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TACTILE CUEING STRATEGIES TO CONVEY AIRCRAFT MOTION OR WARN OF COLLISION

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This report highlights five current vibrotactile display technologies for conveying aircraft motion or approach to obstacles or waypoints, including: 1) a simple on/off vibration cue that activates when a designated position is reached; 2) vibrations whose on-off pulse rate increases as the vehicle moves faster; 3) vibrations whose fundamental frequency rises to cue the approach of an object; 4) vibrations whose body site of spatial cueing signals self-motion in a manner analogous to tactile cues during sliding along the ground; 5) vibrations whose body site of cueing expands in a manner analogous to visual looming cues. The advantages and limitations of these current approaches are discussed, a new display strategy is introduced, and recommendations are made concerning future tactile display development and research needed to provide tactile displays.

During flight, orientation and vehicle motion cues are often inadequate (e.g., due to loss of terrain visibility) or misleading (e.g., due to vestibular illusions). This report provides a brief overview of some of the currently-feasible tactile cueing strategies for restoring accurate perception of aircraft motion or the approach of obstacles or waypoints during flight. Tactile stick/rudder/collective tactile ("shaker") cues have long been used to prevent stalling or inappropriate power settings in flight. More sophisticated and informative tactile spatial orientation/motion technologies have been developed and tested which convey aircraft position and/or motion. These strategies include the following: Strategy 1: an applied vibration cue that simply turns on when one's aircraft reaches a designated waypoint; Strategy 2: an applied vibration display whose number of on-off pulses per second becomes greater as one moves faster away from a desired helicopter hover position[2]; Strategy 3: a laboratory tactile analogue of auditory perception whose vibration frequency rises to cue approach of/to a significant object (looming)[2]; Strategy 4: a laboratory tactile analogue of natural touch, whose site of spatial cueing on the body changes in a linear/laminar manner consistent with the perception of self-motion during sliding across the ground; Strategy 5: a laboratory analogue of vision, whose site of cueing expands radially to convey looming in a manner akin to the perception of visual flow. These currently-feasible cueing strategies are described briefly below, along with a new display strategy that builds upon Strategies 4 and 5 and which has been prototyped but not yet tested[2].

Strategy 1: Activating Vibration When the Target Point has been Reached

Strategy 1 employs vibration cues that simply activate when a target position has been reached or a significant event is imminent. Strategy 1 cues sometimes also convey information concerning the direction of the event, but they do not convey finely-graded cues indicative of the changing *distance* of the event relative to the vehicle operator, as he or she draws closer. For example, Van Erp and Van Veen (2004) tested a belt of eight electrically-driven vibrotactors (Figure 1) around the waist of a vehicle operator (one fast boat driver and one helicopter pilot). In this case, individual tactors activated to convey rich information concerning the direction of the desired waypoints during travel, but not their changing distance over time[3]. When the operator reached the desired waypoint, all eight tactors activated. This display aided the accuracy of wayfinding performance, despite the significant ambient vehicle vibrations present in the two vehicles studied by Van Erp and Van Veen (2004).

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[1] This author is also affiliated with the Oak Ridge Institute for Science and Education.

[2] Strategies 2 and 3, and 6 were demonstrated to the audience attending this presentation.

[3] When the operator was pointing at the waypoint, the rate of vibration pulses in the front tactor would vary its frequency as well, but this was to refine directional information, not distance cues.

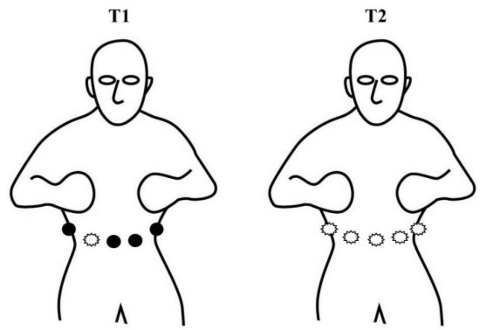

Figure 1. In this example of Strategy 1, a tactor activates (white star on man at left) to indicate the need to turn in that direction, while all tactors activate (see man at right) to indicate arrival at the waypoint. (Three additional tactors on the back are not shown.)

