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"SOFT" CONTROLS FOR HARD DISPLAYS: STILL A CHALLENGE

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ABSTRACT

Future trends in design of controls and displays for cockpit sub-systems (electrical, pneumatics, fuel, etc.), will undoubtedly focus on replacing dedicated "hard" controls with reconfigurable "soft" controls depicted on the sub-system schematic display. This concept would allow for direct manipulation of mechanical components via the display. The case study reported here discusses the approach, redesign, and evaluation of soft controls and multi-functional displays for the Advanced Concepts Flight Simulator (ACFS), a two-engine, "generic" airliner. The redesign effort focused on the input interface (a touch-sensitive screen), the display concept, and improving "navigation" among sub-system displays. The paper concludes with a summary of questionnaire data and comments of 26 airline pilots who flew a four-segment mission in the simulator. The subjective results indicated that pilots favored the direct manipulation concepts and the ability to link alerts, procedures, and configuration tasks. However, the technology used to support this concept still requires improvements.

INTRODUCTION

The current trend in the design of displays for aircraft sub-systems is to depict the sub-system schematic on a multi-functional CRT, while controls (switches, knobs, etc.), are mounted on panels above the two pilots. This trend can be seen in the design of the Airbus A-320, Boeing B-747/400, and Douglas MD-11 aircraft. Future trends will undoubtedly focus on replacing dedicated hardware controls with reconfigurable ones. Examples of this trend are the display and control interface of the Northrop B-2 (a multi-functional CRT with buttons mounted along the side), and the checklist and data-link interface in the new Boeing B-777 (a touch pad that controls a screen cursor) (Scott, 1992, May). Another medium for interacting with reconfigurable controls is touch-screen overlays. The issues involved in implementing a touch-screen interface for a commercial airliner cockpit are the topic of this paper.

The transition from "hard" gauges and switches to menu-driven CRT displays with reconfigurable "soft" controls that are part of the display has already begun. Yet, although the human-computer interaction community studies such topics, many issues that are unique to the design of displays and control for complex systems are still left unanswered (or unpublished). These unique issues include [1] ease of using "soft" controls as compared to "hard" controls, [2] absence of tactile and aural feedback, [3] loss of dedicated, "geographical," location of controls, [4] limited display "real estate," [5] "navigation" between displays during configuration tasks and emergency situations, [6] accuracy in mapping between the display schematic and sub-system components, [7] response time and display update rate of complex systems, [8] reliability of "soft" interfaces for high-risk domains, and [9] several environmental effects (e.g., vibration, glare).

SCOPE

The case study reported here discusses the approach, redesign, and evaluation of "soft" controls and multi-functional displays for the Advanced Concept Flight Simulator (ACFS). The ACFS is a "generic" glass cockpit airliner dedicated for testing new design concepts. This simulator was built with multi-functional displays and touch-screen overlays in order to represent the next generation in cockpit design (Chappell and Sexton, 1986).

The work reported here was part of a full mission simulation experiment to evaluate several concepts of electronic checklist (Palmer and Degani, 1991). The interface redesign effort was largely motivated by several airline and test pilots who flew the ACFS to evaluate initial versions of the electronic checklist system. All the pilots who flew the ACFS had considerable difficulties and frustration while operating the sub-system controls via the touch-screen overlay; they mostly complained about false hits, accidental hits, and poor feedback. It very quickly appeared to us that we could not conduct an effective checklist experiment with the existing interfaces. Therefore, we undertook a task to redesign and modify the cockpit sub-systems and touch-screen interfaces.

THE SIMULATOR

The ACFS simulates a two-engine, 200-passenger airliner with a two-person flight crew.

Avionics. Cockpit displays include five CRTs. Primary flight displays are presented on a CRT in front of each pilot. Synoptic displays, that depict the schematic as well as the dynamic state of each sub-system (fuel, electrical, etc.), are displayed on another CRT. Engine information is displayed on the center CRT. The sub-system caution and alerting systems can be displayed on any CRT. All CRTs (with exception of the two primary flight display CRTs), are covered with touch-screen overlay.

