Chapter 1 – INTRODUCTION TO TACTILE DISPLAYS IN MILITARY ENVIRONMENTS

by

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Challenging situations, such as those encountered by military pilots, are often a major thrust for ergonomic innovation. Examples include the development of advanced, multimodal, and intuitive interface techniques to counteract the danger of visual, auditory, and cognitive overload. Tactile displays (displays that use the skin as an information channel) typically belong to this category. The variety of tactile displays ranges from a single vibrating element (like those in mobile phones) to matrices of elements covering the torso of a pilot, soldier, diver, or other operator. Examples of this matrix display are the TNO Tactile Torso Display (TTTD, see Figure 1.1) and the Naval Aeromedical Research Laboratory Tactile Situation Awareness System (TSAS), which both provide intuitive three-dimensional spatial information.

Figure 1.1: A Helicopter Pilot Showing a TNO Tactile Torso Display (TTTD), Consisting of a Matrix of Vibrating Elements Inside a Multi-Ply Garment Covering the Pilot's Torso.

1.1 JUSTIFICATION FOR THIS EFFORT

1.1.1 Timeliness

This report is a work item of the NATO RTO HFM Task Group 122 "Tactile displays for orientation, navigation and communication in air, sea, and land environments". Objectives of this group were to define critical research issues, to disseminate knowledge and to provide operational guidelines; all of these serve the goal of increasing NATO's successful operations by incorporating tactile displays in advanced human-system interfaces.

There is an increasing number of research efforts focused on applying tactile interfaces for orientation, navigation, and communication. The technology, although initially focused on pilots, is recognised as relevant to land and sea systems as well, including but not limited to divers, dismounted soldiers, UAV operators, and boat and armoured vehicle drivers. Many laboratory and field studies have shown that tactile displays can improve operator performance and reduce operator workload (e.g., [1]).

Given the current progress of technological developments and operational concepts regarding the use of tactile displays in military environments, a strong and combined effort of NATO countries is essential to resolve the unique human-system issues associated with effective applications of tactile displays. Relevant issues include hardware/actuator technology, perception and psychophysics, interface and coding standardisation, operating concepts, and integration with life-support equipment and visual and auditory displays. This report focuses on the aspects important from a NATO Human Factors and Medicine (HFM) panel point of view. However, the task group stresses the need to review progress and to share understanding of the important technical developments and to guide research efforts and standardisation issues across a broad set of NATO participants and NATO RTO panels. The timeliness of NATO's interest in tactile display and standardisation is underlined by the establishment of an ISO working group on tactile and haptic interaction in November 2005 [2].

Despite the fast growing interest in tactile displays, the field is relatively young. The justification for this work is primarily based on the following:

- Tactile displays are pre-eminently 'purple', i.e., applications are being developed for Navy, Army, Air Force and Special Forces.
- Because the field is relatively young and the number of NATO countries involved in the technology is still limited, disseminating knowledge may have a large impact on countries not yet involved. Contrary to the small steps taken in long-standing technologies, these countries can make a large leap forward in this field.
- The same argument holds for industry.
- Because many applications are still in a developmental state, NATO is in a position to easily set standards for design, applications, and use.

1.1.2 Why use Tactile Displays?

There have been several drivers for research groups to start developing tactile display applications, including the eminent need to provide spatial disorientation (SD) countermeasures and solutions to the threats of sensory and/or cognitive overload.

1.1.2.1 Spatial Disorientation Countermeasure

The development and implementation of tactile displays as an SD countermeasure is supported by the conclusion of the NATO Research & Technology Organisation symposium; 'Spatial disorientation in

military vehicles: causes, consequences and cures' held in 2002. In the executive summary, it was stated that: *'The most important advance of recent years with the potential to combat spatial disorientation has been the use of tactile stimuli to give information on spatial orientation'* [3]. SD is a serious threat to military/civilian pilots and aircraft and is a substantial detriment to military aviation operations in terms of cost, lives lost, and mission degradation. Mishap analyses indicate that SD is an important causal factor in aviation accidents, especially for rotary wing operations, and are more deadly than mishaps attributed to other factors. Accurate data on the involvement of SD are critical in the development of aviation safety technologies that have the highest and most cost effective potential to reduce these mishaps. Considerable effort has been put into SD countermeasures such as training programmes and advanced (visual) cockpit displays [4] [5]. Adding tactile orientation displays to this list of countermeasures has the potential to reduce the number of aviation related SD mishaps.

1.1.2.1.1 Mishaps Statistics and Cost Benefit Analysis

To underline the importance of the initial thrust to develop tactile displays as a countermeasure to spatial disorientation, some mishap statistics are given below. The definition of SD as given by the Air Standard Coordination Committee (ASCC) AIR STD 61/117/07 is the following; "*Spatial Disorientation is used to describe a variety of incidents occurring in flight where the pilot fails to sense correctly the position, motion, or attitude of the aircraft or of himself within the fixed co-ordinate system provided by the surface of the earth and the gravitational vertical*". Previous studies have cited the potential for misclassification and underreporting of SD as a causal factor in mishaps.

