Good Vibrations: Tactile Feedback in Support of Attention Allocation and Human-Automation Coordination in Event-Driven Domains

Aaron E. Sklar, IDEO Product Development, San Francisco, California, and **Nadine B. Sarter,** Ohio State University, Columbus, Ohio

Observed breakdowns in human-machine communication can be explained, in part, by the nature of current automation feedback, which relies heavily on focal visual attention. Such feedback is not well suited for capturing attention in case of unexpected changes and events or for supporting the parallel processing of large amounts of data in complex domains. As suggested by multiple-resource theory, one possible solution to this problem is to distribute information across various sensory modalities. A simulator study was conducted to compare the effectiveness of visual, tactile, and redundant visual and tactile cues for indicating unexpected changes in the status of an automated cockpit system. Both tactile conditions resulted in higher detection rates for, and faster response times to, uncommanded mode transitions. Tactile feedback did not interfere with, nor was its effectiveness affected by, the performance of concurrent visual tasks. The observed improvement in task-sharing performance indicates that the introduction of tactile feedback is a promising avenue toward better supporting human-machine communication in event-driven, information-rich domains.

INTRODUCTION

Observed breakdowns in human-automation coordination in event-driven domains such as aviation can be explained, in part, by the nature of current automation feedback, which relies primarily and increasingly on focal visual attention. Such feedback is not well suited for supporting the parallel processing of the considerable amount of data available on modern flight decks or for capturing the pilot's attention in case of unexpected changes and events. One important category of (potentially) unanticipated changes in the modern cockpit is so-called indirect or uncommanded mode transitions – that is, changes in the status and/or behavior of the automation that occur as a result of system coupling, input by another operator, or designer instructions. It is well known that pilots sometimes fail to notice these changes and, as a result, commit mode errors or experience automation surprises (Sarter, Billings, & Woods, 1997; Sarter & Woods, 1995). One possible solution to these problems is suggested by multiple-resource theory: the distribution of tasks and information across various sensory modalities.

Multiple-resource theory proposes that attentional resources differ along several dimensions, including stages and codes of processing as well as input/response modalities (Wickens, 1991). Cross-modal task and information presentation should therefore lead to more efficient processing and improved task-sharing performance. Empirical evidence for these anticipated benefits was found in a number of studies that focused on the distribution of concurrent tasks across the visual and auditory channels (for an overview, see Wickens, 1980). Very little is known, however, about the affordances and effectiveness of another sensory channel: the tactile modality.

Address correspondence to Nadine B. Sarter, Ohio State University, Institute for Ergonomics, 210 Baker Systems Bldg., 1971 Neil Ave., Columbus, OH 43210. **HUMAN FACTORS**, Vol. 41, No. 4, December 1999, pp. 543–552.

Likely advantages of tactile feedback include its omnidirectionality, its ability to be perceived simultaneously with visual and auditory signals, and the small number of competing demands for this resource. To date, a fairly small number of laboratory studies have examined the feasibility and effectiveness of tactile information presentation in the context of rather simple tasks and environments (e.g., Butter, Buchtel, & Sanctucci, 1989; Chapman, Bushnell, Miron, Duncan, & Lund, 1987; Davenport, 1969; Diederich, 1995; Kirman, 1986; Post & Chapman, 1991; Shiffrin, Craig, & Cohen, 1973; Verrillo, 1983). Even fewer attempts have been made to use tactile feedback in the aviation domain in which its major purpose has been to provide navigational or spatial guidance to pilots (Ballard & Hessinger, 1954; Gilliland & Schlegel, 1994; Gilson & Fenton, 1974; Zlotnik, 1988). One possible reason for the limited progress in this area is the fact that the use of haptic feedback has only recently become feasible. The miniaturization of haptic devices has made them more acceptable for operational settings such as the cockpit. Also, technical advances finally allow designers and researchers fine-tuned control over parameters such as the frequency, duration, and amplitude of the signal.

