climbing (a) and simulated annealing (b).

Simulated annealing is not the only option for cost minimization. Other techniques exist that may do just as well or better. The main observation here is that a cost function can measure the quality of a hierarchical structure. Minimization of that cost function allows a designer to identify an optimal hierarchy. The most important part of this process is identifying how to convert the qualitative guidelines for hierarchical design into costs. The next section considers this issue in more detail.

Cost functions

The previous section described a general method that finds a hierarchical structure to minimize a cost. This section considers how to quantify the qualitative design guidelines to produce costs.

Frequently used functions

Guideline one suggests that frequently used functions should be placed in the most accessible locations. This is already accomplished by the equation for C_1 above:

$$C_1 = \sum_{i=0}^{v-1} T_{q(i)} p_i \cdot$$

As figure 5 demonstrates, minimization of this cost term tends to push the functions used with high probability to the top of the hierarchy. Probability estimates can be gathered either through expert opinion, pilot interviews, or data collection during flights.

Time critical functions

Guideline two suggests that time critical functions should be placed in the most accessible locations. Minimizing the following equation will apply this guideline:

$$C_3 = \sum_{i=0}^{v-1} T_{q(i)} I_i \cdot$$

This equation is the same as for C_1, with importance, I_i replacing probability. Minimization of this cost term will place the functions with high importance at the top of the hierarchy. Expert opinion or pilot interviews can provide estimates of function importance.

Ideal locations

The third guideline suggests that frequently used and time critical functions should be activated by buttons that feel ideally located. Assume that the button indices, $h = 0,\ldots,m-1$ correspond to the relative order of page selection buttons on each menu page in the hierarchical

framework, and that the lower the index of the button, the higher its "idealness." Page (j,k) in the hierarchy will then use button:

$$b(j,k) = k - \lfloor k/m \rfloor m.$$

Let the time increase due to being nonideal be some increasing function $f[h]$. Then, during navigation through the hierarchy to reach page (j,k), the sum of time increases at each button push is:

$$B_{jk} = \sum_{l=0}^{j-1} f\left[b\left(j-l, \lfloor k/m^l \rfloor\right)\right] .$$

This summation goes backwards through the hierarchy from page (j,k) to the top and identifies the buttons necessary to reach page (j,k). This time should be added to the overall access time needed to reach page (j,k). Thus, the cost terms for C_1 and C_3 should use the following equation for access time:

$$T_{jk} = j(s+r) + c\sum_{l=1}^{j} m_{(j-l)\lfloor k/m^l \rfloor} + B_{jk} .$$

Quantification of the term "idealness" is needed before the effect of order on button selection can be modeled. Presumably, ideally ordered (i.e., allows user to most efficiently reach needed functions) page buttons and their identifiers will be categorized more quickly, searched faster, or struck more quickly. Experimental studies should be able to determine the influence of ideal button ordering and delineate the appropriate definition or value table for $f[h]$. Then the algorithm elucidated above will allow designers to optimize actual MFDCS display page hierarchies to take advantage of these additional human factors MFDCS-user performance data.

Repeated selection of buttons

Guideline four suggests that the hierarchy structure should minimize the need to switch buttons for the most frequently used functions. Thus, the most common selection from a menu should be on the same button as called up that menu. Presumably switching buttons adds to the overall time for the user to respond because he must move his finger to a new location. Let the time to travel a unit distance be a. Then, while navigating from the top of the hierarchy to page (j,k), the time spent moving between buttons will be:

$$S_{jk} = a\sum_{l=0}^{j-2} d\left[b\left(j-l-1, \lfloor k/m^{(l+1)} \rfloor\right), b\left(j-l, \lfloor k/m^l \rfloor\right)\right] .$$

Here, the first b term is the button associated with a higher level and the second b term is the button associated with the subsequent level on the way to page (j,k). The function $d[\ ]$ is a measure of

the physical distance between the buttons. The summation measures this distance across all the selections that the user must make to reach the desired page.

The time spent moving between buttons should be added to the calculation of access time for the costs C_1 and C_3. The access time to reach page (j,k) should now be:

$$T_{jk} = j(s+r) + c\sum_{l=1}^{j} m_{(j-l)\lfloor k/m^l \rfloor} + B_{jk} + S_{jk}$$

where s, which previously measured the entire strike time, now incorporates whatever parts of the strike movement are common to all keys.

