EFFECTS OF THE SPACE SHUTTLE COCKPIT AVIONICS UPGRADE ON CREWMEMBER PERFORMANCE AND SITUATION AWARENESS

Miwa Hayashi, Ph.D., Valerie Huemer, M.S.
San Jose State University Foundation
Moffett Field, CA

Fritz Renema, Steve Elkins
QSS Group, Inc.
Moffett Field, CA

Jeffrey W. McCandless, Ph.D., Robert S. McCann, Ph.D.
NASA Ames Research Center
Moffett Field, CA

The Space Shuttle Cockpit Avionics Upgrade (CAU) is a proposed cockpit display upgrade designed to address human-factors usability issues of the current suite of cockpit displays, Multifunction Electronic Display System (MEDS). Unlike MEDS, CAU consolidates information in a task-oriented manner, rather than a data-source-oriented manner. CAU also makes greater use of color coding and graphical depictions in systems status presentations. An ascent-phase operation simulation study showed that CAU formats significantly improved the participants' abort-related situation awareness. Participants also performed certain malfunction management procedures more accurately when CAU was used. The Space Shuttles are now scheduled to be retired by 2010 without incorporating CAU; however, the results of the present study suggest that the human-centered design concepts are effective and can be extended to the cockpit interface design of NASA's next generation Crew Exploration Vehicle.

INTRODUCTION

Human-Factors Issues of Current Shuttle Cockpit (MEDS)

The Space Shuttles Atlantis and Discovery have been equipped with a glass cockpit system, called Multifunction Electronic Display System (MEDS). (The Space Shuttle Endeavor's modification to MEDS is also in progress.) As shown in Figure 1, MEDS consists of nine Multifunction Display Units (MDUs), each of which includes a full-color liquid crystal display (LCD) and six edgekeys. These MDUs replaced outmoded components of the original Shuttle cockpits, such as cathode ray tube (CRT) display units, electromechanical flight instruments, and servo-driven tape meters, which had been in use since the 1970s.

The formats of MEDS were intentionally designed to be backward compatible with those of the original cockpit system, both to minimize crew retraining requirements and to preserve as much of the existing display management software as possible (Marchant, Eastin, & Ferguson, 2001). Even though these reasons were legitimate, this backward compatibility also meant that MEDS inherited a number of human-factors issues from the original cockpit. For instance, the three MDUs that replaced the CRT displays in the original cockpit use the same monochromatic formats, i.e., green text and graphics on a black background, as the CRT displays, despite the full-color capability of the LCDs. Also, these MDUs typically display digital data in tightly spaced rows and columns as the CRT displays did. Furthermore, in the original cockpit, the design of the data buses restricted each CRT display to presenting information from only one of the five onboard General Purpose Computers (GPCs) at any given time. This forced the arrangement of the information to be data-source oriented, rather than task oriented, frequently forcing crewmembers to navigate through multiple displays to obtain a set of information required for a particular task. Since MEDS continues using the same display formats as the original cockpit, the same problem occurs in the MEDS cockpit, as well.

Figure 1. Nine MDUs in the forward flight deck of MEDS cockpit (NASA photo)

To make matters worse, some key situation awareness information is completely missing from both the original and MEDS cockpits. For example, during ascent, information about the abort landing site options in the event of a main engine failure is not displayed in either cockpit. This information is computed in real time only on the ground. Thus, in an emergency, the crewmembers must obtain this information by either communicating with the ground, or referencing multiple tables in a Flight Data File (FDF).

Proposed Cockpit Avionics Upgrade (CAU)

To address these human-factors issues with the MEDS cockpit, groups of astronauts, flight controllers, astronaut instructors, engineers, and human factors scientists recently completed a usability-oriented modification of the MEDS formats known as Cockpit Avionics Upgrade (CAU) (McCandless, McCann, & Hilty, 2003). The CAU project included implementation of a new display management hardware architecture that allowed CAU display units to mix information from multiple GPCs (Marchant et al., 2001). This permitted information to be consolidated in a task-oriented, rather than source-oriented, manner. CAU also promoted better use of color to attract crewmembers' attention to critical information. CAU displays also incorporated graphical formats to make it easy to ascertain system health and vehicle navigation status information. In addition, consolidating information created room to accommodate entirely new displays, such as Horizontal Situation (H Sit). The H Sit provides at-a-glance graphical information about the horizontal flight path and current abort capabilities. These are only a part of numerous modifications included in CAU. More modifications relevant to the context of the present study will be described in the METHOD section below.