- US Air Force

Mishaps related to SD in the United States Air Force (USAF) accounted for approximately 21% of all USAF serious mishaps during the 1980's and 90's, and 39% of all fatal incidents between 1991 and 2000. SD costs the Department of Defence over $300 million per year in accident investigations, family compensation, and aircraft reconstruction. "On average, the USAF loses five aircraft with aircrews (and sometimes with passengers) each year due to spatial disorientation, and most of these are related to loss of attitude awareness" [6], p. 489). Between October 1993 and September 2002, accidents related to spatial disorientation cost the Air Force 243 aircraft, 310 lives, and approximately $6.23 billion. In this timeframe, there were 25 high performance fighter or attack mishaps where spatial disorientation was identified as a causal or contributing factor. These mishaps resulted in 19 fatalities and cost the Air Force over $455 million. The continued incidence and seriousness of spatial disorientation has prompted researchers to seek new methods to both predict spatial disorientation and to counteract it.

- US Army

According to Braithwaite [7], SD was the primary contributing factor in 43% of all US Army rotary-wing (helicopter) aircraft accidents. The average lives lost per accident were nearly three times greater for SD accidents (0.38) than for non-SD accidents (0.14) (Braithwaite et al., 1998). SD was a significant factor in 291 (30%) of Class A, B, and C helicopter accidents in the US Army between 1987 and 1995. One hundred ten lives were lost and a cost of $468 million was incurred [8].

- US Navy

Using Naval Safety Center (NSC) AIR STD 61/117/07 classification, 12% of class A mishaps were classified as SD mishaps. Using the ASSC definition, 22% of the class A mishaps could be classified as SD mishaps. The breakdown of rotary wing versus fixed wing SD mishaps was 29% and 18%, respectively. SD mishaps claimed lives 63% of the time versus 28% for non-SD mishaps. Night operations appear to be an important factor, with two-thirds of all SD mishaps occurring at night. In the time frame FY97 to FY02, 47 rotary wing mishaps (rate 1.94 per 100,000 flight hours) occurred, with 14 classified as SD mishaps (rate 0.58 per 100,000 flight hours). These SD mishaps resulted in 35 deaths and $118 million costs. In the same time frame, 120 fixed wing aircraft occurred (rate 1.81 per 100,000 flight hours) with

22 classified as SD mishaps (0.33 per 100,000 flight hours). These SD mishaps resulted in 23 deaths and $475 million costs [9].

- Cost-benefits analysis for tactile countermeasures

Using the mishap data presented above, tactile display mishap prevention analysis data, the projected flight hours, and the tactile display development and procurement costs, a cost-benefit analysis to equip the US Navy H-60 helicopter fleet with a TSAS system was performed. With an initial investment of capital (R&D funds) of $20M, the 5 year internal rate of return was estimated at 4%. This corresponds to the avoidance of two H-60 mishaps and the saving of approximately 8 lives [10].

1.1.2.2 Counteracting the Threat of Sensory and Cognitive Overload

A second important motivation for the application of tactile displays is the threat of sensory and/or cognitive overload in current man-machine interfaces. Although visual displays are usually easy to comprehend, the development of computer driven displays provides the opportunity to provide a vast quantity of information that can overload the individual's capacity to process the information provided. Warnings and procedures have been issued to avoid this, starting with the system's design stage [11][12]. The threat of sensory overload makes designers of human- machine interfaces increasingly apply multi-modal interfaces. An important reason for this is the need for an alternative or complementary information channel in complex operator environments [13]. Traditionally, the auditory channel is considered as an alternative or supplement to visual displays. Examples include the presentation of route navigation [14][15] and tracking error information ([16]; for a review see [17], pp. 480 – 481). However, there are situations in which the visual and auditory channels of an operator are both heavily loaded or in which the visual and/or auditory information is degraded or not available. Examples include:

- Operators in complex environments who work at the limits of their visual and auditory processing capacity, such as pilots [18][19].
- Operators whose visual or auditory attention is preferably focused on a specific area of interest, such as car drivers who need to concentrate on the road [20][21][22]), and dismounted soldiers who want to focus on the environment and possible threats.
- Operators who work in a visually or auditorily deprived environment, such as remote operators [23][24]), virtual environment users [25], divers in dark waters, and drivers of fast boats.
- Operators who work under conditions that require minimization of the transmission of light or sound, as during night or covert operations.

In these situations, it may be beneficial to employ a tactile display.

