Chapter 5 – INTEGRATION ISSUES OF TACTILE DISPLAYS IN MILITARY ENVIRONMENTS

by

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5.1 INTRODUCTION

Tactile displays are versatile and highly valuable in a multitude of different environments, each with characteristics that substantially influence the interface with the human. As a result, a wide range of application specific phenomena must be discussed as they relate to equipment integration with the user. For example, the inertial stresses created in the high acceleration environment (measured in multiples of the acceleration due to the Earth's gravitational pull or G), water submersion, skin-tactor contact issues, vibration, and the unique features of garments and life support equipment can create factors that must be accounted for when implementing tactile technologies. These issues have been divided into their causal factors, namely those related to environmental stressors, and those dependent on the interface between the tactile equipment and the human body.

5.2 ENVIRONMENT

Among the multitude of factors that influence the successful integration of tactile displays with the human body, perhaps one of the most critical to understand is the contributions of the environmental stressors. Because tactile display applications are wide and varied including land, air, space, and sea environments, the list of potential integration issues is extensive. This section attempts to address how these major environmental stressors affect the tactile integration in the military environment.

5.2.1 Temperature

A number of experiments have shown that skin temperature has an effect on vibrotactile perception thresholds. Bolanowski and Verrillo [1] presented observers with stimuli across the frequency scale at varied skin temperatures. They found a flat response from the non-Pacinian (NP) system (< 40 Hz) from 25 to 40°C, however for the 20 and 15°C degree conditions the threshold was raised and displayed a negative slope. In a later study, Bolanowski et al. [2] repeated the temperature manipulation experiment, but included frequencies below 25 Hz. They found that temperature had an effect on thresholds at these low frequencies, especially below 12 Hz, showing a clear increase in thresholds with increased temperature at 2Hz.

5.2.2 Underwater

Verrillo et al. [3] conducted a vibrotactile threshold study in which the observer's arm was immersed in a tank of salt water. Three male subjects were tested for threshold detection of 1, 10, 100 and 250 Hz stimuli after they had been immersed in the water tank for 20 minutes. The experimenters found that there was no significant difference between the results of those conditions conducted in air and those conducted in water. However, due to the fact that water pressure increases with depth, it is possible that the tactors could become ineffective at extreme depths should the hardware reach a point where it cannot overcome the external pressure created by the water (however, please note that pressure caused by high G does not seem to have an effect; see the section below on high/variable G). In addition, this may create discomfort around the tactors themselves. Finally, it should be noted that in the underwater environment it is imperative to keep the divers' equipment simple and robust because complex equipment is more prone to

malfunction. Therefore, the decision to use complex electronic equipment underwater should be weighed carefully as it can significantly affect the results of the mission or operation. An example of underwater operations is provided in Figure 5.1.

Figure 5.1: US Navy SEAL Delivery Vehicle (SDV).

5.2.3 Whole Body Vibration

The majority of individuals experience whole-body vibration (WBV) in transport environments. The exposure of the seated or standing human to whole-body vibration can have a variety of effects on perceived comfort and health, visual acuity, speech, and hand manipulation and control. In particular, the skeletal, muscular, and visceral structure of the human body acts to amplify received vibration at frequencies between 3 and 12 Hz. Discomfort is greatest within the human resonance frequency range. Human resonance to WBV peaks at 4 – 8 Hz in the z-axis (superior/inferior) and around 1 – 2 Hz in the x (anterior-posterior) and y (lateral) axes. In the majority of military transport environments the dominant vibration is received from the z-axis.

