MULTISENSORY FEEDBACK IN SUPPORT OF PILOT-AUTOMATION COORDINATION: THE CASE OF UNCOMMANDED MODE TRANSITIONS

Mark I. Nikolic Aaron E. Sklar Nadine B. Sarter

Aviation Research Laboratory
University of Illinois at Urbana-Champaign
Savoy, IL

The introduction of advanced automation technology to the modern cockpit has created new attentional and monitoring demands for pilots whose primary role has shifted towards supervisory control. Observed breakdowns in pilots' mode awareness, i.e., in their knowledge and understanding of the current and future system configuration, suggest that these demands are not adequately supported by existing automation feedback. In particular, current feedback fails to highlight unexpected changes in system status and behavior due, in part, to designers' tendency to increasingly rely on focal visual attention instead of exploiting the wide range of sensory modalities available to human operators. In this study, we examined the feasibility and effectiveness of multisensory feedback for providing attentional guidance to pilots in case of unexpected mode transitions. Tactile or peripheral visual cues were presented in the context of a simulated flight scenario involving varying levels of competing visual demands. The results of this study indicate that the introduction of multisensory feedback is one effective way of capturing pilots' attention without necessarily affecting their performance on concurrent tasks.

INTRODUCTION

The introduction of highly complex and powerful automation to a variety of domains has been a mixed blessing. Extended machine capabilities have led to improvements in the precision and efficiency of operations and provided operators with more options and flexibility. At the same time, however, new challenges for human-machine communication and coordination were created because these new systems do not always provide effective feedback on their intentions and actions to the human operator. Observed breakdowns in mode-awareness, i.e., a lack of knowledge and understanding of the automation status and behavior, and automation surprises on glass cockpit aircraft (Wiener, 1989; Sarter & Woods, 1994, 1995, 1997) are symptoms of this mismatch between required and available feedback (Billings, 1997). Automation surprises are most likely to occur in the context of uncommanded changes in system behavior which can occur as a result of system coupling, input by another crew member, or due to designer instructions. In these situations, it would be desirable for the automation to play an active role in human-machine communication by providing the operator with external attentional guidance. However, the nature of current automation feedback does not support this role.

In most glass cockpits, autoflight modes are displayed as alphanumeric indications (flight mode annunciations, or FMAs) on the primary flight display (PFD). As a mode changes (whether commanded by the pilot or the automation) the corresponding indication appears on the PFD, sometimes accompanied briefly by a box drawn around the new mode indication. As suggested by empirical studies on pilot-automation interaction as well as recent aviation incidents and accidents (e.g., Dornheim, 1995), this kind of feedback is not salient enough, especially during high-tempo phases of flight and/or phases involving a large number of competing cognitive and visual demands. Flight mode annunciations do not differ significantly from their immediate surroundings in terms of hue, saturation, and brightness. Also, the surround in which these annunciations appear is not sufficiently homogenous to allow signals like the transition box to stand out (Duncan & Humphreys, 1989). Furthermore, current automation feedback relies heavily on focal visual attention, thus requiring serial information-processing and knowledge-driven, rather than data-driven, information search (Sarter, 1995). To enable the automation to better support pilots' attention allocation and to help them process the considerable amount of data available on modern flight decks, new forms of feedback need to be developed.

This paper describes a simulation study that examined the effectiveness and feasibility of multisensory feedback – in particular, tactile and peripheral visual cues – for supporting pilots in maintaining awareness of automation status and behavior in the case of indirect or unexpected changes, without distracting them from concurrent tasks.

PERIPHERAL VISUAL AND TACTILE FEEDBACK

The motivation for considering multisensory feedback as a viable countermeasure to breakdowns in pilot-automation coordination stems, in part, from findings in psychological research on attention. Current feedback design which relies heavily on focal visual attention seems to be based on the assumption that the human attentional capacity consists of a single undifferentiated pool of resources. This model of attention predicts that two cues of equal salience should be detected with equivalent ease or difficulty, regardless of the modality of the cue. Contradictory evidence to this claim has prompted researchers to propose an alternative model of attention – multiple resource theory (e.g., Wickens, 1984). Multiple resource theory suggests that two cues presented to different modalities draw upon different attentional resources. Thus, in situations where one modality is already heavily burdened, utilizing a different modality for presenting additional information should result in improved detection of a cue. Multiple resource theory is based, for the most part, upon evidence from visual and auditory performance tradeoff studies (e.g., Vidulich & Wickens, 1981; Wickens et al., 1983). To date, little empirical evidence exists concerning the possibility and effectiveness of utilizing resources affiliated with the peripheral visual or tactile modality – the two sensory channels examined in the present study.

