UTILTY OF A TACTILE DISPLAY FOR CUEING FAULTS

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Tactile displays have been proposed as a multisensory interface technology that can relieve the typically overburdened visual channel of operators. This study compared the ability of operators, while simultaneously completing a tracking task, to detect and identify system faults in a monitoring task with three types of alert cues: tactile, visual, and redundant tactile and visual. For the tactile display, the location and vibration pulse speed of two tactors were mapped to four system faults. Response time was significantly faster with the tactile cue. Also, the tactile cue resulted in less interference with the concurrent tracking task, while not degrading vigilance to an additional concurrent visual monitoring task. These results suggest that further tactile cue research is warranted to examine potential applications in complex systems, such as control stations for unmanned aerial vehicles.

INTRODUCTION

Background

Multimodal interface technologies that exploit a wide range of human perceptual abilities have been proposed as a means of improving operator performance in complex systems. In situations where one modality is heavily burdened (e.g., the visual channel of unmanned air vehicle operators), utilizing a different modality for presenting additional information should result in improved detection. This is based on the Multiple Resource Theory's assumption that two cues presented to different modalities draw from different attentional resources (Wickens, Sandry, and Vidulich, 1983; Wickens, 1992). A multimodal presentation can increase the saliency of information, making it easier to detect (Welch and Warren, 1986). Additional modalities of information input (such as auditory or tactile) can also provide information simultaneously to the visual channel (Endsley, 1988).

The majority of past multimodal research has dealt with performance tradeoffs of using visual versus aural information (Wickens, 1984). There is a dearth of evidence concerning the effectiveness of utilizing resources affiliated with the tactile modality. Tactile presentation of information is, however, a promising display technology. First, the candidate 'display size' is quite large (the total area of the skin surface of an average-sized adult human is about 1.8 m^2). Reaction times for tactile stimuli are also typically faster than that for visual stimuli (by about 30-40 msec; Riggs, 1971). Moreover, there are few competing demands for this unique resource (Nikolic, Sklar, and Sarter, 1998). Finally, research results suggest that tactile displays can serve as an effective cueing mechanism. Findings by Nikolic, et al. (1998) and Sklar and Sarter (1999) indicate tactile cues can help direct attention to unexpected discrete events (e.g., uncommanded transitions) in an automated cockpit system environment.

Typically, tactile displays transmit information through the skin by varying one or more key dimensions of vibratory stimulation (locus, amplitude, frequency, duration, and spatial/temporal separation). There are also several factors that can impact the detection of tactile stimulation including individual differences, stimulus habituation, cognitive load, and body posture. The surface of the body also varies considerably in terms of tactile spatial and temporal sensitivity. Moreover, there is a possibility that another stimulus can interfere with the detection of a tactile stimulus (i.e., masking) and that an illusion can be created with certain combinations of vibratory dimensions (Craig and Sherrick, 1982). Unfortunately, there are few guidelines on how best to implement tactile cues to present information.

Objective

The present study addressed the utility of a tactile display in a multi-task environment and evaluated alternate tactile/information mappings. Two tactors were employed and their location and vibration settings were mapped to four system faults. Specifically, the independent variables were: tactor location (two tactors on left forearm, two tactors on right forearm, and one tactor on each forearm) and cue modality (tactile, visual, and combined tactile and visual).

METHOD

Subjects

Twelve naive right-handed participants served as subjects (7 males and 5 females). Ages ranged from 20 to 35 with a mean of 24.67 years. Participants reported normal vision.

Design

A 3 x 3 within-subjects factorial design was employed. The tactor location variable was blocked, with participants receiving trials with each cue modality within each tactor location block. (Note: though the tactors did not vibrate during the visual modality, tactor location was evaluated to see whether their presence was distracting. This is important because in envisioned tactile display applications, the tactors will be worn continuously in the work environment.) The order in which the tactor location configurations were employed was determined by the use of a balanced Latin Square. The order in which the modalities were evaluated within each tactor location configuration was also balanced in the same manner.

Tactor Stimulation and Location

Two electromechanical tactors (Audiological Engineering) were used. Each small tactor (1.00 x 0.75 inch) was mounted on an elastic band (Figure 2). The stimulation of the tactors was controlled with a 2 channel, 12 Bit digital-to-analog output plug in board (CIO-DACO2, Measurement Computing Corporation). The tactors were driven with a square wave signal of 5 volts (50% duty cycle) and frequency swept (250 Hz to 500 Hz) over 2 experimenter-specified durations. One sweep duration was 1.0 seconds and was termed the "slower vibration pulse." The other sweep duration was 0.10 seconds and was termed the "faster vibration pulse." For positioning the tactors, participants held their arm, palm side up, with the hand at approximately 90° angle to the arm. Tactors were positioned 1.5 inches up from the wrist line in the two-arm configuration and at 1.5 and 5.5 inches in the single-arm configurations.