Touch-screen interface. The touch screens used in this study were resistive, flat-panel overlays (Transparent Device # 1322-00-0A). They consist of two layers of transparent material with separator dots in between. A force of 30 grams was required to register a touch. The active area of the panels measures 8 inches horizontally and 11 inches vertically. The touch-screen resolution was 1/8 of an inch.

Display architecture. The touch-screen processor translates “touches” to “x,y” coordinates and sends this information to the host computer (a VAX 8830), via a serial link at 9600 Baud. The host computer determines whether a touch is a valid hit by using a look-up table that stores the “x,y” coordinates of each button. This information is then sent to the affected sub-system model (engine, fuel, electrical, etc.). The new state of the affected sub-system is then sent via Ethernet, at an update rate of 5 times per second, to a workstation. The workstation (an SGI 4D20), generates the graphical image of the sub-system synoptic.

Direct manipulation. One advantage of sub-system synoptic display with touch-screen overlay is the capability for “direct interaction with the objects in the domain” (Hutchins, Hollan, and Norman, 1985. p. 332). Controls can be “mounted” *within* the synoptic display. This allows for direct manipulation of components, such as pumps and valves, from the display. Direct manipulation is a powerful concept, very efficient in reducing cognitive effort, search time, and motor movement (Shneiderman, 1983). For example, to transfer fuel from one tank to another, the operator touches the valve between the tanks; the valve icon rotates to the open position and flow of fuel is depicted in the transfer pipes. If the valve malfunctions, the synoptic display will show the valve’s *actual* position and no flow of fuel downstream of the valve. This eliminates the need for the so-called “disagreement light,” a common (and sometimes confusing) feature in today’s cockpit. Such lights illuminate to indicate disagreement between the state of a controller in the cockpit (e.g., a switch moved to the OPEN position) and the state of the actual mechanical component (e.g., a valve stuck in the CLOSED position).

REDESIGN OF THE ACFS INTERFACES

During the earlier evaluations of the simulator, we identified several areas that required redesign. Those areas were [1] input interfaces, [2] display concept, and [3] integration of alerts, procedures, displays, and controls.

Input Interfaces The objectives for the input interface modifications were aimed at [1] improving the touch logic for activating touch areas, and [2] enhancing the synoptic displays (buttons and icons).

Touch logic. Prior to this redesign effort, the ACFS touch-screen overlays were programmed with “first contact” touch logic. This logic selects the first target the user’s finger comes in contact with. If the desired target is missed, the finger must be removed from the screen and the touch must be reinstated. It is also an unforgiving logic—once a touch is registered, an action occurs. To make the touch logic more forgiving, we implemented the “lift-off” touch logic (Sears, Plaisant, and Shneiderman, 1992). In this logic, an action occurred only after the finger lifted off from the touch area (similar to using the mouse button on an Apple Macintosh). If the user fails to hit a touch area on initial contact, he may drag his finger into the touchable area. Likewise, if the user accidentally hits the wrong touch area, he may drag his finger out. This is an important feature, because due to limited display real estate, the size of our standard button was 0.65 inch by 0.65 inch—much smaller than recommended in the literature (Hall, Cunningham, Roache, and Cox, 1988).

Buttons and Icons. While observing how pilots flew and used the displays, we noticed that crews became frustrated when they were not sure which icons in the synoptic displays were touchable and which icons were not. Figure 1 depicts the AC POWER synoptic display prior to the redesign. For example, the VOLTS/LOAD% box in Figure 1 is a non-touchable icon that merely indicates the number of volts and the percentage of load on a generator. However, the LINE SWITCH switch is a touchable icon. Both are represented by a similar square box.