Vibrotactile devices for orientation, navigation or messaging will be used in situations where operators will be continuously exposed to WBV e.g. helicopters, fast-jets, land vehicles, high-speed sea vessels. The majority of these platforms expose individuals to WBV between 0.1 – 80 Hz, with some significant energy within the human resonance frequency range. One group [4, 5] investigated the effect of Whole Body Vibration (WBV) exposure on vibrotactile thresholds (VT). In a series of two experiments, subjects were presented with a 1-second duration 250 Hz vibrotactile stimulus on the lateral obliques, approximately 15 cm to the right of the umbilicus. Vibrotactile thresholds were acquired using a staircase methodology. Experiment 1 was designed to investigate the manipulation of WBV amplitude; subjects

were exposed to 6 Hz WBV at 0.5, 1.5, 2.5 and 3.5m/s^2. Experiment 2 investigated the effect of the manipulation of WBV frequency and amplitude with conditions being: 0.5, 2, 12 and 16 Hz, all at 0.5, 1.5, 2.5 and 3.5m/s^2. The results of these experiments showed that the perception threshold for a 1-second 250 Hz sinusoidal VT stimulus is increased during exposure to WBV. However, the magnitude of the effect is governed by the frequency and amplitude of WBV.

5.2.4 High/Variable G

The operation of high-speed aircraft exposes the pilot and crew to high levels of G forces. Therefore the potential exists for these forces acting on the body to reduce the effectiveness of a tactile display used within the cockpit environment. Several factors exist that are capable of negatively affecting tactile perception. These include the mechanical aspects of the skin receptors, use of an anti-G suit, anti-G straining maneuvers, the overall physiological stress (including perceptual and cognitive aspects), and the mechanical function of tactors. For example, the muscle straining and respiratory activity of anti-G straining maneuvers (used to counteract the +G_z effects of reduced blood pressure and blood flow in the retina and brain) could negatively affect not only the skin receptor threshold, but also the ability to integrate tactile cues into meaningful information.

In a pilot study, Van Veen and van Erp [6] showed that vibrotactile stimulation was not substantially impaired up to +6G_z, even though wearing a pressure suit for the legs and performing straining maneuvers were part of the experimental conditions. By utilizing the Swedish Dynamic Flight Simulator (DFS), capable of accelerations up to +9G_z in closed-loop control mode, and a version of a TNO TTD for the tactile cueing, Eriksson et al. [7] investigated tactile threat cueing at increased G_z. Fighter pilots detected and intercepted threats while pulling up to +8 or 9 G_z. In addition to wearing the TNO TTD, the pilots wore their regular military underwear, anti-G suit without pressure vest, and flight boots. Anti-G straining maneuvers were performed according to regular flight procedures. The high G-stress neither critically affected the tactile vest equipment nor the human sensory system.

In addition, a study performed by Rupert and McGrath [8] tested the Tactile Situational Awareness System (TSAS) system at high G_z (up to +7 G_z) in an effort to quantify the force and frequency changes (if any) of the tactors in the high-G environment. The standard TSAS configuration consists of a vest equipped with 24 pneumatic tactors arranged in 8 columns and 3 rows. Two additional electromechanical tactors are placed on the shoulders and two more are located in the seat cushion. The pneumatic tactors are comprised of plastic bodies with latex bladders. Air is pulsed through the tactor and it is felt as a distinct tapping when placed against the body. The electro-magnetic tactors have a magnet and electrical coil and when energized produce a unique tapping sensation that “feels” different than the pneumatic tactors. The TSAS system was installed on NAMRL’s Coriolis Acceleration Platform (CAP), which is a 20 ft centrifuge capable of generating G_z levels up to 7 G_z. The various TSAS tactors were installed on a calibrated load cell that permitted measurement of the force and frequency of each type of tactor. Tactors were tested at various +G_z levels up to and including 6.5 G_z. The results of the experiment suggested that the TSAS hardware performed successfully at 6.5 G_z. The force level and frequency generated by each type of tactor were not significantly affected by G level.

As a follow-up, a high-G equipment checkout was performed on TSAS Model HT-1 utilizing the Dynamic Flight Simulator located at Wright-Patterson Air Force Base. This study was a rapid response to operational issues to validate new equipment that may warrant further testing. Of specific interest was how well different anatomical locations perceive vibration stimuli at high G_z levels. Subjects donned the standard TSAS configuration and experienced several 15-sec G_z plateaus including 5, 7 and 9G_z. Tactors were randomly excited (one at a time) and the subject was tasked with orally describing the tactor that he/she perceived. The preliminary data showed that the subjects did not have difficulty perceiving any of the tactors in any of the locations, even at 9G_z [9].