Strategy 2: Varying the Rate of On/Off Vibration Pulses to Indicate Self-Motion

A second tactile cueing strategy was employed by McGrath et al. (2004) during a helicopter flight demonstration (Figure 2). Two rows of eight tactors each went around the pilot's waist and supplied directional and velocity cues. When the pilots (*n* = 4) drifted outside their designated hover range, two vertically-oriented tactors both activated in the direction of the unwanted drift, much as a rumble strip on a freeway warns an automobile driver of lane deviations. In addition, relative cues concerning the pilots' rate of self-motion were provided by pulsing the on-off periods of vibration at a higher frequency per second as horizontal velocity of the helicopter increased. The pilots were found to have better flight control when tactile cues were available than when they were not.

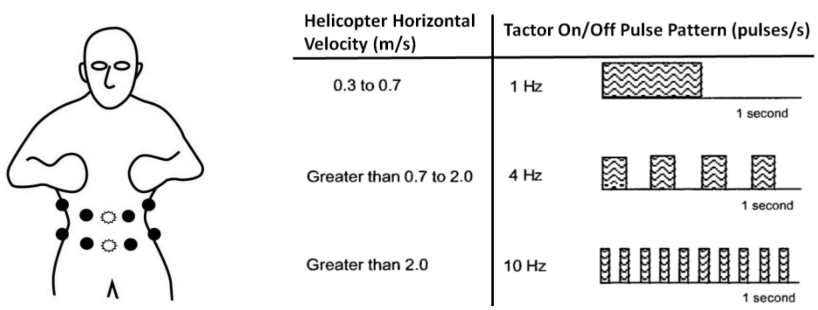

Figure 2. In this example of Strategy 2, when the helicopter drifts horizontally, two tactors (see white stars on man at left) vibrate on the side of the drift (in this case, forward). In addition, the temporal frequency of on-off vibration pulses corresponds to the velocity of the drift deviation (right, from McGrath et al., 2004).

Strategy 3: Varying the Fundamental Frequency of Vibration

Gray (2011) reported that an auditory vehicle collision warning that increases in sound intensity in a way analogous to a real sound source approaching the subject aids faster initiation of braking than other types of cues[4]. Since simple loudness and pitch changes can help to convey looming, we wondered whether a localized tactile stimulus of varying vibration frequency could convey information consistent with looming even when the spatial site of the tactile stimulus was held constant at a given body site. We sought to establish whether a varying vibration cue could be interpreted as a meaningful tactile icon or *tacton* consistent with an object that is approaching (Brewster and Brown, 2004). The relevant stimuli and findings are summarized briefly, below.

Various vibration stimuli were evaluated by thirty-five participants, using semantic differential ratings (Lawson et al., in press). The stimuli varied in terms of their tactor vibration frequency and duration of firing over the course of a three s train of twenty vibratory bursts (or beats). Two (of the six) vibration stimuli are shown in the graph in Figure 3, because these two stimuli are relevant to display Strategies 2 and 3 discussed in this report. Our study

[4] The single exception was the sound of a car horn, which unfortunately also produced a greater likelihood of false positive braking responses.

indicated that Strategy 2 (varying the rate of on/off pulses) conveyed looming less well than Strategy 3 (varying the fundamental frequency of vibration). In fact, the highest scoring condition for looming was “increasing frequency” (Strategy 3), which was interpreted differently from a random control stimulus and all other stimulus patterns evaluated, including Strategy 2 (Bonferroni-adjusted pairwise comparisons, $p < 0.01$). These findings imply that frequency (Strategy 3) may be a better aspect of the stimulus to manipulate than rate of on/off pulses (Strategy 2), at least when the purpose is to convey the concept of an object moving towards or away from the observer.