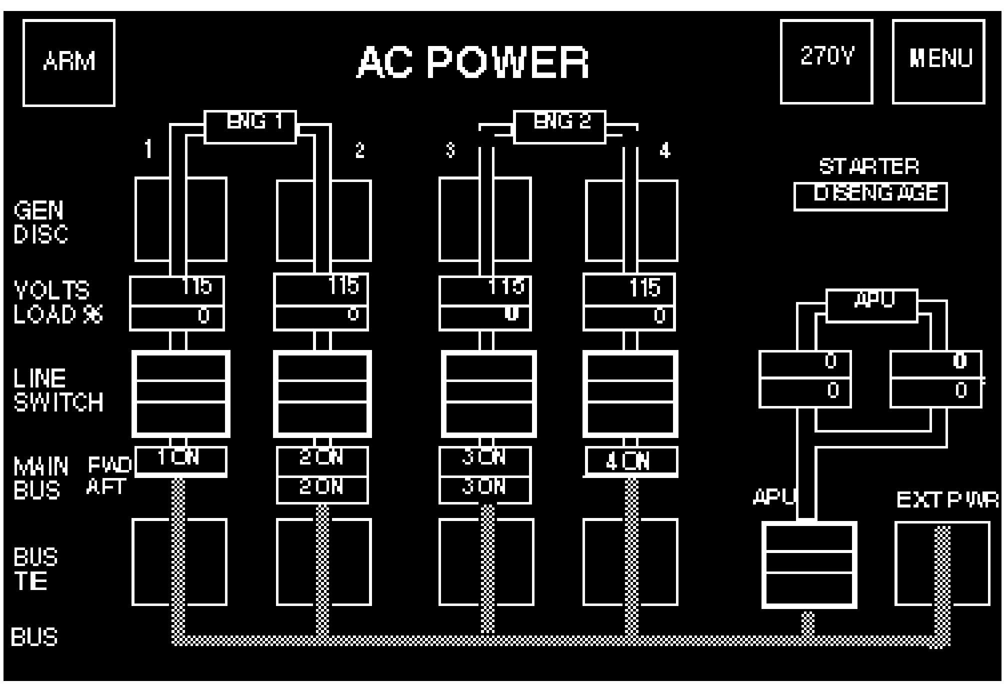

Figure 1. The old AC POWER sub-system display

Therefore, we attempted to distinguish between touchable and non-touchable areas. Touch areas were given a 3-D button shape and were opaque. Non-touchable areas were represented by a 2-D box with rounded corners and were transparent (see Figure 2). The 3-D button appearance also enhanced the lift-off logic. When the operator's finger was in the touch area, the 3-D button appeared as if the button was depressed into its slot. This provided visual feedback to the operator that his finger was inside the touchable area. Lift-off of the finger resulted in an action (e.g., switch moving from ON to OFF), and the button came out of its slot.