Thus, all available evidence suggests that electromechanical and pneumatic tactors function under high G_z levels, which is extremely important in fast fighter jet applications. However, it should be noted that a multitude of electromechanical tactors exist (cref Chapter 4) and only a few specific types have been studied under G_z acceleration. Hence, these results cannot be extrapolated to cover all types of electromechanical tactors. It is the opinion of the authors that most electromechanical tactors with properties similar to those presented in this section will function during high-G acceleration. Although no high-G studies have yet been performed using purely electrical shock tactors, it is expected that changes in tactile performance will be minimal given that there is no mechanical force to overcome and the electrodes themselves are extremely light-weight.

5.2.5 Space-Zero/Micro G

Van Erp et al. [10] compared reaction time (RT) to tactors worn on the torso by an astronaut in a 1G and zero G environment. Despite the overall performance gain in microgravity (i.e., faster RTs), the RTs for tactors located in the upper and lower ring on the torso were negatively affected by weightlessness: the RTs were higher than in 1 G. This indicates that, although the garment that held the tactors was custom made for the astronaut, the fit at the lower and upper rings may be improved. The optimized fit for 1G may be less optimal in microgravity due to a different posture and shifts in body fluids.

5.3 TACTOR-BODY INTEGRATION ISSUES

The tactile display will be ineffective if the tactor does not maintain contact with the operator's body. Therefore what proves effective in the laboratory and trials setting must be transferable to the operational setting. This means that the method of ensuring the tactor remains in contact must be highly reliable and not be an encumbrance or irritation to the operator. Therefore the effective integration of the tactile display system with the individual must have a high priority in the system design phase.

Beyond the environmental issues described previously, it is important to discuss the general integration issues unique to tactile displays. A thorough understanding of these key concerns is paramount to avoiding potentially serious complications that could arise from substandard display integration. For example, poor skin-tactor contact could render some or all of the tactors in the display completely useless or sporadically available at best. In turn, the display itself would become unpredictable and untrustworthy forcing it to be removed from the product or ignored. These integration issues have been described in detail in the literature. A more concise summary can be found in the following section.

5.3.1 Skin-Tactor Contact

5.3.1.1 Skin Issues

Integration issues also specifically focus on the tactor placement. The first concern is a result of varying receptor cell types and densities throughout the body. Each of the six types of receptor cells differ in rate of adaptation rate, receptive field size, sensitive frequency range, and the sensation evoked (cref Chapter 2). For example, Pacinian corpuscles create sensation of vibration/tickle whereas Ruffini endings provide sensations of stretch, shear, and tension. In addition, each of the six types of receptor cells is not uniformly distributed throughout the body. Likewise, the relative densities of each of the receptor cell types vary depending on body location. This results in the evoked sensation being dependent on the location of the tactor (stimulus).

5.3.1.2 Electromechanical Tactile Stimulation

Vos et al. [11] performed an extensive mathematical study on wave propagation in the skin and skin-tactor contact. It is expected that mechanoreceptors are best stimulated by shear waves, as shear waves exert a

local force difference on two neighbouring particles that is approximately a thousand times larger than with longitudinal waves. Consequently, shear stimulation of the skin results in more local stress in the mechanoreceptors; the receptor is stretched and compressed instead of pushed forwards and backwards when a wave passes. However, a vibrator that oscillates along the surface of the skin slips more easily than a vibrator that oscillates perpendicular to the skin. This results in a less efficient transfer of the vibration energy. Unfortunately vibration devices that are used in a tactile display often do not have a primary oscillation direction and will therefore evoke a mixture of longitudinal and shear waves with varying polarisations.