Minimize number of levels

Guideline five suggested that a hierarchy should have as few levels as possible. Too many levels could lead to fatigue or cause the user to become lost. A simple measure of depth would be to add up the level indices of all function positions:

$$C_4 = \sum_{i=0}^{v-1} J[q(i)] \ .$$

Here, $J[q(i)]$ refers to the level index at the position of function i, $q(i) = (j,k)$. When many functions are at deep levels, C_4 will be large. It appears that current MFDCS designs consider this cost to be very important (Holley and Busbridge, 1995). One easy method of minimizing the number of levels in the MFDCS hierarchy is to provide a large number of buttons. However, with such an approach, the user trades the search of the hierarchy for the search of the proper button. A cost for such a search could easily be included in the method described here.

Minimize overall access time

Guideline six suggests that the hierarchy should minimize the overall access time. Minimizing C_1 already applies this guideline.

Related functions on close pages

Guideline seven suggests that related functions should be placed on the same page or on adjacent pages. Minimization of C_2 places functions as close as possible.

Consistent location of related items

Guideline eight suggests that related items should be in a consistent location, across different pages. Assuming that being close to each other corresponds to being close to each other among

the buttons, minimization of the following cost function will put related functions as close as possible:

$$C_5 = \sum_{i=0}^{v-1}\sum_{j=0}^{v-1} R_{ij} d\left[b(q(i))\ ,\ b(q(j))\right] .$$

With the relatedness function, R_{ij}, as defined in the section "Cost for related functions."

Related functions on the same page

Guideline nine suggests that, when they are on the same page, related functions should be placed next to each other. Minimizing C_5 already applies this guideline.

Errors

Guideline ten suggests that the hierarchy should anticipate likely errors and minimize the effect of those errors. A full enumeration of likely errors and the manner in which they depend on various aviation-related human factors will require extensive experimental work. Such research must consider at least: the physical layout of buttons, the labels for options, the effects of fatigue, and effects of aircraft vibration. If designers can quantitate the relationship of various variables or factors that predict different types of errors associated with MFDCS use, then a cost function can be determined such that its value will be large when an MFDCS function, or group of functions, is in a high error risk location in the hierarchy. A precise definition of this cost term will depend on the analysis of errors and their relative operational impacts.

Dedicated displays

Guideline 11 suggests that some frequently used and time critical functions should be removed from the MFDCS and given dedicated displays. Consideration of this issue does not require a new cost function. The cost functions discussed previously will optimize information across multiple MFDCS hierarchies simultaneously and place functions in separate MFDCSs. The designer need only specify the number of MFDCSs, the number of levels for each, and the number of menu options for each. A dedicated display would simply be an MFDCS with one level and one option. With the cost functions described above, reducing the overall cost should place the most commonly used and time critical functions in the dedicated displays, secondary information in the MFDCSs, and place related functions in the hierarchy of a common MFDCS. This approach also could decide which functions to place on a HUD.

Discussion

This paper described a new quantitative method for optimally distributing control and input functions across a hierarchy of MFDCS display pages. The flexible method is based either on minimizing a single composite cost function that is a weighted linear combination of separate cost functions or minimizing a set of simultaneous cost functions. Such cost functions can accommodate an arbitrary number of design or pilot performance constraints. We illustrated how these cost functions can be developed from qualitative MFDCS design and human factors constraints. Cost function coefficients are the elements in the equations that quantitate the effects of operationally important MFDCS human factors. It is important to emphasize that the method described here does not necessarily guarantee ideal hierarchical MFDCS display structure for all conceivable situations. A designer must still verify that the quantitatively determined hierarchy is a good design by experimentally demonstrating better performance than nonoptimized baseline designs in realistic scenarios. The proposed cost function minimization method does find the best MFDCS page hierarchy for the selected design and human factor constraints. If the cost functions do not adequately represent or emphasize the factors important for effective use of a particular MFDCS, the method may not produce a content page hierarchy that maximizes actual performance.

We anticipate that this design method, when validated, will be a useful design tool that can be used to produce optimal or near optimal relationships and interpage navigational paths for MFDCSs. However, specific applications will still need to be augmented with verification studies and evaluated in the light of experience and good judgment since it is unlikely that any single MFDCS information content design tool could take into account all potentially important factors for all conceivable operational circumstances. Quantifying the layout of MFDCS allocated functions, however, will assist designers to more rapidly evaluate the relative effectiveness of alternative MFDCS display page hierarchies and better select from alternative hardware-software combinations. For example, the design method described in this report could be used to obtain an optimal design for an MFDCS that includes both push-button and speech-recognition as alternative interfaces for accessing identical information. Since the human factors and performance parameters for these two disparate types of interface would differ, minimization of an overall cost function or weighted sum of separate cost functions value could serve as an objective measure for selecting the best interface. The designer would optimize the MFDCS information and control function layout for each interface alone and in combination and compare total system performance for each alternative (Reising and Curry, 1987). Such optimization would be difficult to perform without the quantitative techniques described here.