Goal of the Study

This paper reports the results of a simulator evaluation of the effects of the proposed CAU formats on crewmembers' situation awareness, workload, and performance during nominal and off-nominal operations. The MEDS formats served as a baseline for this evaluation. Ascent-phase operation scenarios were selected for the evaluation, where participants must closely monitor a sequence of safety-critical events and respond quickly and correctly in case of anomalies. An eye-tracking system was utilized to investigate the effects of display formats on participants' scan patterns.

METHOD

Simulator

A fixed-base, part-task Space Shuttle cockpit simulator at NASA Ames Research center was used for the experiment. The simulator was configured to replicate the Commander-side (left) environment in the Shuttle cockpit. Four 20" touch-screen LCD monitors presented seven displays (i.e., the MDUs) and a Caution and Warning light panel. Seven 20" touch-screen LCD monitors were used to simulate switch panels, and a 12" touch-screen LCD monitor was used as a simulated keyboard. A network of seven PCs and an SGI Octane was used to compute the Shuttle's flight dynamics and the display output. The flight dynamics, system parameter tables, and engine sound were obtained from NASA Johnson Space Center. Display graphics were generated using VAPS, OpenGL®, and winGDI.

Displays

Figures 2(a) and 2(b) show the formats of the seven displays presented to the participants in the MEDS and CAU cockpits, respectively, during the ascent-phase simulation. In Figure 2, reference numbers for each of the displays are provided in square brackets (i.e., [M1] to [M7] for MEDS and [C1] to [C7] for CAU) for readers' convenience. Each square display area is 7.5" × 7.5".

Key features of the CAU formats compared to the MEDS formats relevant to the context of the present simulation study are as follows:

- The H Sit [C1] presents graphical information pertaining to the vehicle's horizontal flight path and current abort options. This information is not provided in MEDS.
- The MEDS Primary Avionics Software System (PASS) Ascent Trajectory [M3] and Backup Flight System (BFS) Ascent Trajectory [M5a] information is consolidated on a single CAU display, the Ascent Trajectory [C3].
- Graphical representations of the Main Propulsion System (MPS) components, their operational status, and their interconnections are provided on the CAU MPS Sum [C4]. The equivalent information in MEDS is distributed across the Orbital Maneuvering System (OMS)/MPS Sum [M4] and the BFS System (Sys) Sum [M5b].
- Data Processing System (DPS) information, including the PASS and BFS GPCs' operating status health, is consolidated on a single display, the DPS Sum [C6].
- Systematic use of a color-coding scheme, i.e., red for warning, yellow for caution, and cyan for missing data, is applied throughout the CAU formats.

Participants

Five Airline Transport Pilots with an average of 15,000 total flight hours (ranging from 11,000 to 22,000 hours) participated in the study. All the participants received a one-week intensive training course in the Shuttle's system, ascent operations, the FDF, and simulator familiarization prior to the MEDS trials. The participants also received a two-day refresher course prior to the CAU trials.

Scenario

The ascent-phase operation from launch to Main Engine Cutoff (MECO), about 8.5 minutes in length, was simulated. One nominal and two different off-nominal scenarios were simulated. During the nominal trials, the participant monitored several discrete safety-critical events, such as, launch, Solid Rocket Booster (SRB) separation at 2:00 Mission Elapsed Time (MET), and MECO at 8:30 MET, as well as overall systems health and navigational state on a continuing basis. No simulated malfunction occurred during the nominal trials.