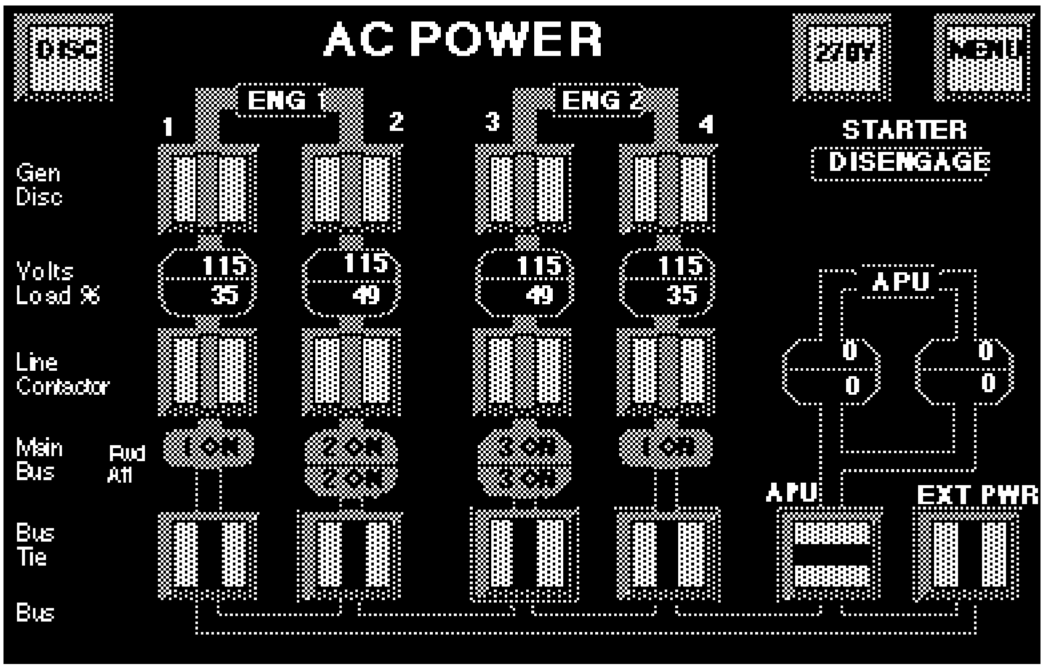

Figure 2. The redesigned AC POWER sub-system display

We were also concerned that by using a touch screen, the tactile and aural feedback associated with "hard" switches would be missed by the pilots. Therefore, an audio recording, simulating the "click-clack" sounds normally present when activating and releasing a button, was played through the pilot's headphones in synchronization with button touch (Begault, Stein, and Loesche).

Display and Color Concept

Since the early 1970s, airframe manufacturers have embraced and implemented the "dark/quiet" concept for cockpit design. This concept dictates that buttons and indicator lights are illuminated only if they require attention. When sub-systems are in the correct configuration, their indicators will not be illuminated or annunciated. Recently some have argued that "no information can mean either that everything is normal or that the annunciator has failed" (Billings, 1991, p. 90; De Groot, 1990).

We used a somewhat different concept in modifying the ACFS displays. Dark green was used throughout every synoptic display to "paint" dynamic icons (pipes, valves, etc.) as well as numerical values (volts, load %, etc.), when these components were in the correct configuration and operating normally. Gray was used for stationary icons, labels, etc.

Since the display background was black, dark green and gray were not irritating and in most cases blended well with the screen background. On the other hand, blue, amber, and red were used throughout the displays to indicate transition, caution, and danger, respectively. This extensive use of green, to indicate normal status, was designed as an aid for the crew in monitoring sub-systems and engine status. It was even incorporated into a checklist task (e.g., ENGINE STATUS.....ALL GREEN). Although beyond the scope of this paper, it should be noted that there are some concerns about this type of aiding.

Another design issue that is unique to direct manipulation interfaces is the necessity for accurate mapping. If the synoptic displays are to depict the "real world," then the state of every system component depicted on the display must be accurate. For example, in order to display fuel flowing in the pipes, fuel flow must be sensed by sensors along the pipes. Displaying this information based just on inferencing, e.g., "if the valve is open, *then* display fuel flowing in the pipes," can be misleading, as the operator is led to believe that the synoptic display accurately portrays the real world. Accurate mapping can be "faked" in a simulator; it should not be done in a real aircraft.

Integration and Navigation

Another advantage of computer-based displays and controls is the potential for integrating them with other systems in the cockpit. Our design concept called for integration of the synoptic display and associated controls with an alerting system and an electronic checklist system. This architecture provided links among all the above systems and allowed for an efficient way to "navigate" between displays, especially during abnormal situations (Woods, 1984). The link was hierarchical. When a malfunction occurred, the caution and alerting system displayed the failure and registered the appropriate procedure on a dedicated menu. As the pilot selected the procedure from this menu, the appropriate synoptic display for each checklist item was automatically displayed. The pilot then used the soft controls to configure the sub-system according to the procedure detailed on the checklist display.