The goal of the current study is to use tactile feedback to inform pilots effectively and in a timely manner about uncommanded discrete changes in the status of an automated flight deck system. Tactile automation feedback is expected to lead to improved task-sharing performance and to better support data-driven monitoring in case of unanticipated changes and events (Sarter, in press).

METHODS

Participants

The participants in this experiment were 21 certified flight instructors (16 men and 5 women) from the Institute of Aviation at the University of Illinois. Their average age was 24.5 years ($SD = 3.4$), and they had an average of 618.1 h of flight experience ($SD = 502.8$). None of the pilots had prior experience with highly automated cockpit systems, which was not considered a prerequisite for participation in this research; our focus was on data-driven rather than knowledge-based monitoring of the automation configuration. The 21 pilots were randomly assigned to one of three experimental groups that received visual, tactile, or redundant visual and tactile automation feedback. The three groups did not differ significantly with respect to flight experience.

Apparatus

Dynamic and interactive flight scenarios were generated using a modified version of the NASA Ames Stone Soup Simulator (SSS) that was run on a Silicon Graphics Indigo2 (Silicon Graphics, Mountain View, CA) workstation. Displays and controls typical of a modern glass cockpit were presented on two monitors that were embedded in a mock-up of a modern flight deck (see Figure 1). Pilots controlled aircraft pitch and roll with a sidestick using their right hand, and they interacted with other aircraft interfaces and controls using a trackball with their left hand.

Procedure

First, participants received a training session that lasted approximately 1 h 15 min. They were introduced to the various cockpit displays and had the opportunity to fly two practice flight scenarios in order to experience the indications and actions associated with the various tasks and events of the experimental scenario.

Throughout the flight, participants had to monitor for unexpected mode transitions (a total of 24 transitions per flight) as well as traffic conflicts and deviations of an engine parameter (eight occurrences each per flight). These three tasks served to recreate some of the competing attentional demands on a modern flight deck. The latter two tasks were also used to explore whether tactile feedback affected concurrent task performance. Pilots were trained to signal the detection of any of the aforementioned events by orally announcing them to the experimenter. In the case of mode transitions, pilots also had to press one of two sidestick buttons to indicate what kind of transition had occurred (autothrottle or roll mode). Pilots were told that all three tasks were of equal importance and would determine their overall performance score. Mode transitions

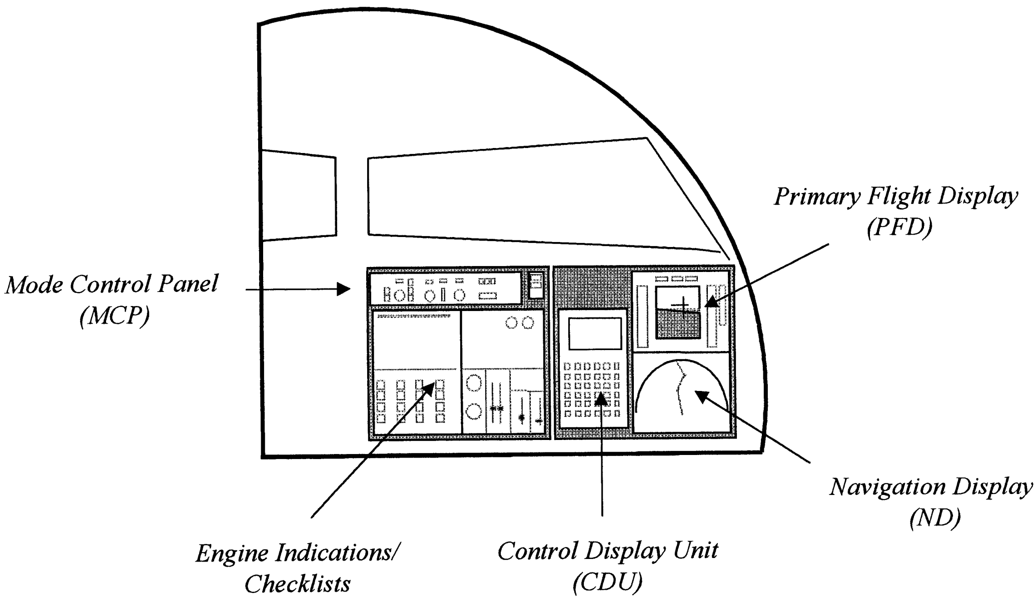

Figure 1. The experimental cockpit.