Since the epidermis skin layer is stiffer than the dermis, the vibration energy waves will propagate farther in the epidermis parallel to the surface of the skin. Shear and longitudinal waves will most likely penetrate through the dermis and the subcutaneous fat layer and reflect almost entirely on the much stiffer, underlying layer that consists of muscle or bone. The reflected waves arrive at the epidermis-air boundary under every possible angle, because of the spherical-like form of the waves. The propagation velocity of longitudinal waves in air is smaller than the velocity in skin and shear waves cannot exist in air. Therefore, only longitudinal surface waves that originate from shear waves can exist. Perpendicular excitation of the skin would of course result in a shear wave travelling along the surface of the skin starting at the rim of the source, because of the up and down motion of the skin. In the case of parallel excitation, a longitudinal wave would travel along the surface (see Figure 5.2).

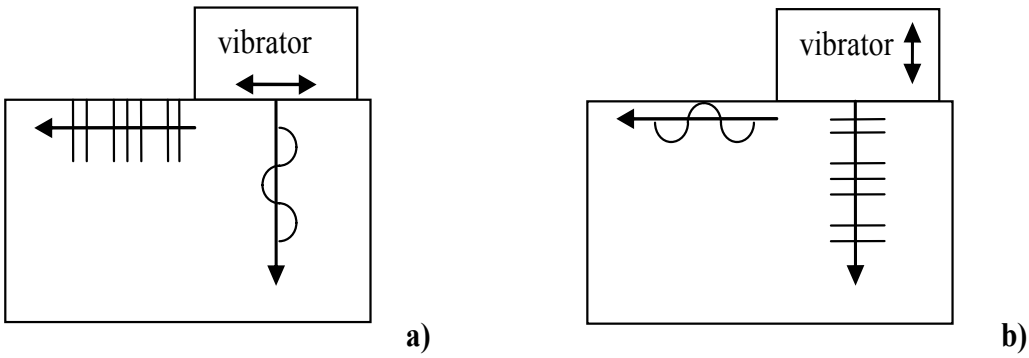

Figure 5.2: a) When the Vibrator Oscillates Horizontally, a Shear Wave Moves Downwards and a Longitudinal Wave Propagates Along the Surface. b) When the Vibrator Oscillates Vertically, a Longitudinal Wave Moves Downwards and a Shear Wave Propagates along the Surface. A combination of shear and longitudinal waves will occur at different angles.

The interface between the tactor and the skin should be designed such that the transfer of vibration energy from the tactor to the skin is large. A well designed contact will reduce the need for strong vibrators that have high energy consumption. The insertion of a material between the vibrator and the skin with the appropriate impedance will help to increase the tactor efficiency. A perfect match is not feasible in the case of longitudinal waves, because its wavelength in solid materials is meters long. For shear waves, the matching of impedances is easier. However, the impedance of the skin varies with the location on the skin so the match will never be perfect.

Another way to improve the transfer of wave energy is achieved by gluing the tactor to the skin. This will give the highest friction between the tactor and the skin. Often it will be impractical to attach the vibrator rigidly to the skin. In that case, the vibrator will be pressed onto the skin with or without a material like clothing in-between. In the first case, the vibrator should have enough static friction or else it will slip. In the latter case, it is expected that the fibres in clothes slip easily and reduce the energy transfer. With simulation, it should be possible to predict the influence of different types of clothing between the tactor and the skin.

The friction between the tactor and the skin can also be increased by applying more pressure on the tactor. However, this will stretch the skin and since it is a nonlinear material, it becomes stiffer when it is stretched. This is caused by the mechanical properties of collagen networks. In a stiffer material, there will be less attenuation of waves and a higher wave propagation velocity. Skin stretch can also occur during body movement, contact with objects in the environment, or during stimulations with large amplitudes. To keep a constant sensation, the amplitude of pressure fluctuation must be reduced. This could be accomplished by letting the force act on a large surface.

The interface between the tactor and the skin also plays a role in localising the vibrations in the skin; all waves will attenuate with the distance from the source. When the contact area between the vibration source and the skin is large, the waves will behave more like plane waves. When it is small, the wave will behave more like spherical waves. Consequently, vibrations originating from a small contact area will dampen more quickly than waves originating from a large contact area. A small contact area is preferable, since it reduces the spreading of the vibrations. It also reduces the need for strong vibrators, because less skin mass has to be moved.