During the off-nominal trials, the participants were required to handle multiple simulated system malfunctions, in addition to the nominal monitoring tasks described above. One of the off-nominal trials (the "GUF" trial) consisted of a GPC malfunction at 1:50 MET, a low ullage pressure condition in the external tank at 2:00 MET, and a Flash Evaporator System (FES) malfunction at 3:05 MET. During the other off-nominal trial (the "HGF" trial), a left-engine Helium supply system regulator malfunction was inserted at 1:50 MET, followed by a GPC malfunction at 2:00 MET and a FES malfunction at 3:05 MET. Appropriate procedures to manage some of these malfunctions required more than one switch-throwing action; the FDF listing all the steps for various malfunction management procedures was available to the participants during the trials.

Data Collection

For both display formats, each participant flew four trials consisting of two nominal, one GUF, and one HGF trial. The MEDS trials were conducted first, followed, one year later, by the CAU trials. The one-year interlude was inserted to reduce the chance that the participants would remember the details of the scenarios. For each display format, the first and the last (i.e., the 4th) trials for each participant were always nominal. The order of the off-nominal trial scenarios was balanced among the participants.

A head-mounted eye camera (ISCAN ETL-500, ISAN, Inc., Burlington, MA) and a head tracker (FasTRAK, Polhemus, Colchester, VT) were used to collect the participants' eye-movement data with a sampling rate of 60 Hz. Their malfunction management performance (i.e., switch throws) was also recorded.

Following a trial, each participant filled out subjective ratings questionnaire forms. The subjective ratings scores collected were the Bedford workload (WL) scale (Roscoe & Ellis, 1990), five situation awareness (SA) scores, and 13 vehicle situation awareness (VSA) scores specifically regarding the vehicle states. The range of the SA and the VSA scores was 0 (poorest SA) to 10 (highest SA). In addition, following each off-nominal trial, three malfunction situation awareness (MSA) scores, which rated the difficulty to diagnose the malfunctions, difficulty to work the malfunctions, and impact of the malfunctions on the overall SA, were also collected. The MSA score range was from 0 (easiest, most improved) to 10 (hardest, most impaired). Note the reversed direction of the MSA; that is, unlike for the SA and the VSA, lower scores were more desirable for the MSA.

RESULTS AND DISCUSSION

Nominal Trial Results

The average of each participant's subjective rating scores over the two nominal trials was computed for both display formats, and paired t-tests were applied. The results showed that the following abort-capability-related VSA scores significantly increased when CAU was used rather than MEDS: "current abort option" ($t(4) = -16.8$, $p < 0.001$) (Figure 3, left), and "vehicle location with respect to available abort sites" ($t(4) = -15.0$, $p < 0.001$) (Figure 3, right).

It is not surprising that CAU resulted in higher VSA scores related to the abort options, as CAU includes a dedicated graphical display of the abort-related information (i.e., the H Sit [C1]), while MEDS provides no horizontal flight situation information. The eye-movement data showed that, on average, the participants looked at the H Sit 14.7% of the time. This large percentage of the scan time, combined with their high VSA scores, indicates that the abort-related information on the H Sit was actually utilized.

One of the main usability requirements of CAU was the task-oriented consolidation of information onto a single

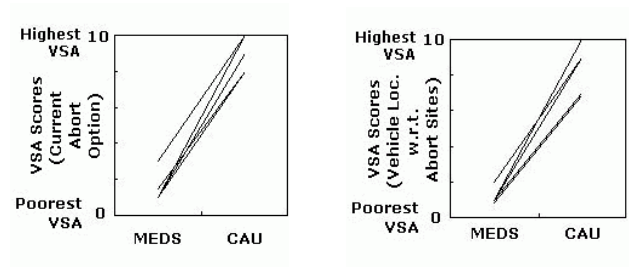

Figure 3. Average VSA scores for the "current abort option" (left) and "vehicle location w.r.t. available abort sites" (right) during nominal trials. Each line connects scores of the same participant.

display. A priori, this consolidation is expected to reduce the need to crosscheck information across multiple displays. Indeed, the average frequency with which participants transitioned from one display to another was significantly lower with CAU (25.3 transitions/minute) than with MEDS (32.2 transitions/minute) ($t(4)= 3.87$, $p = 0.018$). This reduction in transitions implies that the lost time associated with moving the eyes and re-accommodating on a new display was less with CAU than with MEDS, and, thus, the participants had slightly more time to observe each display when CAU was used.