SUBJECTIVE EVALUATIONS

Our design and evaluation approach, adopted partly from Gould and Lewis (1985), called for an iterative design process with frequent evaluations. Therefore, each major design phase was followed by a "dry run." Those runs were conducted by several airline crews who flew the simulation scenario and evaluated the cockpit displays. Flight crews performance and suggestions were evaluated, and some led to design changes. We repeated these design and test iterations until we felt the displays and controls were suitable for the upcoming experiment. We found this design approach to be laborious and time consuming. However, it appeared to be very effective for this type of design process.

Method

Thirteen airline crews participated in the final empirical evaluation. All crews were rated in "glass" cockpit aircraft. The experimental scenario was a four-segment flight between several California airports. After completing the experiment, the crews were debriefed verbally and filled a detailed questionnaire that included questions about the sub-system displays, navigation within the displays, and touch-screen operation. Some questions were open ended and some were to be answered on a graphical rating scale.

Results

The following are some of the subjects' responses about the displays, navigation, and the touch-screen interface. Although we could not summarize these subjective responses as effectively as one can present numerical data, we have attempted here to convey some of the verbal and written responses of the subjects. Due to space limitation, only part of this data is presented here.

Sub-system displays. Questionnaire data and debrief comments indicated that most subjects found it relatively easy to locate information on the sub-system displays. All subjects were very enthusiastic about the direct manipulation concept. They liked the immediate feedback, both in response to manipulating a component (e.g., the valve moved) and in seeing the effect of this manipulation (e.g., the flow of fuel downstream of the valve). One pilot stated that "with the simple pictures and color codes, it was easy to determine configuration and failed components without having to deal with superfluous information." Another pilot stated that synoptic displays "made problem definition and normal operations much easier on an aircraft we had so little experience with." Table 1 is the tabulation of responses to two questions about the sub-system displays (the bar graph on the side presents the number of subjects who responded similarly).

State the one feature of the system displays that you liked *most*	
▪ Graphical and color display of synoptics	13
▪ Accessibility of various sub-system	4
▪ Checklist items drive system displays	3
▪ Simplicity of displayed information	1
State the one feature of the system displays that you liked *least*	
▪ Difficulty in activating a button	6
▪ Slow response of the touch-screen	3
▪ Over simplified synoptics	3
▪ APU power and External power display	2
▪ Light switches should be hard switches	1
▪ The flow-pattern was not obvious	1

Table 1. Subjects' responses to two questions about the system displays

Subjects commented that they liked the link between the alerting system and the checklist system. Namely, that a system alert triggered the appropriate checklist procedure (the procedural text, however, did not pop up automatically—it was stored in a special menu, ready to be selected by the crew). They also liked the feature that automatically called up the appropriate sub-system display while conducting a specific checklist item (Figure 3).

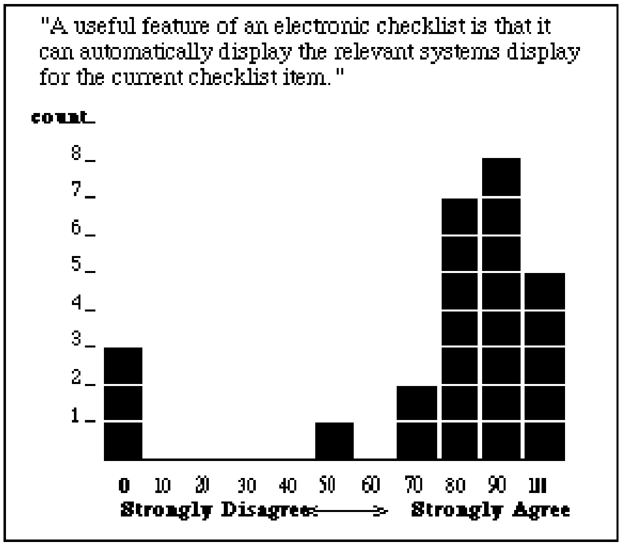

Figure 3. Subjects' response (graphical scale)

Touch-screen interface. Almost all subjects expressed concerns about the usability of the touch screen in a cockpit environment. There were three major concerns: [1] button activation and accidental touches [2] response time, and [3] loss of tactile feedback.