This report described some relatively simple models of the interaction of pilot factors with the structure of MFDCS display contents and distribution of control functions. A designer could introduce more involved models with no change in the fundamental computational technique (although substantially more bookkeeping would be required). For example, the models discussed in previous sections assumed that MFDCS computer response time was constant for all functions. That is probably not realistic, but inclusion of more realism would only require estimating the

response time for each function and using that estimate in the appropriate calculations for access time. Likewise, using an interface other than push-buttons would require modifying some of the cost functions and deleting and creating others.

Models such as the one developed in this technical report can enhance understanding of the interrelationships between human factors, the organization of MFDCS display content, and distribution of interface objects (e.g., push-buttons) by explicitly delineating the hypothesized relationships as equations that can be solved with either analytic or numerical techniques. Parameter or variable sensitivity analysis can be performed to determine which parameters or variables, when perturbed, cause the greatest changes in the cost function(s). This can assist designers to focus on the more influential parameters. Likewise, changes in parameters can be linked to operational settings so that designers can identify the scenarios for which a selected MFDCS content hierarchy may be suboptimal or problematic.

A quantitative human factors oriented MFDCS design model also can assist in identifying specific knowledge gaps in this topic area that need additional research. Such model-directed research can result in focused practical goal-oriented research efforts that generate results that have immediate application. The model developed in this report also may play a role in making the MFDCS design effort more efficient and cost-effective by reducing requirements for prototyping and repetitive expensive and time-consuming design-test-modify-retest cycles.

Conclusions

Having elaborated the general structure for a quantitative method for incorporating human factors into MFDCS design, follow-on experimental work will be required to establish realistic and useful parameter values (e.g., means and standard errors) for the coefficients in the cost functions. Sensitivity analysis may also be performed to quantify the relative effectiveness of the descriptive MFDCS design guidelines currently used by experienced designers. Further investigation into the issues presented in this report may also result in the delineation of additional important physical, cognitive, and psychomotor human factors for the efficient and effective use of MFDCSs during inflight emergencies or other high workload or high stress situations. Potential theoretical expansion of the concepts enumerated in this report, as well as the results of supporting experimental work, can lead to the eventual development of useful quantitative human factors-oriented MFDCS software design tools. Such design aids may lead to improvements in aircraft MFDCSs which allow crewmembers to more efficiently utilize the capabilities of complex aircraft, particularly in emergency or high workload situations where navigating to the required information and function buttons must be performed rapidly and without error.

References

Behar, I., Bachman, W., and Egenmaier, W. 1988. Contrast sensitivity in Army aviator candidates: Cycloplegia effects and population norms. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 88-16.

Calhoun, G. 1978. Control logic design criteria for multifunction switching devices. In: Proceedings of the Human Factors Society 22nd Annual Meeting. 383-387.

Cote, D., Krueger, G., and Simmons, R. 1982. Comparison of helicopter copilot workload while using three navigation systems during nap-of-the-earth flight. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 82-9.

Department of Defense. 1981. Military standard: Human engineering design criteria for military systems, equipment, and facilities. MIL-STD-1472D.

Dohme, J. 1995. The military quest for flight training effectiveness. In: Vertical Flight Training. W. Larsen, R. Randle, and L. Popish (eds.) NASA Reference Publication 1373.

Fisher, D., Yungkurth, E., and Moss, S. 1990. Optimal menu hierarchy design: Syntax and semantics. Human Factors. 32: 665-683.

Frezell, T., Hofmann, M., and Oliver, R. 1973. Aviator visual performance in the UH-1H: Study I. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 74-7.

Frezell, T., Hofmann, M., Snow, A. and McNutt, P. 1975. Aviator visual performance in the UH-1: Study II. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 75-11.

Geman, S., and Geman, D. 1984. Stochastic relaxation, Gibbs distributions, and the Bayesian restoration of images. IEEE Transactions on Pattern Analysis and Machine Intelligence. PAMI-6: 721-741.

Graf, V., and Holley, C. 1988. Human factors impact on the V-22 Osprey cockpit development: An overview. In: Proceedings of the American Helicopter Society 44th Annual Forum. 201-212.

Hannen, M., and Cloud, T. 1995. A case study in the design and testing of hands-on controls: The Longbow Apache grip development process. In: Proceedings of the American Helicopter Society 51st Annual Forum. 1417-1435.

Holley, C., and Busbridge, M. 1995. Evolution of the venom variant of the AH-1W Supercockpit. In: Proceedings of the American Helicopter Society 51st Annual Forum. 1436-1449.

