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Recent Advances in Tactile Cueing

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Flight tests conducted by the Army and Navy have demonstrated the utility of the Tactile Situation Awareness System (TSAS) as an adjunct to visual instruments to improve pilot performance in degraded visual environments or under conditions of high workload. The tactile stimulators (tactors) used in each of the flight tests have been incorporated into aircraft components (seat cushions and shoulder straps) and a torso garment (belt or vest). Current tactors must operate at full magnitude and a very restricted frequency range (240 to 250 Hz) in order to provide consistent and perceptible stimuli in the aviation environment. Fortunately, recent developments in piezoceramics permit the frequency of tactors to vary from 50 to 500 Hz. This wider range of tactor stimulus frequency has significantly increased the available information content for tactile cueing systems. Several recent tests of TSAS will be presented to include additional capabilities that can be expected as piezoceramic tactors are incorporated into tactile designs.

Spatial disorientation (SD) occurs when a pilot does not correctly sense the position, motion or attitude of an aircraft relative the surface of the Earth. Since the U.S. Army established their consolidated database in 1972, SD has consistently accounted for at least 20% of U.S. Army class A/B mishaps (Flightfax, 2014). Mishap reports involving SD routinely attribute the cause of the mishap to the pilot with phrases such as: “The pilot failed to maintain an adequate crosscheck of the instruments” or “The pilot failed to respond in a timely manner.”

SD events and mishaps have occurred from the time pilots entered the aerospace environment. Between the Wright brothers’ first flight in 1903 and the 1929 introduction of orientation instruments to permit “blind flight,” pilots were unable to maintain spatial orientation awareness unless there was a clear view of the ground or horizon to provide orientation. However, SD mishaps continued even after planes were equipped with instruments to include the attitude indicator, heading indicator, turn rate indicator, altimeter, vertical velocity indicator, and airspeed indicator. Despite having these visual instruments to provide all of the necessary aircraft state parameters to be aware of orientation, pilots routinely became disoriented whenever they did not frequently refresh their knowledge of aircraft state parameters. How often pilots needed to refresh orientation was a function of aircraft stability and the dynamics of the flight regime. Only a few seconds of failure to scan the instruments could result in disorientation simply because visual instruments only provide orientation while the pilot is attending to the display. The pilot has more than just the task of “aviating” and must attend to other tasks including navigating and communicating. Anytime the pilot is not attending to the orientation instruments, the aircraft can slowly depart from controlled flight.

In instrument flight conditions and without the auto pilot engaged, the pilot is constantly making minor corrections to restore straight and level flight and to maintain the desired heading and altitude. The instrument scan requires a few seconds, so by the time the pilot has completed the scan and made minor corrections to any observed deviations, it is necessary to repeat the scan if the pilot is to maintain tight control of the aircraft. During any task or off-nominal condition that distracts the pilot’s attention away from the instruments (including boredom and fatigue), the aircraft frequently departs from the desired pitch, roll, or heading requiring the pilot to make significant corrections during the next scan. Strictly speaking, the pilot is disoriented many times during typical hand-flown instrument flights.

The TSAS was developed in response to the failure of visual modality instruments to provide pilots with continuous orientation information during flight. The concept of using tactile cueing as a means of intuitively maintaining spatial orientation for pilots was introduced at the 1989 Advisory Group for Aerospace Research and Development (AGARD) meeting on Situation Awareness in Aerospace Operations. The below diagram was used to explain the relation of the tactile stimulators (tactors) to the external environment.

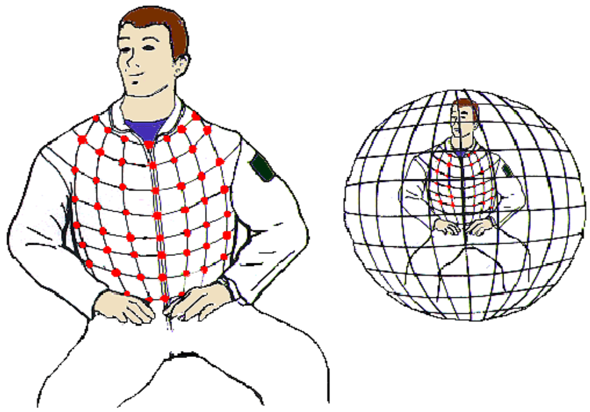

Figure 1. Columns and rows of tactile stimulators on the pilot mapped to the external environment (Rupert, 1993).

Since the pilot's torso is rigidly fixed to the aircraft via a multipoint harness, a matrix (columns and rows) of tactors incorporated into the pilots garment, harness, and seat can be mapped to the world surrounding the aircraft. Data from the aircraft orientation instruments provides the aircraft performance parameters to the pilot including the critical parameters of the direction down and the velocity vector. Most importantly since the matrix of tactors can provide pitch and roll information continuously to the pilot, it was no longer necessary to refer to the attitude indicator to maintain pitch and roll orientation information.