In addition to sensory overload, an operator may experience cognitive overload. One example of this involves navigation information in cars, which may result in an over demand of the (momentarily available) cognitive capacities of the driver. Evaluation has shown that visual in-vehicle information systems may negatively influence the drivers' scanning behaviour and attention allocation (i.e., they distract the driver). A possible effect is that the driver is temporarily out of the loop. There is a general belief that driver overload and distraction resulting from the actions of in-vehicle support systems can form a threat to the positive effects expected from these systems (e.g. [26][27][28]; see also Wickens, 2006). Warnings and procedures have been issued to avoid this, starting with the system's design stage [11]. In cockpit applications, visual displays have a specific disadvantage when presenting three dimensional (3D) navigation information. Because the displays are flat or 2D, one (or more) dimensions must be compressed. This results in loss of information and usually requires a cognitive component to reconstruct the 3D picture from the 2D display. An example is a 2D planar display depicting a bird's eye view of a set of waypoints while the altitude is displayed alphanumerically.

In Chapter 3, we will further discuss why employing tactile displays may be a solution to lessen the threats of sensory and cognitive overload.

1.2 POTENTIAL APPLICATIONS

The number of current and potential applications in which tactile displays are employed is still growing. A short overview is provided in the section below. The applications that are within the scope of this report are further elaborated in Chapter 6.

Information Presented by Tactile Displays

- Spatial orientation cues: gravity vector indication to reduce SD, particularly under conditions of sustained acceleration, absence of external visual cues, and high cognitive workload.
- Navigation cues: way-point direction cues, no-go areas, obstacle avoidance cues, collision avoidance information.
- Vehicle control: course control, turbulence, helicopter drift (especially imperceptible movement indications where visual cues are absent; e.g. helicopter drift whilst hovering in white/brown out conditions).
- Directional warning and attention allocation: threat indications, indicating areas of (visual) interest, ground proximity warnings.
- Spatial information/Situation Awareness support: direction of wingman, points of interest, group members, enemy contact, line of attack.
- Synthetic environments: reproducing or simulating perceptual cues of remote or virtual worlds (e.g., in controlling Uninhabited Military Vehicles) and in training and simulation.
- Communication:
  a) Non-visual communication especially under the following conditions: bright light environment where visual display screens are difficult to comprehend, scenarios where vision is required for primary tasks (e.g. battle field patrolling), covert operations where displays may produce an unacceptable visual signature, and night time operations where visual displays disrupt night vision adaptation; and
  b) Non-acoustic communication under the following conditions: high-noise environments where aural communication is difficult or would require excessively loud signals, low noise environments where audio signatures are unacceptable and/or may result in tactically relevant noises being missed.
- Non-visual and acoustic warning: used for control rooms that utilize lean manning where individuals are unable to continuously monitor an array of information, and for warning displays.

1.2.1 Air

The military aviation environment is both physically and cognitively demanding. We typically are not accustomed to navigating in three-dimensional space, and our orientation system did not develop under the extreme conditions of flight. Pilots are tasked with much more than simply flying the aircraft – they must perform navigation, make mission critical decisions regarding weapons deployment, conduct search and rescue operations, perform precision hovers in high threat environments, and maintain constant communication with tactical teams. These difficulties can be compounded by high levels of stress, fatigue, vibrations, sustained accelerations, hypoxia, thermal stress, and very poor visual conditions (e.g., night operations, white out, and brown out). Because aviation visual and auditory displays have been tasked to

provide enormous amounts of information, it is only natural that the military aviation community has begun to investigate the use of tactile displays to convey information to the pilot. One concept developed by the U.S. Air Force is the Spatial Orientation Retention Device (SORD). This device combines off-boresight visual symbology, 3-D audio cueing and a tactile vest. A conceptual drawing is displayed in Figure 1.2.

Figure 1.2: Spatial Orientation Retention Device (U.S. Air Force).

One of the most promising applications of tactile displays is for pilots performing precision hovers in poor visual environments, which may be in windy conditions. If a pilot drifts too far off the targeted position, tactors can be activated at various frequencies to indicate the direction and amplitude of the deviation. Similarly, a tactile display can be used for navigational purposes to inform a pilot when they have strayed too far off course. As described in more detail in Chapter 6, tactile cues are also highly effective for communicating the direction of potential threats. A pilot's attention can quickly be directed to the direction of a threat in a very intuitive fashion. A final application is for spatial orientation. Tactile information can be used to depict an artificial horizon, a down-pointer or up-pointer, or a command signal to convey a desired stick input.

1.2.2 Sea

The maritime environment is one of the harshest for human operations. It regularly subjects operators to arduous weather conditions and degraded visibility. To perform the required task with a suitable level of safety and aptitude requires operators to be provided with the appropriate tools for the job. This dictates that required information is available to the operator to ensure the correct level of situational awareness is attainable. It stands to reason that any system that enhances situational awareness will consequently improve performance and safety.