occurred either alone or in combination with one of the other two events that pilots had to monitor (traffic detection or engine parameter deviation). An equal number of simultaneous and individual event presentations were distributed evenly among the four phases of flight, described in the following section. Prerecorded air traffic control commands were issued to guide the pilot along the flight path and to create further competing attentional demands.

Phases of Flight

Pilots experienced equal amounts of time (15 min) in each of four phases of flight that differed with respect to the number and difficulty of concurrent tasks. Two of the phases involved manual flight control. In these two phases, pilots manually flew the airplane following flight director (FD) guidance (Manual/FD-on), or they ignored the flight director bars and instead controlled the flight path according to air traffic control instructions (Manual/FD-off). The latter phase involved rather demanding flight tasks such as establishing a holding pattern or executing a missed approach. The other two flight phases were associated with automatic flight path control. During the autopilot (A/P) Cruise phase, the pilot's only task was to monitor the performance of the automation, whereas in the more challenging A/P Dynamic phase, pilots had to interact with the automation (e.g., by changing targets on the mode control panel) and perform concurrent tasks such as checklists or approach briefings.

Feedback Conditions

Three kinds of feedback – visual only, tactile only, and combined tactile-visual – were used to indicate mode transitions. The baseline visual-only condition was modeled after current automation feedback on modern flight decks (so-called flight mode annunciations), in which a green outline appears around the indication of the changing mode for 10 s before the new mode indication appears. Because the focus of this study was on the detection of transitions rather than the assessment of the current automation status, the mode indications simply switched between the labels "OFF" and "ON." Pilots were trained to associate activation of the left and middle column with autothrottle and roll mode transitions, respectively.

In the tactile-only condition, a vibration of 250 Hz was applied to the participant's right wrist for 500 ms. The type of signal was chosen based on recommendations published on tactile perception (e.g., Verrillo, 1962) and based on pilot studies (Nikolic, Sklar, & Sarter, 1998). A square wave signal of 4.8 V was sent to a transducer (V1242, Audiological Engineering Corporation, Somerville, MA) to initiate each signal. Participants were wearing a wristband with one tactor attached on each side of the wrist (see Figure 2). Participants in this condition were instructed to associate vibration of the inner wrist with autothrottle modes and vibration of the outer wrist with roll mode transitions. This condition was introduced to explore the ability of tactile feedback to support both early and later stages of processing (i.e., both detection of a signal and identification of the associated mode transition).

In the third condition, redundant tactile and visual cues were presented simultaneously to examine whether a redundancy gain would be observed. The same wristband with two tactors was used, but only the inner wrist was stimulated whenever a mode transition occurred. The pilot had to identify the mode category by referring to the visual indications described previously.

Dependent Measures

Detection rates were recorded for mode transitions (independent of whether or not the transition was identified correctly), traffic conflicts, and engine deviations. In addition, the reaction time to mode transitions and the accuracy of transition identification were measured. Note that because of limitations of the simulator, the reaction time measure in this experiment is a combination of the time until detection and the time until identification of the cue. During a debriefing interview, participants were asked to estimate the total number of mode transitions that occurred during the scenario.