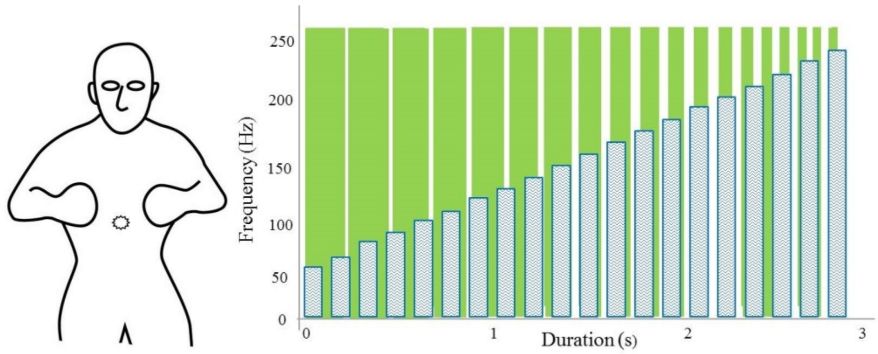

Figure 3. In this example of Strategies 2 and 3, looming is conveyed by vibrations at a given body site (see man at left) that either pulse more frequently (on/off) over time (Strategy 2, shown as green/shaded bars in background of the graph) or increase their fundamental vibration frequency over time (Strategy 3, see pattern-filled bars in the foreground). Strategy 3 was rated a better looming tacton (Lawson et al., in press).

Strategy 4: Varying the Site of Body Cueing in a Laminar or Linear Manner

Amemiya, Hirota, and Ikei (2013) presented subjects (n =7) with simulated optical flow cues (radial expansion of ~1,000 random dots on a twenty inch monitor) for forward self-motion. The found that the subjects’ estimates of the speed of their illusory forward self-motion (vection) could be reduced or increased by varying the speed of a front-to-back tactile flow stimulus (i.e., by varying the inter-stimulus interval of tactor activation in a 4 x 5 array of tactors, each of which consisted of nineteen vibrating pins) across the seat of subjects’ pants. This is a very natural way to convey self-motion tactually (Lawson, 2014) and an approach that could be explored for the cueing of pilots.

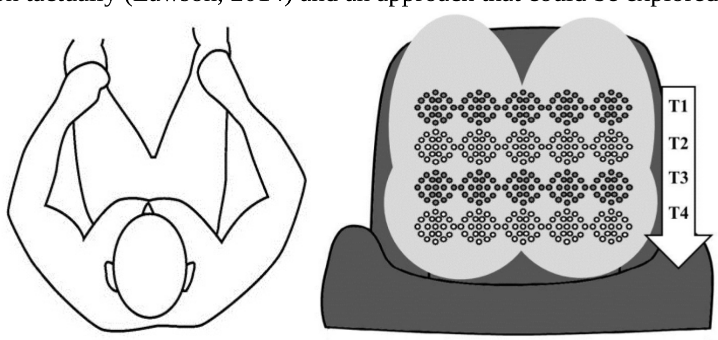

Figure 4. In this example of Strategy 4, a top-down view of a seated operator is shown at left, with the light gray shading at right approximating where the operator’s posterior contacts the seat. Four rows activate at Times (T) 1, 2, 3, and 4, to provide a sweeping cue from front to back of the operator’s posterior.

Strategy 5: Varying the Site of Body Cueing in a Radial Manner

In a study by Cancar et al. (2013)[5], tactile flow cues concerning the approach of a real ball[6] were sufficient (without visual cues) to enable participants (*n* = 12) to hit the ball at the correct time in 71% of the trials. The expanding tactile flow field Cancar et al. employed (Figure 5, partially adapted from Cancar et al.) has two possible advantages over a simple on/off vibratory “looming warning cue” (such as the vibrating mode of a cell phone). First, the expanding flow field is a logical analogue of an approaching optical target or three-dimensional auditory target (Lawson, 2014). Second, the perceived magnitude of the stimulus will increase as more tactors are activated (Cholewiak, 1979), thus increasing saliency. This approach also is worth exploring further.