A vibrator can be isolated from its carrier by embedding it in a soft material with an impedance that greatly differs from the impedance of the vibrator, which in turn is surrounded by another dense material. This second layer causes the vibration to be reflected back to the source. Care should be taken that vibrations do not leak to the bulk material via the skin. Fixation of the skin just around the vibrator will damp the waves travelling on and near the surface of the skin, but not the waves deeper below the surface.

5.3.2 Electrical Tactile Stimulation

Perhaps one of the most critical concerns with tactile displays involves the perception of the tactor when it is energized. Human observation of each individual tactor is only possible when the tactor is in contact with a part of the body or skin. This consideration is certainly most prevalent in purely electrical tactor systems due to the fact that each electrode (tactor) must be in *direct* contact with the skin to produce a perceptible stimulation. Because the excitation of the skin receptor cells is performed by delivering electrical current directly to the skin, several integration issues arise. First, the impedance between the skin and the tactor electrode must remain low. Dry skin/tactors yield very high impedance that tends to produce an uncomfortable “prickly” sensation. It is believed that this is a direct result of the inconsistent current distribution within the skin-tactor interface. Hence, an electrolytic solution should be applied to each of the tactors prior to use. However, it should be noted that generally subjects develop a layer of sweat under each of the tactors (electrodes) after a few minutes of wearing the garment. The sweat has been informally shown to provide an acceptable substitute for the electrolyte solution. Nevertheless, long term changes in impedance have not yet been investigated without the use of a manufactured solution (e.g., saline solution). Finally, securing the electrode wires and incorporating the tactors into appropriate garments in an unobtrusive manner remains a challenge.

5.4 HARDWARE ISSUES

The final set of concerns deal with the tactile display hardware integration with the operator.

5.4.1 Weight

The development of ‘future soldier systems’ is anticipated to increase the mass of the equipment carried by the operator. The addition of a multi-tactor system has the potential to add to this mass burden by the inclusion of tactors, a driver system and a power supply. If the tactile display has a minimum number of tactors then this may not be an issue, whereas a multi tactor system (e.g., 64 tactors) may have a significant weight penalty. This may serve only to further compromise the effectiveness of the individual

by reducing mobility, increasing physical workload, and adding bulky items that are capable of being snagged on obstacles and building features. It is likely that future developments in power supply and tactor technology will significantly reduce the weight of the systems and make portable, high-resolution tactile systems relatively easy to implement on the dismounted soldier.

5.4.2 Equipment Ditching

Many operations require that an operator's equipment can be quickly removed to ensure safety. This requires that the wiring system for the tactile display must not inhibit the removal of the personal equipment. Therefore designers will be required to identify whether wireless links or quick-disconnect connectors are more appropriate in the systems' design.

5.4.3 Emergency Egress

For the same safety and mission effectiveness reasons that specify personal equipment must be easily removable, personnel must also be able to evacuate their vehicle or workstation in a minimum time frame. This again means that the systems designer must include quick disconnect connectors or wireless links where appropriate. For example, helicopter pilots should not need to physically disconnect the tactile display electrical connections from the aircraft in order to egress in emergency situations. The device should operate via wireless connections or the connector should automatically disconnect when moderate tension is applied.

5.4.4 Comfort

Comfort is an essential part of clothing and equipment that is worn by an individual. If the operator is uncomfortable they are unlikely to use the tactile display and thus its potential advantages will not be realized. This issue is discussed in more detail by van Erp [12].

5.5 CONCLUDING REMARKS

Chapters 2 and 3 discussed the physiology and the human factors issues related to tactile displays. These issues must be considered when attempting to integrate laboratory-based system in actual military environments. A robust system must be able to withstand a myriad of environmental stressors, which may include vibration, large variations in temperature, underwater submersion, sustained accelerations, impacts and microgravity. The tactile display must be integrated with the current military garments, which may cause challenges in skin-tactor contact, weight, ditching, emergency egress, and comfort. Although these integration issues are complex, there have been many successful applications of tactile displays. A number of these will be discussed in Chapter 6.

5.6 REFERENCES

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