RESULTS

Detection of Unexpected Mode Transitions

A repeated-measures multivariate analysis of variance (MANOVA) was conducted on the detection data with feedback type as the between-subjects factor and two within-subject factors, concurrent task load and simultaneity. A significant effect was seen for feedback type, $F(2, 18) = 17.76$, $p < .001$. Pilots receiving visual-only feedback detected approximately 83% of the unexpected mode transitions that occurred throughout the flight, whereas pilots in the other two conditions (tactile-visual and tactile only) detected close to 100% of all changes in mode status. None of the mode transitions were missed in the tactile-only condition, and only two changes in status were missed across all pilots in the tactile-visual

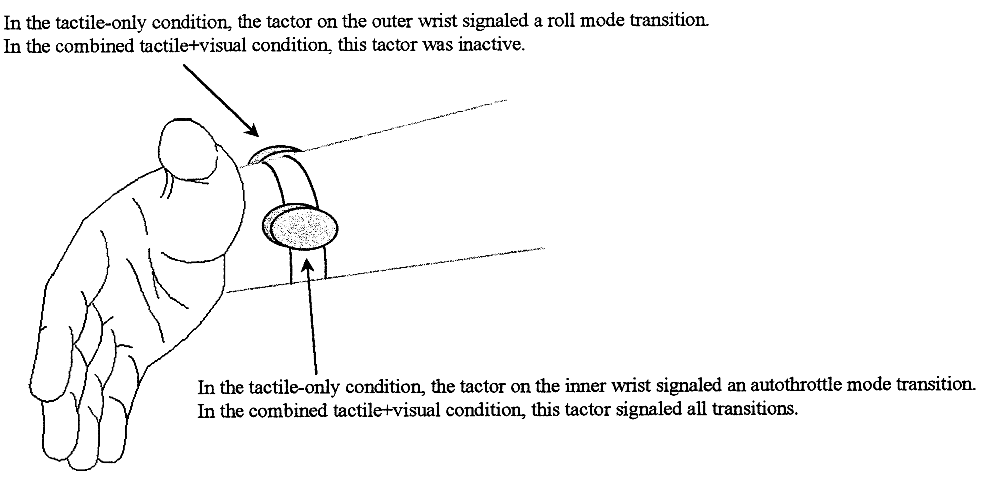

Figure 2. Tactor placement. Tactors were placed on the pilot's right wrist. This hand remained on the sidestick throughout the flight.

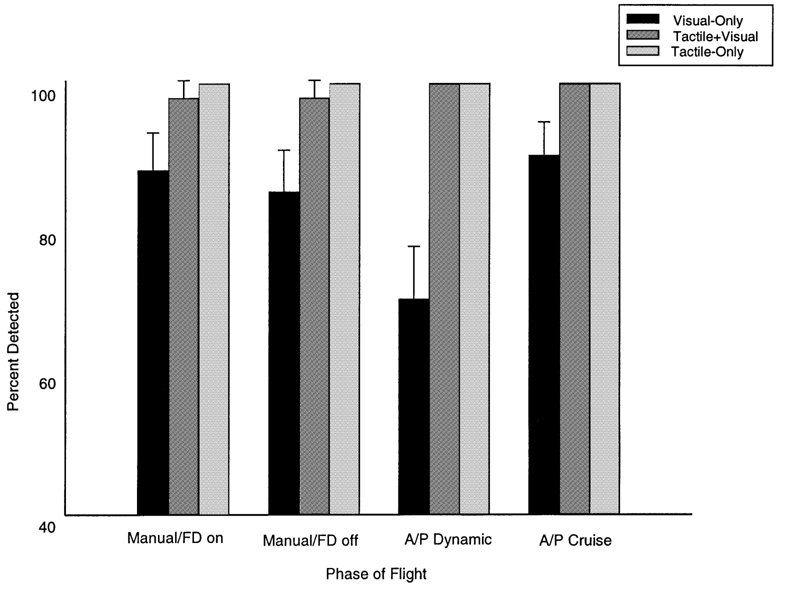

Figure 3. Detection of mode transitions (condition by flight phase; error bars show one standard error from mean).

condition (during the manual phases of flight). Both of the missed transitions were presented alone (as opposed to simultaneously with either a traffic conflict or an engine parameter deviation).