One potential solution to breakdowns in pilot-automation coordination is to redistribute some information from foveal to peripheral vision (Venturino & Rinalducci, 1986). Several properties of peripheral vision make it a promising candidate for providing external attentional guidance. Despite its lower acuity relative to the fovea, the periphery is very effective at detecting motion and luminance changes. This adaptive feature of peripheral vision makes it useful for detecting potentially interesting objects or events (such as uncommanded mode transitions) that warrant subsequent focal attention. Information that is presented in the periphery is obtained with little or no conscious effort (Jonides, 1981), making peripheral vision a resource-economical channel. Finally, empirical evidence from physiological, functional, and cognitive research seems to support the dual nature of vision which would allow focal and peripheral inputs to be processed in parallel (Christensen et al., 1985). These properties and affordances of peripheral vision make it a promising candidate for supporting mode awareness without interfering with other ongoing focal visual tasks.

Still, a number of questions related to peripheral visual feedback remain unresolved. For example, some research has shown that abrupt onsets of peripheral signals effectively capture attention in an exogenous, stimulus-driven manner (Jonides & Yantis, 1988) while others have found that capture by peripheral onsets may be mediated by top-down control settings and may not even occur when attention is in a focused state (Folk et al., 1992, 1993; Theeuwes, 1991; Yantis & Jonides, 1990). Also, the functional field of view has been shown to shrink away from the periphery under conditions of increasing stress and cognitive task loading – a phenomenon known as "attentional narrowing" or "tunnel vision" (Leibowitz & Appelle, 1969; Williams, 1982). It appears, however, that this phenomenon affects operators who are highly trained for and experienced in dividing their attention across multiple displays (such as pilots) to a lesser extent (Williams, 1995).

Another promising avenue for presenting information on changes in system status and behavior is the use of tactile feedback. Advantages of skin sensations include their omni-directionality, their ability to be perceived simultaneously with visual and auditory input, and the fact that there are few competing demands for this unique resource. Despite the acknowledged potential of tactile feedback, little empirical research on its use and effectiveness has been conducted. This may be explained, in part, by the fact that only recently, technical advances have allowed researchers fine-tuned control over parameters such as the frequency, duration, and amplitude of tactile stimulation. Furthermore, miniaturization of tactile devices now makes their use feasible in operational settings.

To date, most of the research on peripheral visual and tactile feedback has been performed in highly controlled laboratory environments, using relatively simple tasks and displays. Thus, the generalizability of findings from this research to complex information-rich operational environments is not ensured. Only a small number of studies have examined the use of multisensory feedback in the aviation domain for work on peripheral visual feedback see Christensen et al., 1985; Hasbrook & Young, 1968; Majendie, 1960; Malcolm, 1984; Reising et al., 1995; Schwank et al., 1978; Weinstein & Wickens, 1992 – for work on tactile feedback see Ballard & Hessinger, 1954; Gilliland & Schlegel, 1994; Zlotnik, 1988). The objective of these efforts was to support pilots in spatial orientation and navigation.

In contrast, our goal is to examine the feasibility and effectiveness of peripheral visual and tactile feedback for capturing attention in case of unexpected discrete events such as uncommanded mode transitions. As a first step towards this goal, the current study tries to establish whether peripheral visual and tactile feedback can be reliably detected amidst competing stimuli in a complex operational environment. In addition, the costs and benefits of multisensory feedback under varying conditions of workload are being evaluated.

A SIMULATOR STUDY ON THE USE OF MULTISENSORY FEEDBACK ON HIGHLY AUTOMATED FLIGHT DECKS

This paper presents a simulator study that was conducted to assess whether peripheral visual or tactile feedback are effective means of supporting pilots in maintaining mode awareness on modern flight decks. This research also examines how competing demands (such as flight path tracking or the detection of other aircraft) affect the detection and discrimination of unexpected mode transitions.

Participants

Twelve instrument-rated pilots from the University of Illinois Institute of Aviation pilot training program participated in the study. None of the participants had any previous experience with operating a highly automated aircraft or a flight management system (FMS). This was considered acceptable for the current study since we were interested exclusively in pilots' detection of mode transitions that would be unexpected even for highly experienced airline pilots. In other words, our focus was on data- rather than knowledge- or expectation-driven monitoring. Pilots were randomly assigned to one of the three experimental conditions described below. Each pilot received ten dollars per hour as compensation for their voluntary participation.