Test Environment

Three tasks in the NASA Multi-Attribute Task Battery (MATB) were employed (Comstock and Arnegard, 1992; Figure 1). The resource management task operated in an automatic mode solely to increase the complexity of the visual scene. The other two tasks required participants' inputs. One was the compensatory tracking task controlled via a right-hand joystick and set at the most difficult level. The other was the monitoring task that involved both warning lights and parameter scales (Figure 2). There were two warning lights: green (participant presses F5 key when light goes off) and red (participant presses F6 key when light goes on). The four parameter scales had moving pointers that fluctuated slightly around the scale center, ±1 tic mark. When cued to be abnormal, the pointer shifted to being more than one deviation away from center. The participants' task was to indicate, via distinct key presses (F1-F4), which of the four scales had the fault.

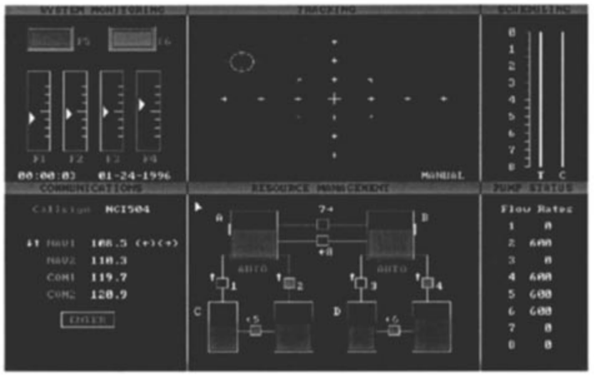
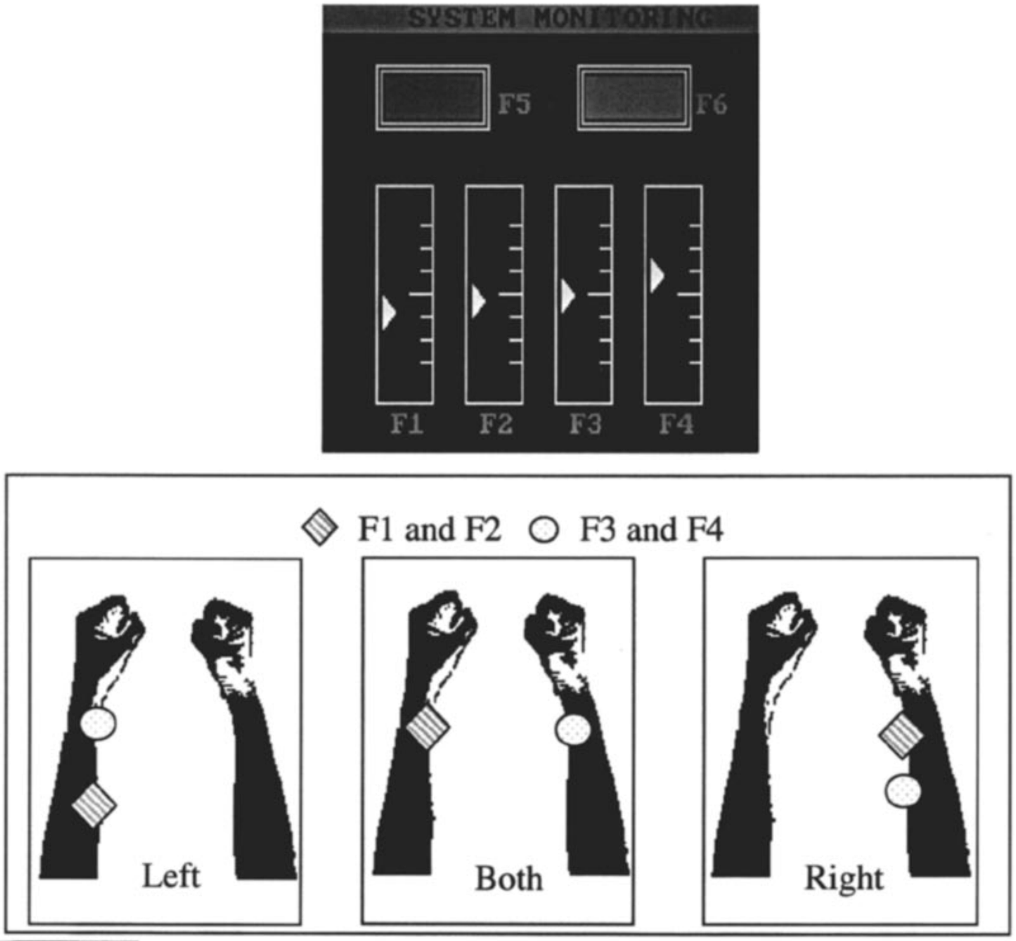


Figure 1. Multi-Attribute Task Battery Display.