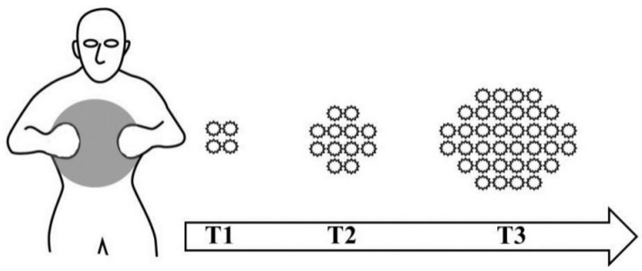

Figure 5. In this example of Strategy 5, the approach of an object is cued at three times (T1-T3) by the number of activated tactors in an expanding array on the chest (gray region).

Conclusions, Developing Strategies, and Future Recommendations

Table 1 summarizes and compares the five currently-available tactile display strategies discussed in this paper. Strategy #1 (indicating when the pilot has reached a waypoint) is simple, but cannot provide a graded warning that would be useful in a wide variety of situations. A variant of strategy #2 is employed in some current tactile cueing systems intended for aviation, but a recent study implies that Strategy #3 may be better for conveying looming. Strategy #3 may be better than Strategy 2 for conveying imminent collision. Strategies #4 and 5 are rich, but require further research evidence. The first issue that should be studied during flight is whether Strategy #3 works better than the currently-used Strategy #2. The second issue that should be studied is whether tactor arrays (Strategies #4 and 5) are superior to single-point displays (Strategies #1-3).

Table 1.

Comparison of Five Available Tactile Cueing Strategies for Conveying Aircraft Motion.

	Strategy #1	Strategy #2	Strategy #3	Strategy #4	Strategy #5
Application	Simple event warning	Rate of closure	Rate of closure	Rate of drift	Rate of closure
Simplicity:	Simple	Intermediate	Intermediate	Complex	Complex
Maturity:	High	High	Medium	Low	Low
Richness:	Low	Medium	Medium	High	High
Pros:	Low cost, time, weight, size	Tested in-flight	Optimal tacton	Intuitive	Compatible with visual displays
Cons:	Inadequate for many applications	Non-optimal tacton	Limited stimulus range	Limited testing	Limited testing

Each display strategy above has certain advantages but none will be exploited optimally unless a clear understanding of tactile display design principles for conveying aircraft motion or collision is obtained first (Lawson, 2014). In the long run, we recommend that strategies 2, 3, 4, and 5 should not continue to develop separately, but rather, coalesce into a suite providing multiple cueing capabilities within one display system. At first, such a display system may represent a smorgasbord of insufficiently integrated cues. With each round of development and testing,

[5] See also Jansson (1983).
[6] The ball was tethered on a string and swinging towards the subject.

the display should become more similar to the natural somatosensory (and ultimately, multisensory) cues that specify self-motion and imminent collisions. In addition, a wider body surface should be exploited in future displays. None of the displays presented in this report stimulated the feet or lower legs, for example. This should be corrected, since these body regions are important to the somatosensory appreciation of natural body orientation, motion, and balance, and the feet have a large representation in the brain homunculus.

Different aviation groups hold differing and deeply-entrenched preferences concerning whether currently-available visual, auditory, or tactile displays are the best choice for avoiding mishaps by conveying aircraft attitude, altitude, motion, and proximity to obstacles. Nevertheless, few experts in perception or display design would argue that the wisest choice for conveying vehicle motion to an operator is to provide a single, abstract cue that is unlike the intuitive, multisensory cues one receives during motion through the natural world. We recommend that the developers of visual, auditory, and somatosensory displays place the needs of pilots ahead of their own interests in seeing their particular unimodal display solution adopted. Instead, display experts should coordinate a multisensory display solution that feels most natural to the user and best exploits the natural functions of each sensory modality (Lawson, 2014). The goal of multisensory display systems for vehicle control, virtual environments, and teleoperation should be to provide visual, auditory, vestibular, and somatosensory cues that are similar to the cues available during real motion in the natural world. We have developed a naturalistic tactile seat display that is shown in Figure 6. The display is a working proof-of-concept that requires testing to determine whether it aids situation awareness and vehicle control. In the prototype shown, Strategies 4 (varying the site of cueing linearly) and 5 (varying the site of cueing in a radial manner) are both incorporated into one display. Seven rows of tactors fire successively (at T1-T7) to convey forward drift (left side of figure 6), while the array fires in a radially-expanding pattern (right side of Figure 6) to convey descent towards the ground (at four successive time periods, T1-T4). As with Strategy 5 discussed above, descent towards the ground triggers more tactors as one gets closer to the ground, leading to increased saliency of the critical ground collision hazard (Cholewiak, 1979).