Simulator

A modified version of the NASA Ames Stone Soup Simulator (SSS) was used to generate interactive flight scenarios. The SSS is a desktop version of NASA's Advanced Concepts Flight Simulator (ACFS), and provides graphical representations of the major interfaces and displays used by pilots on highly automated aircraft. The simulation was run on a Silicon Graphics Indigo^2 workstation. The simulation displays were presented on two monitors placed in front of the participant. In order to simulate a cockpit environment, the monitors were embedded in a mock-up of a modern flight deck. Participants interacted with the simulation through a sidestick located on their right-hand side which was used to control the aircraft in pitch and roll as well as to record responses via a trigger/push-button. Additionally, a left-handed trackball was used by the participants to interact with cockpit interfaces and operate controls (e.g. Mode Control Panel, landing gear and flap levers, electronic checklist buttons).

Design

The two independent variables studied were display modality and competing attentional demands. Four display formats were examined:

FMA - (n = 12) This is the standard 3-column flight mode annunciator that is currently implemented on the PFD of many glass cockpits. On these aircraft, the three columns are reserved for indicating the active autothrottle, roll, and pitch modes, respectively. Since our pilots were not knowledgeable about the functionality and logic associated with all possible automation modes, the simulator simply indicated a mode transition by reverting from "OFF" to "ON". A green box surrounding the word appeared for 10 seconds to indicate a transition. After 10 seconds, the box disappeared and the display reverted back to the "OFF" indication. Every participant was exposed to this FMA condition as well as one of the three experimental conditions.

Enhanced FMA - (n = 4) The salience of the FMA indications was increased by signaling transitions with the onset of a filled rather than an outlined green box. The box was also larger and more luminant than the existing FMA box, thus making it more accessible to peripheral vision.

Ambient strip - (n = 4) In this third condition, mode transitions were signaled by the onset of a thin wide band of green light (equiluminant with the enhanced FMA), spanning the bottom of the left monitor for autothrottle modes, and of the right monitor for roll modes. Each monitor and strip was 15 inches wide, and subtended about 30° of visual angle. This condition was introduced since pilots' attention is widely distributed across various displays on the flight deck. This makes it very difficult if not impossible to define the peripheral visual field at any given time. By using the ambient strip, we expected to be better able to capture their attention independent of other visual tasks and demands.

Tactile signal - (n = 4) The stimulus used in this condition was a vibration of 250 Hz applied to the participant's right wrist for 500 msec. Two tactors were worn on a wristband. This group of participants was instructed to associate vibration of the left tactor with autothrottle modes and the right tactor with roll mode transitions. The signal was presented using the V1242 transducers from Audiological Engineering Corporation, MA. A square wave signal of 4.8 volts was sent to the transducer to activate each signal.

Attentional load and competing visual demands were varied within subjects by introducing tasks and events that would typically be experienced by a pilot (flight path tracking with or without flight director guidance, traffic conflicts, checklists, equipment malfunctions, etc.) during different phases of flight. Pilots were hand-flying the aircraft during the takeoff and landing phases. The dependent measures were the detection of and the reaction time to mode transitions. These data were recorded on-line by the simulator.

Procedure

Upon arriving in the simulator, participants received a 15-minute familiarization course during which the experimenter explained and demonstrated the basic functions and use of automation controls and displays. A thorough understanding of the functional structure of the system was not considered necessary since the participants' task was limited to the detection of unexpected transitions. Participants were then given the opportunity to fly a 15-minute practice scenario from take-off through landing. This trial familiarized the participant with using the sidestick for manual flight, autopilot engagement, entering automation targets, and responding to the transition displays and scenario events. Pilots were told to pull a trigger on the sidestick whenever they detected that a mode transition had occurred. Participants were instructed to respond as quickly as possible and to give equal importance to the detection of all events. After the training period, participants then completed two half-hour scenarios: one in the FMA condition and another in one of the three experimental conditions. Condition order was counterbalanced across pilots.

All scenarios involved a flight from Sacramento to San Francisco, California. Fifteen experimenter-induced, and thus unexpected, mode transitions were distributed throughout the simulated flight under varying levels of visual and cognitive taskloading. Subjective comments on the mode transition displays and the perceived difficulty of the scenario segments were solicited during a debriefing interview.

RESULTS

Detection of Mode Transitions

A repeated measures multivariate analysis of variance (MANOVA) was conducted on the detection data with display condition as the between-subjects factor and phase of flight as a within-subject factor. A main effect was found for display ($F(3, 20) = 6.486$, $p=.003$).