When pilots are flying in instrument meteorological conditions (IMC) more than 60% of their visual scan time is devoted to attending to two visual flight instruments, the directional gyro, and the attitude indicator (Simmons, Lees, and Kimbal, 1978). With the use of continuous non-visual displays, the pilot is now free to attend to other instruments that require visual attention or to other cockpit duties

Tactile displays have been proposed for use in aviation beginning as early as 1954. A few prototypes were attempted, but none met with success during in-flight trials as devices to maintain orientation. The two primary reasons early attempts at tactile cueing failed in the aviation environment were:

1. Non-intuitive displays: An early display using tactile cues on the hand to provide orientation information did not succeed since the pilot needed to devote significant attention to the tactile cues to interpret the information (Gilson and Fenton, 1974). It takes many years to become proficient at Braille, and many never succeed when it is necessary to learn this difficult task late in life. In contrast, minimal or no learning is required to present targeting information on the torso since the central nervous system is wired to reflexively interpret the location of taps on the torso and there is constant reinforcement of this experience during daily life events. This reflex is the example of a tap on the shoulder that draws attention to a point in space. The TSAS uses the same principle as a tap on the shoulder for targeting information. For pitch and roll information, TSAS provides the gravity vector in the same way as a person strapped firmly to a chair when the chair is moved in space in varying pitch and roll orientation. For this reason, minimal training is required to understand and use the system.

2. Inadequate tactile transducers: When the TSAS concept was first presented, the state of tactile transducers or tactile stimulators (tactors) was quite rudimentary. Early tactile stimulators were too large[1] and not salient enough to be appreciated in the noisy and high vibration environment of the cockpit. The first prototype transducer used for the TSAS proof of concept for torso displays were miniature speakers (Fig 2) derived from toys.

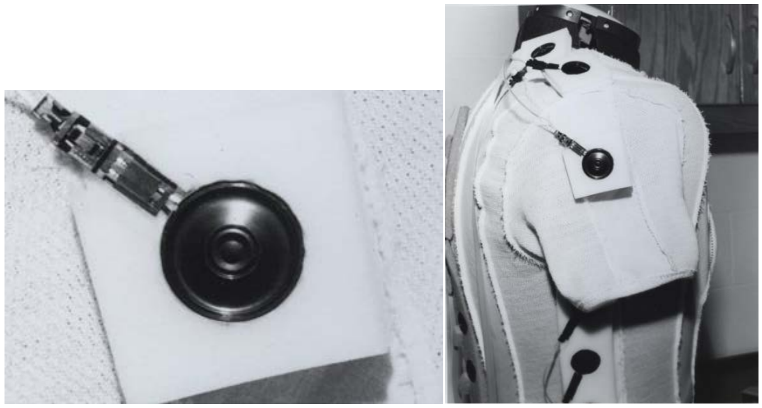

Figure 2. Miniature speaker on left and shown installed as a linear array on inside-out garment.

The fragile speakers frequently failed after short periods of use, and although they provided adequate saliency in the laboratory, they were not consistently perceived in the noisy and high vibration environment experienced in both fixed-wing aircraft and helicopters.

The second generation speakers for TSAS were custom built in-house vibrators consisting of a polyethylene block with an off-center rotating mass inside, similar to a pager motor but much larger. Again these tactors could not provide amplitude and frequency control of the stimulus. When funding was provided to support eight companies via the Small Business Innovative Research (SBIR) and Broad Agency Announcement (BAA) processes, it was possible to define the requirements for aviation tactile transducers. The requirements called for tactors that were: 1) small; 2) lightweight to permit easy integration into flight garments; 3) highly efficient to minimize power requirements and generate little heat as a by-product; 4) insensitive to contact pressure to enable tactors to be placed in seat cushions; 5) large dynamic range (50 to 500 Hz); 6) of a low failure rate to ensure reliability; 7) designed to provide minimal discomfort; 8) easily maintained by the military; 9) rugged for military environments; and 10) inexpensive.

Clearly, trade-offs were required to develop an acceptable tactor. The eight companies used different approaches to develop tactors based on varying principles. The best overall tactor was the C2 electromechanical tactor, developed by Engineering Acoustics Inc., that we have used for the past 15 years (Fig 3).

[1] An exception was direct electrical stimuli (Ross, 1973). However, the difference between a just perceptible electrical stimulus and a painful stimulus on dry skin was small and without using a paste or gel to control the interface, it was not possible to provide consistent stimuli without inducing pain.