[1] Button activation. The majority of the pilots stated that it was sometimes difficult to activate a touch area. They complained about difficulties in determining the size of the area that registered a hit—"finding the sweet spot" (see Figure 4). Parallax was another concern (the upper surface of the touch-screen overlay was 7/16 of an inch above where the screen image was generated). As one stated, "you had to have your finger right on the button, or it wouldn't switch or maybe activate something else that was close by."

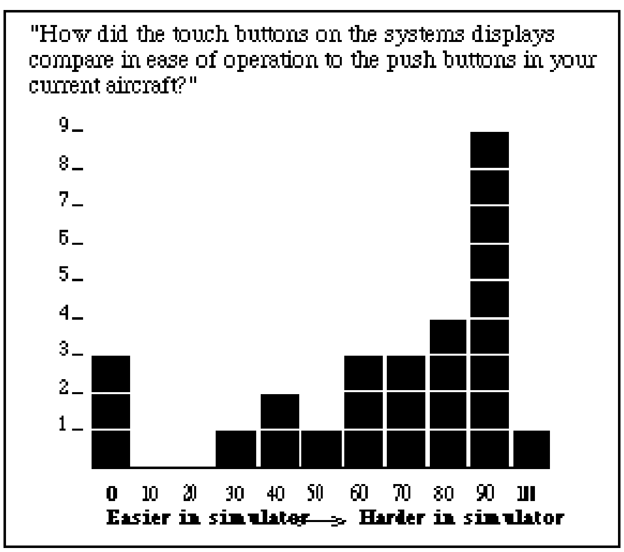

Figure 4. Subjects' response (graphical scale)

[2] Response time. The simulator response time, i.e., the time elapsed from lift-off of a finger to seeing the effect on the display, was nominally about 250 milliseconds. This response time, however, could vary up to 450 milliseconds in the worst case of communication sequences. This, obviously, was too slow. Coupling of slow response time with activation problems sometimes resulted in successive attempts to manipulate a control. This would usually result in an additional delay. The final result was frustration.

[3] Loss of tactile feedback. Several subjects stated that loss of tactile feedback was a problem—"Mechanical controls can be found in the dark by feel and operated the same way." Similarly, some were concerned about loss of the dedicated "geographical" location of hard control. Another subject complained that "having to physically touch the screen to accomplish each item in a checklist does not allow any outside visual [scan]. I noticed this especially on AFTER TAKEOFF and AFTER LANDING checklist." Several pilots felt that adverse conditions such as turbulence might further reduce the efficiency of the touch screen, as "this is a problem with the ACARS [Aircraft Communications Addressing and Reporting System] touch screen display already in use." Table 2 is the tabulation of responses to two questions about the touch screens.

State the one feature of the touch panel that you liked *most*	
▪ Presentation and accessibility	7
▪ Ease of reach, "no craning of neck"	3
▪ Easy and simple to use	2
▪ Size of print/clarity	2
▪ Being able to see a response	2
▪ Large targets to touch	1
▪ "Clicking" sound	1
▪ Big boxes to push	1

State the one feature of the touch panel that you liked *least*	
▪ Activation, "finding the sweet spot"	13
▪ Not responsive enough	2
▪ Not very reliable	2
▪ Hard to see across cockpit	1
▪ Over automated	1

Table 2. Subjects' responses to two questions about the touch screens

CONCLUSIONS

The redesign of the touch-screen interface and the synoptic displays allowed us to conduct a successful experiment to evaluate different electronic checklist systems. Nevertheless, it did not allow us to provide the perfect "illusion" that the components manipulated via the synoptic display were the components of the "real world." Hutchins et al. (1985), stated that "one factor that seems especially relevant to maintaining this illusion is the form and speed of feedback" (p. 334). In our case, this critical factor was the simulation response time. The "bottleneck" in the ACFS display architecture was the slow update rate between the host computer and the workstations. The problem, as we noted in our observations, was not just the slow mean response time, but also the variability in response time. This variability was one factor that the subjects had difficulty adapting to.