The analysis did not yield a main effect for flight phase but did show a significant interaction between feedback condition and phase of flight, $F(6, 54) = 2.91$, $p < .05$. As illustrated in Figure 3, both tactile conditions yielded near-perfect detection rates in each phase of flight, whereas performance in the visual-only condition was markedly affected by the concurrent demands in the A/P Dynamic phase. An additional analysis conducted on the two tactile conditions alone confirmed that detection of tactile cues was not affected by concurrent load.

No effect was found for simultaneity. Mode transitions were detected equally well regardless of whether they were presented alone or in combination with another event.

Reaction Time to Unexpected Mode Transitions

For the reaction time data, a significant effect was found for feedback type, $F(2, 18) = 40.62$, $p < .001$. Pilots receiving only visual cues were significantly slower to respond to transitions than were participants in either tactile condition. A significant main effect was also seen for phase of flight, $F(3, 54) = 6.91$, $p < .01$. The A/P Dynamic phase was associated with the slowest reaction times. Finally, the interaction between condition and phase of flight was significant as well, $F(6, 54) = 4.36$, $p < .01$. The visual-only condition was markedly affected by concurrent load. Additional analyses of each condition confirmed that reaction times in the tactile-only condition were consistently rapid regardless of concurrent activities, whereas pilots in the tactile-visual condition showed a significant decrement in the A/P Dynamic phase of flight, $F(3, 18) = 9.19$, $p < .01$ (see Figure 4).

Again, the analysis did not yield a main effect for simultaneity. Responses to mode transitions were equally fast independent of whether they were presented alone or in combination with another event. Likewise, no interaction between simultaneity and display type was found.

Identification of Mode Transitions

In the visual-only and in the tactile-visual conditions, if a transition was detected it was always properly identified. In contrast, 3 participants in the tactile-only group misidentified a total of 7 cues (out of a total of 168 cues for all seven pilots in that group). These identification

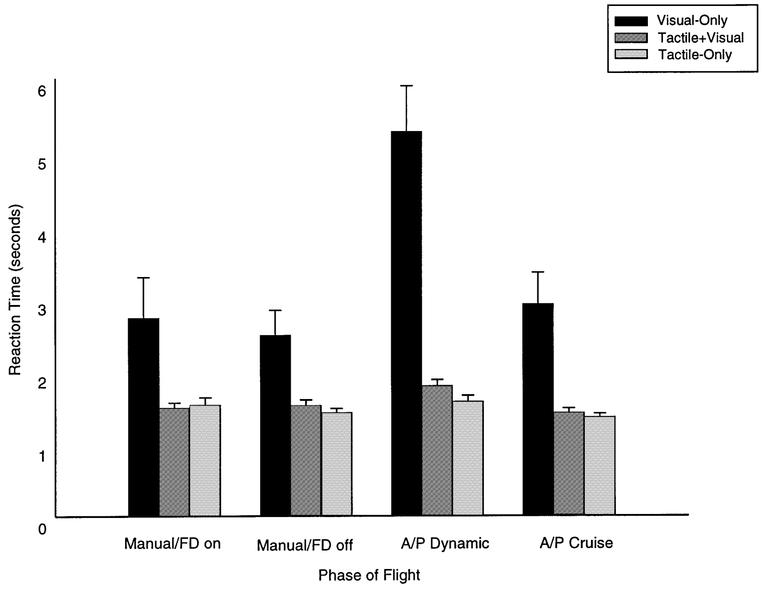

Figure 4. Reaction time to mode transitions (condition by flight phase; error bars show one standard error from mean).

errors were distributed across all four phases of flight (see Table 1). They included transitions that were presented individually and those that were presented in combination with another event. The one common aspect of the 7 misidentified transitions was that they were all associated with signals to the outer wrist (see Figure 2).