Cue Modalities

When one of the four vertical scales was out-of-tolerance (i.e., a 'fault'), either the visual (conventional MATB), tactile (vibration stimulation initiated, visual scales on display occluded from view), or combined tactile/visual cue was presented, depending on the specific treatment for that trial. The alert cue ceased when the participant made a key response or after five seconds had elapsed.

It should be noted that the inherent modality differences between the cues had implications on how the participants retrieved information on scale faults. In the visual cue condition, operators visually acquired that part of the display and, presumably, simultaneously detected and identified which scale had a fault. With the two conditions involving a tactile cue, the vibration alerted participants that a fault had occurred. In the tactile only condition, the fault had to be detected and identified by the tactile codes alone; visual acquisition was not possible. With the combined cue, participants could either use the visual cue or identify the scale at fault by the pulse speed (without redirecting visual attention away from the tracking task). The cues also differed between being continuously available (visual cue: pointers indicated current value on all four scales and participants judged their proximity to the deviation threshold) and being available only when a fault occurred (tactile cue).



SCALE FAULT	LOCATION	VIBRATION PULSE
F1	Left-most Tactor	Slow Pulse Sweep: 1.0 sec.
F2	Left-most Tactor	Fast Pulse Sweep: 0.1 sec.
F3	Right-most Tactor	Slow Pulse Sweep: 1.0 sec.
F4	Right-most Tactor	Fast Pulse Sweep: 0.1 sec.

Figure 2. Tactile Display's Location and Vibration Pulse Speed Coding for Four Scales.

The tactile stimulation was mapped to the four faults in the manner described in Figure 2. With this mapping, the left-most tactor on a single arm corresponded to the two left-most scales in the MATB monitoring task and the right-most tactor corresponded to the two right-most scales. When both arms were used, the one on the left arm corresponded to the two left-most scales and the one on the right arm, the right-most scales. The other coding dimension was mapped to the four scales in the order of vibration pulse speed: slower vibration pulse for F1 and F3 scales, faster vibration pulse for F2 and F4 scales. This mapping of the tactile stimulation with the four scales was held constant across all participants/trials, because it is compatible with existing population stereotypes -- the common association of moving from left to right, with items positioned horizontally and changing from slower to faster (i.e., in vibration pulse speed).

Procedures

Training. Participants were given 40-50 minutes of training, prior to beginning data collection. Practice sessions were conducted for each task separately, then simultaneously. Practice was first given on the conventional MATB (visual modality), followed by training on the tactile display. Prior to each experimental trial, refresher training was conducted with the tactor location/cue modality to be presented next. Training was conducted until performance stabilized.

Experimental trials. Participants were instructed to continuously perform the tracking task as well as monitor lights and scales for abnormal deviations and to make the appropriate key presses as soon as a fault was detected. Three script files were developed to drive the occurrence of 32 faults per trial. For each subject, the three files were randomly assigned to one of the modality cue conditions within each tactor location condition. The faults within each file were randomly ordered with the constraint that there were 16 scale faults (4 for each of the 4 scales, 2 in each direction) and 16 warning lights (8 red and 8 green). The time interval between faults was randomly varied between 6 and 19 seconds. Each trial took approximately 6 minutes to complete and each participant completed one trial with each of the nine cue modality/tactor location combinations.

Data collection. Faults not detected within 5 seconds were scored as missed events; responses to non-abnormal conditions were scored as errors of commission. Besides these accuracy measures, response time was another dependent variable. Performance measures for the concurrent tasks were examined to verify that participants attended to the warning lights and continuous tracking task. Subjective ratings and comments were obtained with a debriefing questionnaire. The questionnaire included the Subjective Workload Dominance (SWORD) Technique to assess the mental workload associated with the three cue modalities (Vidulich, Ward, and Schueren, 1991).

RESULTS

Response Time to Scale Faults

A two-way within-subjects ANOVA on response time revealed main effects of Tactor Location ($F(2,22) = 13.39$, $p < 0.001$) and Cue Modality ($F(2,22) = 7.002$, $p < 0.004$) as well as an interaction of Tactor Location X Cue Modality ($F(4,44) = 4.432$, $p < 0.004$; see Figure 3). Both conditions employing tactile stimulation resulted in faster response times, except when both tactors were on the left arm. In this case, the mean response time with the combined tactile/visual cue was equal to the mean for the visual cue. Response time was the fastest with one tactor on each arm.

Figure 3. Mean Response Time for Scale Faults by Tactor Location and Cue Modality.