Holly, F., and Rogers, V. 1982. Direct and neighboring sensitivity changes produced by red and blue-white adapting fields. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 82-1.

Knuth, D. 1973. The Art of Computer Programming. Volume 3: Sorting and Searching. Reading, MA: Addison-Wesley Publishing Co.

Kotulak, J., and Rash, C. 1992. Visual acuity with second and third generation night vision goggles obtained from a new method of night sky simulation across a wide range of target contrast. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 92-9.

Kotulak, J., Morse, S., and McLean, W. 1994. Does display phosphor bandwidth affect the ability of the eye to focus? Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 94-34.

Lee, E., and MacGregor, J. 1985. Minimizing user search time in menu retrieval systems. Human Factors. 27: 157-162.

Lind, J. 1981. Evaluation of cockpit procedures, displays, and controls for stores management in the advanced aircraft armament system (AAAS). China Lake, CA: Naval Weapons Center. NWC Technical Memorandum 4538.

Lorin, H. 1975. Sorting and Sort Systems. Reading, MA: Addison-Wesley Publishing Co.

McBryan, B., and Hall, J. 1995. Engineering approach for rotorcraft pilot's associate cognitive decision aiding systems development. In: IEEE/AIAA Digital Avionics Systems Conference Proceedings. IEEE: Piscataway, NJ. 76-81.

Newman, R. 1995. Head-Up Displays: Designing the way ahead. Brookfield, VT: Ashgate Publishing Co.

Paap, K., and Roske-Hofstrand, R. 1986. The optimal number of menu options per panel. Human Factors. 28: 377-385.

Rabin, J., and Wiley, R. 1996. Differences in apparent contrast in yellow and white light. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 96-21.

Rabin, J. 1994. Forward-looking infrared: Capabilities for search and rescue. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 94-11.

Rabin, J. 1995. Luminance effects on visual acuity and small letter contrast sensitivity. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 95-14.

Rabin, J. 1996. Image contrast and visual acuity through night vision goggles. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 96-26.

Rash, C., and Becher, J. 1982. Analysis of image smear in CRT displays due to scan rate and phosphor persistence. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 83-5.

Rash, C., and Verona, R. 1989. Cockpit lighting compatibility with image intensification night imaging systems: Issues and answers. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 89-6.

Rash, C., Monroe, D., and Verona, R. 1981. Computer model for the evaluation of symbology contrast in the integrated helmet and display sighting system. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 81-6.

Reising, J., and Curry, D. 1987. A comparison of voice and multifunction controls: Logic design is the key. Ergonomics. 30: 1063-1077.

Rogers, W., Cabrera, E., Walker, N., Gilbert, K., and Fisk, A. 1996. A survey of automatic teller machine usage across the adult life span. Human Factors. 38: 156-166.

Roske-Hofstrand, R., and Paap, K. 1986. Cognitive networks as a guide to menu organization: An application in the automated cockpit. Ergonomics. 29: 1301-1311.

Sanders, M., and McCormick, E. 1987. Human Factors in Engineering and Design. New York, NY: McGraw-Hill Book Co.

Sarter, N., and Woods, D. 1995. How in the world did we ever get into that mode? Mode error and awareness in supervisory control. Human Factors. 37: 5-19.

Seidler, K., and Wickens, C. 1992. Distance and organization in multifunction displays. Human Factors. 34: 555-569.

Sirevaag, E., Kramer, A., Wickens, C., Reisweber, M., Strayer, D., and Grenell, J. 1993. Assessment of pilot performance and mental workload in rotary wing aircraft. Ergonomics. 36: 1121-1140.

Snowberry, K., Parkinson, S.R., and Sisson, N. 1983. Computer display menus. Ergonomics. 26(7): 699-712.

Spiger, R., and Farrell, R. 1982. Survey of multi-function display and control technology. Seattle, WA: NASA-CR-167510.

Stokes, A., and Wickens, C. 1988. Aviation displays. In: Human Factors In Aviation. E. Wiener and D. Nagel (eds.). San Diego, CA: Academic Press.

Teitlebaum, R., and Granda, R. 1983. The effects of positional constancy on searching menus for information. In: Proceedings of Human Factors in Computing Systems. New York, NY: Association for Computing Machinery.

Vandierendonck, A., Van Hoe, R., and De Soete, G. 1988. Menu search as a function of menu organization, categorization, and experience. Acta Psychologica. 69: 231-248.

Williges, R., Williges, B., and Fainter, R. 1988. Software interfaces for aviation systems. In: Human Factors In Aviation. E. Wiener and D. Nagel (eds.). San Diego, CA: Academic Press.