Detection Performance for Traffic and Engine Deviations

A repeated-measures MANOVA on the detection rates for traffic conflicts and engine deviations did not yield a significant main effect for feedback condition. Significant main effects were found, however, for both simultaneity, $F(1, 18) = 5.86$, $p < .05$, and for flight phase, $F(3, 54) = 6.36$, $p < .01$. Traffic and engine deviations that were presented individually were more likely to be detected than those presented simultaneously with a mode transition (see Figure 5). Also, detection rates were significantly higher during the A/P Cruise phase of flight (see Figure 6), when pilots were not required to perform any concurrent tasks. Repeated-measures analyses of variance (ANOVAs) did not show any significant differences between feedback conditions for other flight-related tasks,

TABLE 1: Misidentified Cues

Pilot ID	Phase of Flight	Signal Location	Individual or Simultaneous	Scenario Context
57	Manual/FD-on	Outer wrist	Individual	At decision height
57	Manual/FD-off	Outer wrist	Simultaneous	Deviation from route
57	A/P Dynamic	Outer wrist	Simultaneous	During ATC command
57	A/P Cruise	Outer wrist	Individual	Cruise, no activity
59	Manual/FD-on	Outer wrist	Individual	At decision height
59	Manual/FD-off	Outer wrist	Individual	Maintaining holding pattern
62	A/P Dynamic	Outer wrist	Simultaneous	Coincident with malfunction

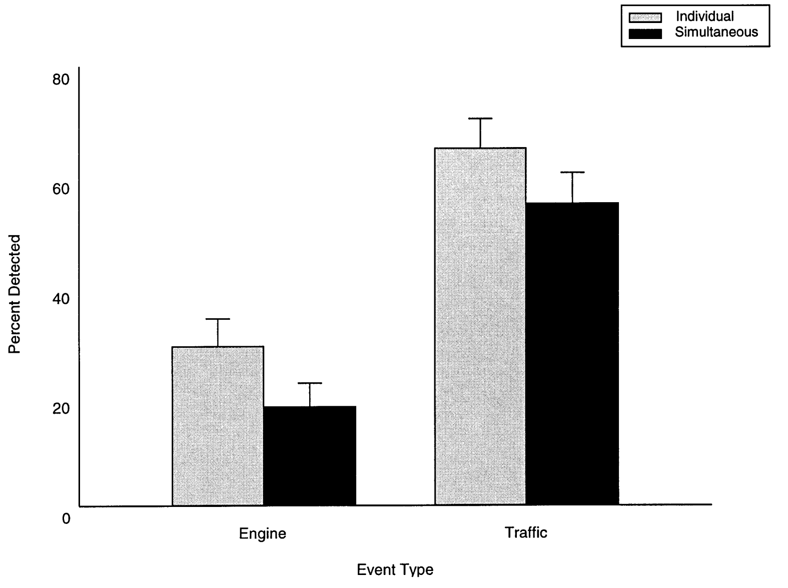

Figure 5. Detection of traffic and engine deviations (main effect for simultaneity; error bars show one standard error from mean).

such as flight path tracking or compliance with air traffic control commands.

Debriefing Data

During the debriefing, participants were asked to estimate the number of mode transitions that occurred throughout the flight. Pilots' estimates were consistently low (see Figure 7). No significant difference was found between the three display conditions despite the observed difference in actual detection performance.

DISCUSSION

Expected and Observed Benefits of Tactile Feedback

Overall, both the tactile-only and the tactile-visual conditions led to higher detection rates