Off-Nominal Trial Results

The percentages of correct completions of the malfunction management procedures were as follows: for the GPC malfunction, 50% with MEDS, and 80% with CAU; for the Helium system malfunction, 20% for both MEDS and CAU; for the low ullage pressure, 100% for both MEDS and CAU; and for the FES system malfunction, 60% for MEDS and 70% for CAU. The malfunction whose percentage of correct completion was most improved by CAU formats was the GPC malfunction (30% improvement). The CAU DPS Sum [C6] provides the current health of the five parallel running GPCs, using an appropriate color-coding scheme for easy scanning. The MEDS cockpit does not include such a dedicated data processing system display; and, therefore, multiple displays need to be scanned to obtain the same level of GPC health information. Better accessibility to the GPC information on CAU may have contributed to the improvement of the GPC failure management performance.

The subjective rating scores for the two off-nominal trials were subjected to General Linear Model (GLM) repeated measures analysis with the trial types and the display formats as main effects (SPSS v.11.0.3, SPSS Inc.). The following SA scores increased significantly when CAU was used rather than MEDS: "information is displayed such that it is easy to access the vehicle state" (display-format main effect: $F(1, 4) = 7.34$, $p = 0.054$), "the display of information enhances my ability to make correct decisions" ($F(1, 4) = 7.66$, $p = 0.050$), and "the display of information enhances my ability to correctly complete tasks" ($F(1, 4) = 7.75$, $p = 0.050$). In addition, the following abort-related VSA scores also significantly increased when CAU was used rather than MEDS: "current abort option" ($F(1, 4) = 246$, $p < 0.001$), and "vehicle location with respect to available abort sites" ($F(1, 4) = 184$, $p < 0.001$).

Furthermore, the analogous GLM repeated measures analysis on the Bedford WL scales revealed that the participants judged workload of the HGF trials as significantly higher than that of the GUF trials (trial-type main effect: $F(1, 4) = 12.4$, $p = 0.024$) (Figure 4, left). This agrees with the low correct completion percentage of the Helium system malfunction procedures, as the Helium system malfunction occurred only during the HGF trials. However, interestingly, paired t-tests on the MSA scores also indicated that, during the HGF trials, the difficulty of diagnosing the malfunctions was significantly reduced with CAU compared to MEDS ($t(4) = 3.52$, $p = 0.024$) (Figure 4, right). No significant display-format effect was found in the same MSA score during the GUF trials. The results suggest that during the HGF trials, the CAU formats, especially the MPS Sum [C4], where the Helium system information was graphically shown, helped participants diagnose the Helium system malfunction more rapidly than the MEDS BFS Sys Sum [M5b], which contains largely digital and monochromatic information. The fact that the average reaction time between the Master Alert and the first switch throw for the Helium malfunction procedure was about 30 seconds faster when CAU was used instead of MEDS (91.0 seconds with MEDS, 61.7 seconds with CAU; only the data from the three participants who performed the first switch throw correctly for both display formats were counted) also supports this view.

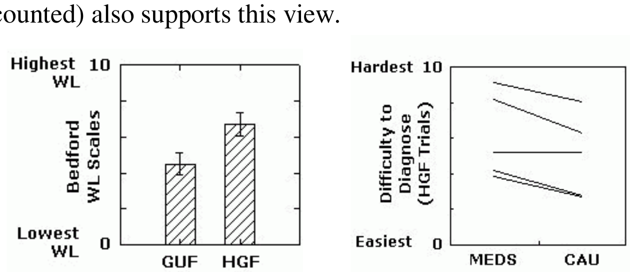

Figure 4. Grand means of Bedford WL scales with standard error bars for off-nominal trial types (left) and MSA scores for difficulty to diagnose malfunctions during the HGF trials for each participant (right).

Future Work

The results of the present study indicated that the CAU formats greatly improved the subjective ratings of situation awareness regarding the vehicle's current abort capability. Thus, suggested future work includes a further investigation of how CAU assists crewmembers during actual execution of the abort operations and how the proposed CAU formats can be further improved.

The data also showed that the CAU formats helped in quickly diagnosing certain types of complex system malfunctions. Since these malfunction management procedures are likely to be automated in the future, it is also of interest to see how the proposed CAU formats can effectively incorporate the automation command interface.