Accuracy

Separate two-way within-subjects ANOVAs did not reveal any significant effects of Tactor Location or Cue Modality on the number of missed events and the number of errors of commission. Participants were very accurate. Over 97% of the faults were detected and over 96% of the responses were without errors of commission. There was a trend in the number of errors of commission for Tactor Location ($F(2,22) = 3.277$, $p < 0.057$). Post-hoc analyses indicated that there tended to be less errors of commission when the tactors were located one on each arm, compared to when both tactors were located on the right arm ($p = 0.063$).

Response Time to Warning Lights

A two-way within-subjects ANOVA failed to reveal any significant effects of Tactor Location or Cue Modality on response time to the colored warning lights. Thus, utility of the tactile cues for scale faults did not impact participants' monitoring of the warning lights.

RMS Tracking Error

A two-way within-subjects ANOVA on root-mean squared (RMS) tracking error revealed a main effect of Cue Modality ($F(2,22) = 28.25$, $p < 0.001$, see Figure 4). Post-hoc analysis indicated that RMS tracking error was significantly less with the two conditions employing tactile cues compared to the visual cue ($p < .01$). The interaction of Tactor Location X Cue Modality approached significance ($F(4,44) = 2.413$, $p < 0.063$). RMS tracking error with the combined tactile/visual cue was less when tactors were on both arms, compared to single arm configurations.

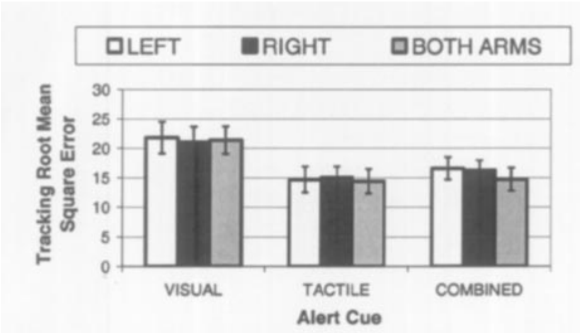


Figure 4. Mean Tracking RMS Error by Cue Modality and Tactor Location.

Subjective Data

Questionnaire responses were analyzed with Kolmogorov-Smirnov nonparametric tests of significance.

Cue Modality. Analysis of responses to the SWORD Technique indicated that the participants thought the visual cue required more mental workload than the tactile ($p < .01$) and combined ($p < .01$) cue conditions. Participants rated the identification of the faulty scale as more difficult ($p < .05$) and tending to be slower ($p < .10$) with the visual cue as compared to the tactile cue. The data showed similar trends when comparing the visual and combined tactile/visual cues ($p < .10$). Participants thought the tactile cue was equal or better than the combined cue in terms of speed ($p < .05$). For the combined cue condition, one participant noted, "you are not looking at the scale, you are waiting to feel the tactile cue." Another commented that there is less need to refocus the eyes. This explains responses that the visual cue interfered with tracking more than the conditions that employed a tactile cue ($p < .01$).

Tactile Display. The majority of participants rated the tactors as comfortable and found the slower and faster vibration pulses as "easy" to perceive at both wrist ($p < .01$) and elbow ($p < .05$) locations. Participants responded that having one tactor on each arm was better than having the tactors on a single left ($p < .05$) or right ($p < .05$) arm. They also rated having one tactor on each arm as "easy" for identifying the faulty scale ($p < .01$).

DISCUSSION

Cue Modality. The results of this study indicate that a tactile display can significantly improve detection of faults in a multi-task environment. Moreover, the tactile display resulted in less interference with the concurrent tracking task and did not degrade vigilance to the concurrent monitoring of warning lights. Participants favorably rated the tactile cues and had little difficulty perceiving the vibratory stimulation settings employed.

Tactor Location. The data support the use of both arms in tactor location coding, as opposed to two tactors on one arm. The finding of faster response times for tactors on the right arm as compared to the left suggests that manipulating the joystick with the right hand did not produce masking effects, as predicted by Chapman, Bushnell, Miron, Duncan, and Lund (1987). Perhaps this was due to heightened attention to the tactors (Sklar and Sarter, 1999) or due to a preference for right side locations for tactile interfaces (Craig and Sherrick, 1982). A study is underway to further examine the influence of handedness.

Conclusion. The present results suggest that a tactile display has potential of improving operator performance efficiency on monitoring tasks in complex systems. Further research is needed to determine how best to map information to the tactile stimulation and codify vibration dimensions to ensure cues are easily distinguishable. Is it better for operators to glean information by simply detecting that a tactor is activated or by varying an individual tactor's activation in some dimension? How many tactile codes can be remembered? Can a tactile cue be a distraction or interfere with the performance of other tasks? Research addressing such questions will help determine constraints on the application of tactile displays in complex systems.

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