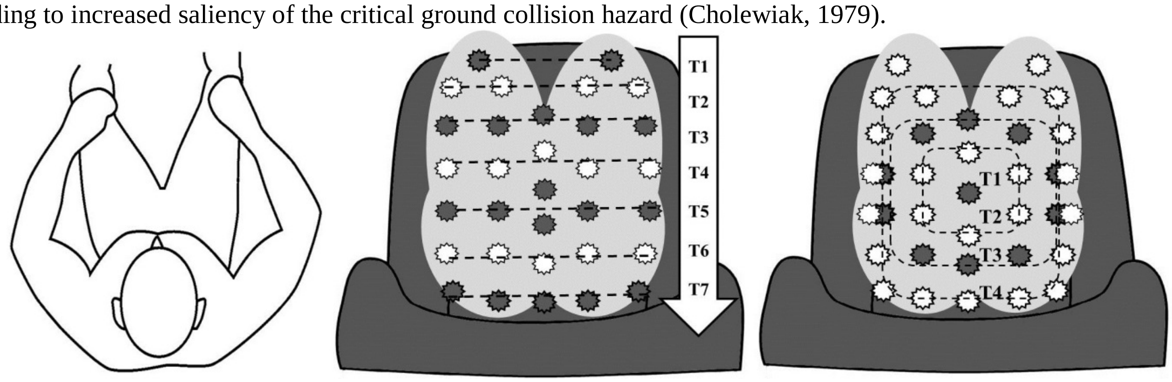

Figure 6. A top-down view of a prototype seat display that can cue horizontal drift (middle) or change in altitude (right) using the same tactor array. Light gray shading approximates where the operator's posterior contacts the seat.

A more sophisticated concept for a future tactile display is shown in Figure 7. The seated pilot is shown partially from below, to emphasize the stimulation of cutaneous receptors naturally associated with self-motion relative to the substrate. The display would incorporate large regions of skin and would intuitively convey body motion in six degrees of freedom. For clarity, Figure 7 only depicts two degrees of freedom, viz., linear translation up, down, for, or aft. Many types of cues are possible, including activating rows of vibrators linearly (to convey self-motion), radially (to convey imminent collision), and on distinct body parts successively (e.g., feet, then wrists, then chest, to convey approach to an obstacle or waypoint) (Meng et al., 2014).

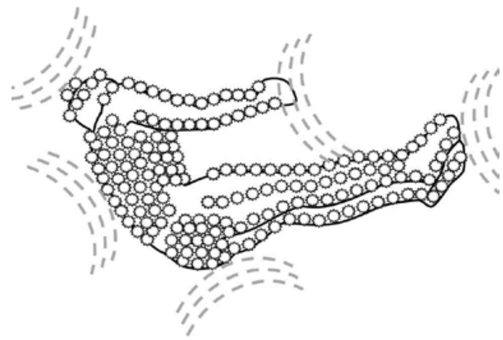

Figure 7. A tactile display concept to convey motion or approach to objects in multiple directions.

Current tactile displays are primitive compared to visual or auditory displays. However, tactile displays are rapidly growing more sophisticated, just as occurred for visual and auditory displays. Many of those who dismissed the need for a visual display of orientation in the 1920s lived to see visual attitude indicators become indispensable. Similarly, those who dismiss the usefulness of augmenting the perception of vehicle state with a tactile display will soon become routine users of high-resolution tactile displays during (real and simulated) air, sea, and ground travel.

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