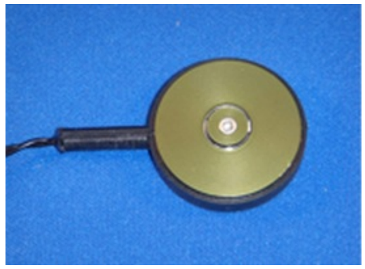

Figure 3. C-2 tactor manufactured by Engineering Acoustics Inc. The tactor is roughly the same diameter as a U.S. quarter coin.

The C-2 tactor provided consistent, highly salient stimuli for the aviation environment and was tuned for 240 Hz, which is peak sensitivity for skin vibration. The primary deficiency of the C-2 tactor was the narrow-frequency response which prevented tactile algorithm designers from using both frequency and amplitude modulation in the design of clearly interpretable tactile icons, also known as tactons.

In response to a DARPA-sponsored SBIR, the Midé Technology Corporation developed a piezoceramic tactor with a wide, dynamic response in frequency (50 to 500 Hz). When four experienced tactile researchers informally compared the C-2 electromechanical and the Midé ST-25b piezoceramic transducer, the ST-25b was felt to be more punctate and as good or better in terms of saliency.

Figure 4. SHIVR™ ST-25b piezoceramic tactile stimulator (quarter for reference).

The importance of variable frequency tactors in the generation of rich tactons is demonstrated in Fig 5. By varying only the frequency and amplitude stimuli for the auditory sense, it is possible to produce variations in four different psychophysical dimensions, namely: pitch, loudness, volume, and density.

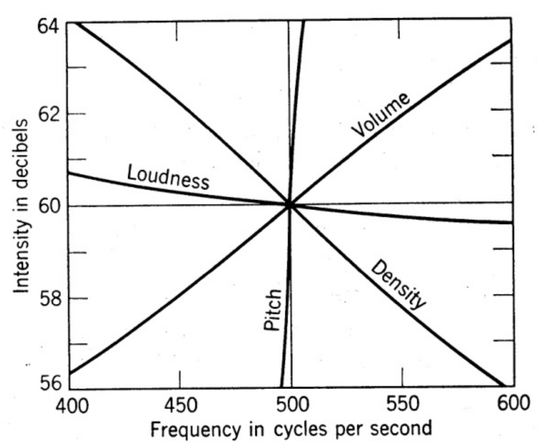

Figure 5. Isomorphic contours for pitch, loudness, volume, and density. Each contour defines the combinations of frequency and intensity at which a comparison tone will be perceived as equal in pitch or loudness or volume or density to the standard tone of 500 cps and 60 db. From Geldard (1953).

This concept was best expressed by Hans-Lukas Teuber (in Young, 1984) when he said, “The number of dimensions of perception exceeds that of the stimuli.” There are so many variables that tacton designers have to manipulate including magnitude/amplitude, frequency, waveform, pattern, duration, location, and interstimulus interval. For this reason, the range of tactile experiences is almost limitless.

When Georg von Békésy was conducting his Nobel prize-winning research on hearing mechanisms in the cochlea, he also conducted research on tactile sensation; reasoning that the inner ear is derived from the same embryologic ectoderm that produces skin receptors and so likely possesses similar mechanisms of sensory perception. He was correct but learned that the skin sensation was far more complex due to the variation in the number and types of sensory receptors and so returned to research the “trivial” system of the cochlea. This complexity of skin sensations can be used to advantage in developing rich tactile displays.

With the development of improved tactors, it will be possible to take advantage of tactile illusions that are inherent to the skin perceptual system. The “phantom sensation” (Von Békésy, 1957; Gescheider, 1965; Alles, 1970; Verrillo and Gescheider, 1975), occurs when two stimuli of equal loudness are presented at the same time to two nearby locations on the skin. The two stimuli are not felt separately but rather as a single stimulus halfway between the two stimulators. It is also possible to create the sensation of motion between two tactors by manipulating the relative intensities of two adjacent tactors. When one tactor intensity is increased while an adjacent tactor is decreased, the tactile sensation will be experienced as moving from one tactor to the other.

Another illusion providing the sensation of motion is the Rabbit illusion or cutaneous saltation (Cholewiak, 1976; Geldard, 1975). For example, a rapid sequence of 5 taps delivered first near the wrist, then halfway between the wrist and elbow, and then near the elbow, will be perceived as 15 equally spaced sequential taps “hopping” up the arm from the wrist towards the elbow and cannot be distinguished from 15 equally separated taps placed from the wrist to the forearm.

By using the Phantom and Rabbit illusions, it is possible to create “virtual tactors” located between the physical tactors which will reduce the number of tactors required in an aviation belt or garment. These illusions are a function of the separation of the tactors, the magnitude of the stimulus and the timing separation of the stimuli.

Recent tests using traditional C-2 tactors have demonstrated the capability of tactile cueing to maintain hover capabilities. Soon we will have even better capabilities with the recent development of piezoceramic tactors.

Acknowledgements

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