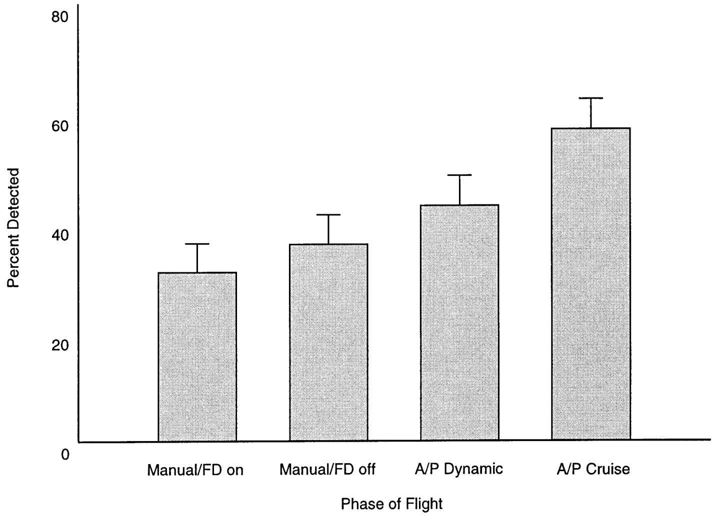

Figure 6. Detection of traffic and engine deviations (main effect for flight phase; error bars show one standard error from mean).

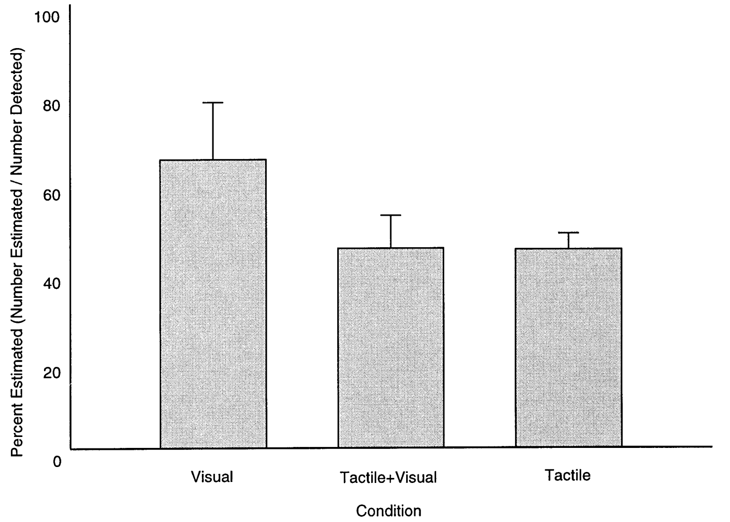

Figure 7. Estimated number of mode transitions (relative to number of detected transitions; error bars show one standard error from mean).

and faster reaction times to uncommanded mode transitions than visual feedback alone (see Figures 3 and 4). These findings confirm our own predictions and those of other proponents of tactile feedback (e.g., Endsley, 1988; Gilliland & Schlegel, 1994; Zlotnik, 1988). Between the two tactile conditions, no significant difference in detection rates was found, which may be explained by the observed ceiling effect-detection performance of participants in the tactile-only condition was already perfect. Similarly, overall reaction times to mode transitions did not differ significantly between the two tactile conditions. A more detailed analysis revealed, however, that pilots in the tactile-visual condition were significantly slower to respond in the presence of high concurrent visual load (see Figure 4). This effect may be explained by the fact that reaction time in this study was a combined measure that included both the time until detection and the time until identification of the transition. Thus the reaction time of pilots in the tactile-only condition may have remained constant independent of concurrent task load because both detection and identification of a transition were performed based solely on the tactile cue and could be performed in parallel with other tasks. In contrast, pilots in the tactile-visual condition were required to direct or redirect their visual attention to the flight mode annunciations on the primary flight display for identification purposes after they were alerted to the transition by the tactile cue.

The advantage of both tactile conditions over visual feedback is particularly pronounced under conditions of high concurrent load as present in the A/P Dynamic phase of flight. Whereas the detection of and reaction time to tactile cues in those conditions was not at all (tactile-only) or only minimally (tactile-visual) affected by concurrent visual demands, pilots who received only visual feedback showed a significant decline in their detection and reaction time performance (see Figures 3 and 4). In the dynamic phase of autopilot flight, pilots had to perform a number of tasks that directed their visual attention away from the right-hand monitor where the mode transitions were indicated on the primary flight display (see Figure 1). As a result, pilots in the visual-only and tactile-visual conditions were at a disadvantage because of visual scanning penalties (see Wickens, 1991).