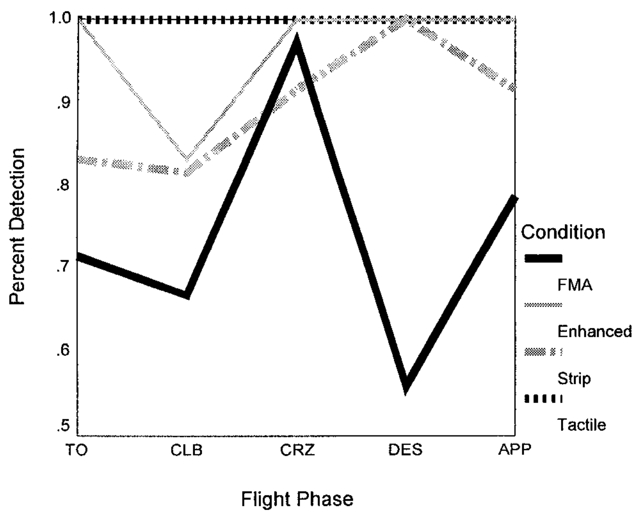

Figure 1. Detection of Mode Transitions (Condition by Flight Phase)

As Figure 1 illustrates, all three experimental conditions showed significantly enhanced rates of detection over the current standard FMA condition. Although no significant effect was found for phase of flight or the interaction between condition and flight phase, Figure 1 highlights some interesting trends.

As expected, the FMA had the lowest detection rates and was shown to be highly vulnerable to workload variance. In contrast, the two peripheral displays showed improved detection performance relative to the FMA, and were less affected by workload. Furthermore, pilots using tactile cues detected 100% of the mode transitions, regardless of the changing workload induced by each flight phase.

Reaction Time to Mode Transitions

Another repeated measures MANOVA was conducted for the reaction time data. Again, a main effect was found for condition ($F(3,16) = 4.523$, $p = .018$). The FMA-cued transitions took longer to detect than the peripheral and tactile cues (Figure 2). The reaction time data also yielded a main effect for phase ($F(4, 64) = 3.471$, $p = .039$), but no interaction between phase and condition. The slowest reaction times occurred during climb and descent when pilots' attention was drawn away from the PFD to perform other tasks. Figure 2 illustrates the consistently rapid detection of the tactile cues, which again remains unaffected by the level of concurrent workload. In contrast, the visual conditions, particularly the focal visual FMA, are affected by the varying concurrent tasks in each phase of flight.

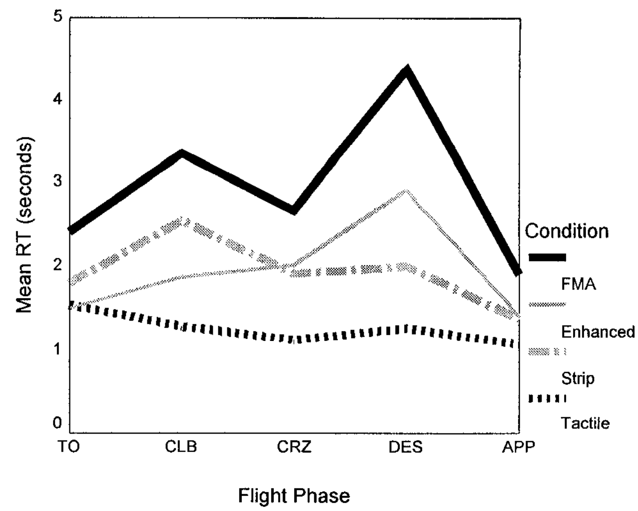

Figure 2. Reaction Time to Mode Transitions (Condition by Flight Phase).

CONCLUSION

As highly independent automated systems become more pervasive in a variety of domains, the need to support human-automation coordination by providing operators with external attentional guidance becomes more critical. Observed breakdowns in operators' ability to track system status and behavior suggest that the automation needs to play a more active role in human-machine communication, especially in the case of changes in system behavior that are not explicitly commanded and possibly not expected by the human. Current automation feedback which relies increasingly on focal visual attention does not support this role. Instead, new forms of multisensory feedback which exploit the wide range of human perceptual abilities need to be developed and introduced. Two promising but currently underutilized modalities for presenting automation-related information are the tactile and the peripheral visual channel.

The results of the present study show that we were successful in replicating glass cockpit pilots' vulnerability to missing unexpected mode transitions with currently available automation feedback. Peripheral visual and tactile feedback led to improved detection rates and reaction times without interfering with pilots' performance of concurrent tasks. These initial findings suggest that multisensory feedback indeed affords parallel processing of information, thus supporting operators in coping with the considerable amount of data in highly dynamic multi-display environments such as the modern flight deck. Further studies are currently under way in our laboratory to identify the most promising implementations of as well as potential costs associated with these new forms of feedback.

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