The Space Shuttles are now scheduled to be retired by 2010; therefore, NASA has decided not to install CAU on the Shuttles. After 2010, the Crew Exploration Vehicle (CEV) will be used to transport astronauts to low Earth orbit, the Moon, and eventually to Mars. CAU was originally designed for Shuttle operations; however, since it was developed mainly based on human-centered, usability-oriented specifications, rather than limitations particular to the Shuttle's systems architecture, the concepts and the results of the CAU project can be extended to CEV cockpit interface development, as well. For instance, the future work suggested above will also apply for the CEV operations.

CONCLUSION

The present simulation study showed that the proposed CAU formats, the human-centered modification to the current MEDS formats, significantly improved the participants' abort-capability situation awareness. The task-oriented information consolidation of CAU also reduced the display crosschecking during nominal scanning. During off-nominal trials, the CAU formats helped participants correctly complete the GPC malfunction management procedures, as well as diagnose complex Helium system malfunctions. CAU formats are not designed to be backward compatible with either MEDS or the original cockpit formats, but its usability benefits may outweigh the potential disadvantages, such as the need for additional crew training. Because of its human-centered approach, the CAU project's concept and results can be applied to the development of the next generation CEV cockpit interface as well.

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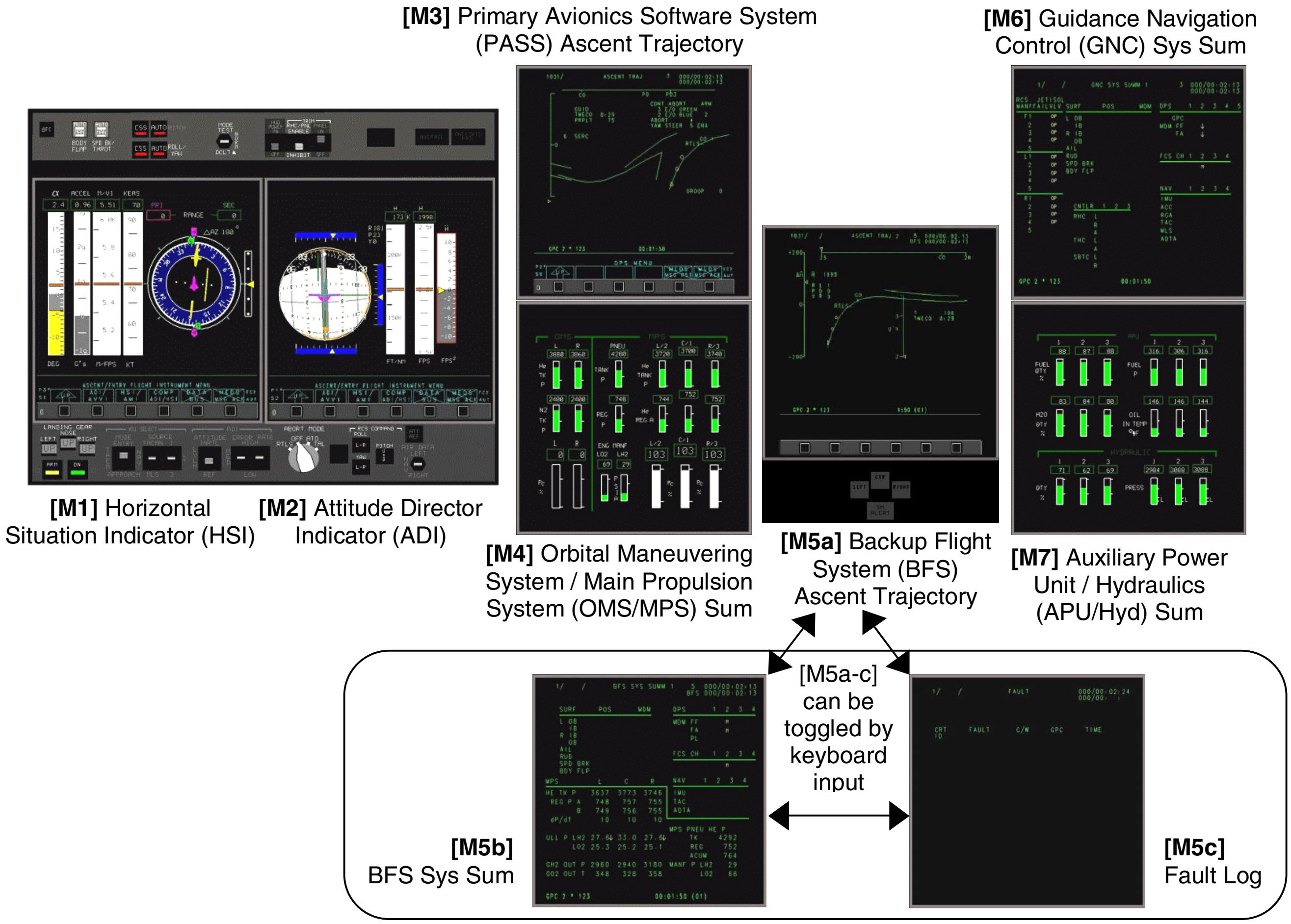
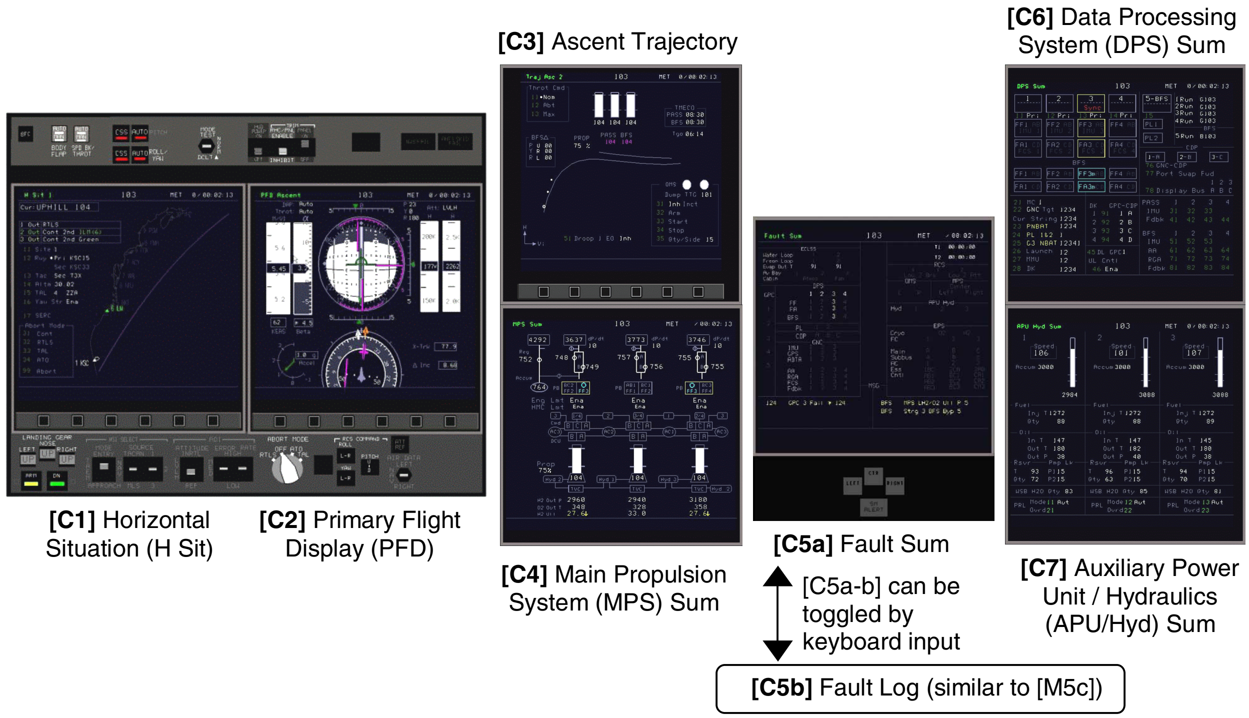


(a) MEDS



(b) CAU

Figure 2. Seven displays of MEDS (top) and CAU (bottom) formats used during ascent-phase simulation