Potential and Observed Limitations of Tactile Feedback

Both tactile conditions yielded near-perfect detection rates and identification accuracy. Only two tactile cues were missed by pilots in the tactile-visual condition during manual phases of flight. Masking effects may have played a role, as both cues occurred while the stimulated hand was also actively manipulating the sidestick. Chapman et al. (1987) found decreased physiological sensitivity to tactile stimuli that are applied to an active part of the body. This masking effect may not have been observed in the tactile-only condition because those pilots were required to devote far more attention to tactile stimuli to be able not only to detect, but also to identify mode transitions. Thus, increased attention to the tactile stimuli may have counteracted their decreased physiological sensitivity to some extent (see Chapman et al., 1987).

The fact that a small number of transitions was missed in the tactile-visual but not in the tactile-only condition is somewhat surprising because the literature on cross-modal attention would lead us to expect enhanced detection performance in case of redundant cues (Davenport, 1969; Diederich, 1995). However, during the debriefing, pilots in the tactile-visual condition pointed out that they depended exclusively on the tactile stimuli to alert them to mode transitions; they did not monitor the visual cues.

Three pilots in the tactile-only condition misidentified the mode category in seven cases (see Table 1). One common element associated with all seven misidentified cues is that tactile feedback was presented to the outer wrist. Although in earlier pilot studies none of the participants had commented on a difference in perception between the two wrist locations, several participants in this experiment mentioned during the debriefing that signals to the outer wrist were perceived as being weaker than those to the inner wrist.

The Tactile Modality – A Separate Resource?

Multiple-resource theory proposes that different modalities represent separate attentional resources and that cross-modal task and information presentation should therefore lead to improved task-sharing performance. This prediction is confirmed by the findings of the current study. Even though performance on concurrent tasks was not affected by the introduction of tactile feedback, the improved detection rates for and response times to unexpected mode transitions led to a net gain in overall performance.

One question that cannot be answered conclusively based on this study is whether the observed task-sharing performance enhancements are the result of structural factors (such as removing visual scanning penalties) or central factors (e.g., Pashler, 1998; Wickens, 1991). Structural factors clearly played some role in our study, as indicated by the poor performance of participants in the visual-only condition, who, in the A/P Dynamic phase, had to perform visual tasks on the left-hand screen while also trying to monitor for mode transition indications on the right-hand screen. However, the observed performance improvements in the tactile conditions may be attributable to more than just the removal of peripheral interference, as suggested by earlier studies that controlled for this factor (e.g., Martin, 1980; Treisman & Davies, 1973), and were still able to show an advantage for cross-modal presentation (for a more detailed discussion, see Wickens, 1999).

CONCLUSIONS AND FUTURE DIRECTIONS

The current experiment clearly demonstrates the promise of introducing or reintroducing multimodal feedback in the interest of supporting the communication and coordination between human operators and highly independent automated systems. Still, a number of important questions remain to be explored in future investigations. In addition to refining the implementation of tactile feedback, its ability to support more complex discrimination tasks and its vulnerability to attentional narrowing in highly demanding nonnormal situations need to be investigated. It will also be important to study whether long-term use of tactile feedback leads to significant decrements in its effectiveness. Finally, the feasibility of tactile feedback in the actual flight deck environment needs to be examined to determine whether environmental conditions such as vibrations interfere with the ability to detect tactile stimuli.

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Aaron E. Sklar received his M.S. degree in engineering psychology from the University of Illinois at Urbana-Champaign in 1998. He is employed at IDEO Product Development in San Francisco, CA.

Nadine B. Sarter is an assistant professor in the Department of Industrial and Systems Engineering and the Institute for Ergonomics, The Ohio State University. She received a Ph.D. in industrial and systems engineering from Ohio State University in 1994.

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