Other factors also contributed to reducing the ease of using soft controls as compared to hard switches, knobs, buttons, etc. We therefore believe that further improvements in activation methods, precision, parallax, and screen sensitivity must also be achieved before this touch-screen technology is suitable for controlling complex systems in high risk domains. As one subject summarized it, "During a line operation it would be a hassle if the switches would not turn ON with the first touch."

Multi-functional displays and direct manipulation concepts afford many advantages for interacting with mechanical sub-systems. They allow the operator to act on, "feel," and observe the real world through the display—a powerful medium for working with complex systems. They also provide the designer of a high-risk system the capability to link alerts, procedures, and configuration tasks—a much sought after operational objective. Furthermore, such displays allow the designer to present these three critical steps in one centralized location.

Like the introduction of any new technology, the application of direct manipulation concepts affords exciting new advantages (e.g., interacting with the "real world"), challenges existing design concepts (e.g., the "dark/quiet cockpit"), and gives birth to new problems (e.g., loss of tactile feedback). All must be addressed prior to incorporating these concepts in a fully operational setting.

REFERENCES

Begault, D. R., Stein, N., and Loesche, V. *Advanced Audio Applications in the NASA-Ames Advanced Cab Flight Simulator* (Submitted for publication as a NASA Technical Memorandum). Moffett Field, CA: NASA Ames Research Center.

Billings, C. E. (1991). *Human centered automation: A concept and guidelines* (NASA Technical Memorandum 103885). Moffett Field, CA: NASA Ames Research Center.

Chappell, S. L., and Sexton, J. A. (1986). Advanced concepts flight simulation facility. *Applied Ergonomics, 17(4)*, 252-256.

De Groot, H. (1990). *Flight safety—a human factors task*. Fokker Aircraft company: The Netherlands.

Gould, J. D., and Lewis, C. (1985). Designing for usability: Key principles and what designers think. *Communication of the ACM, 28(3)*, 300-311.

Hall, A. D., Cunningham, J. B., Roache, R. P., and Cox, J. W. (1988). Factors affecting performance using touch-entry systems: Tactual recognition fields and system accuracy. *Journal of Applied Psychology, 73(4)*, 711-720.

Hutchins, E. L., Hollan, J. D., and Norman, D. A. (1985). Direct manipulation interfaces. *Human-Computer Interaction, 1*, 311-338.

Palmer, E. A., and Degani, A. (1991). Electronic checklists: Evaluation of two levels of automation. In R. S. Jensen (Ed.), *Proceedings of the Sixth International Symposium on*

Aviation Psychology Conference (pp. 178-183). Columbus, OH: The Ohio State University.

Scott, W. B., (1992, May). B-2 handling, automation tailored for two-pilot crew. *Aviation Week and Space Technology, 136(20)*, 40-44.

Sears, A., Plaisant, C., and Shneiderman, B. (1992). A new era for touch-screen applications: High precision, dragging icons, and refined feedback. To appear in: R. Hartson and D. Hix (Eds.), *Advances in Human-Computer Interaction (Vol. 3).*

Shneiderman, B. (1983). Direct manipulation: A step beyond programming languages. *IEEE Computer, 16(8)*, 57-69.

Woods, D. D. (1984). Visual momentum: A concept to improve the cognitive coupling of person and computer. *International Journal of Man-Machine Studies, 21*, 229-244.