The contemporary demand for higher tempo operations, specifically in the military, coastguard and rescue domain, suggests that the demand for enhanced situational awareness has also grown. The ability for

surface, sub-surface, and airborne craft to operate at higher speeds means that the pilots and operators must be provided with the appropriate information at the right time so that optimal decisions can be made. This is particularly important when operating in poor weather conditions, close to land/obstacles, and at night.

The ability of computerised systems to provided operators with vast quantities of information has been found in all modes of transportation, but is particularly prevalent in the aviation sector. However, this phenomenon has been recently become evident in the marine operations where surface craft information systems must now display navigation, radar, boat systems and tactical information simultaneously. Unfortunately, the human operator possesses a finite ability to process this plethora of information. As a consequence, computerised displays can quickly overwhelm the operator's visual channel, which is further compounded with the fact that much of the data presented is of little use during certain periods of an operation. Therefore, the ability to provide information via non-visual senses can be an advantage for enhanced performance and safety.

A number of high speed craft trials have been successfully undertaken either in the maritime environment, or are such that they can be directly related to the marine environment [29][30]. These have primarily been for the provision of navigation/orientation cues, although other specific applications have been identified. Diver navigation using tactile cues has been successfully demonstrated by both US and UK researchers [31][32] by integrating the tactile display into computerised underwater navigation systems. An additional diving application for tactile displays is to provide enhanced situational awareness for mini-submarine (e.g., US Seal Delivery Vehicle (SDV) operations). This could include navigation, depth control and obstacle avoidance warning. Figure 1.3 shows a diver navigation system manufactured by Engineering Acoustics, Inc.

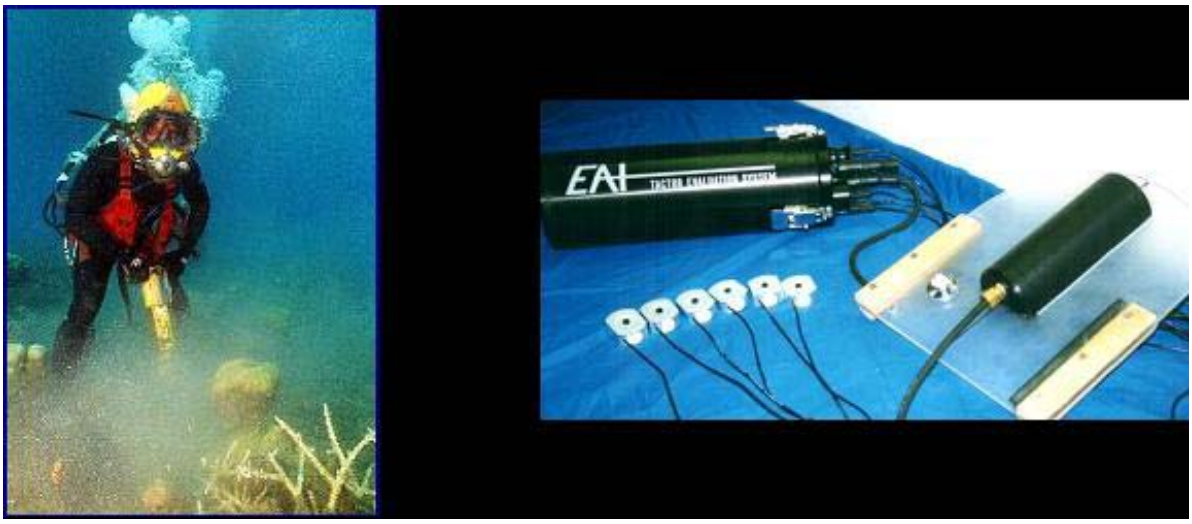

Figure 1.3: Diver Navigation System.

1.2.3 Land

Soldiers have specific and sometimes unique requirements for operation. Dismounted soldiers have a limited ability to carry power and equipment to support tactile displays and must have low noise and electrical signatures. They often operate in extremely demanding physical environments, and signals may be affected by the equipment they must wear and their close contact with the ground. Several concepts have been tested for dismounted soldiers both in daytime and in night operations. End users are particularly interested in the hands-free, eyes-free, and mind-free aspect of tactile displays. This allows

them to move with their weapon at the ready and with their eyes and attention focused on terrain and enemy threats. Applications include displaying waypoint navigation, terrain obstacles, off-limits areas, direction of threats, alerts on command decision making, threat location, target acquisition, support information for shooting performance, and tactile commands as substitutes for visual hand and arm signals. Studies have also been performed with tank operators using tactile displays as navigation aids as well as for target location. Soldiers in tanks or other ground moving vehicles do not have to deal with the same environmental stressors as dismounted soldiers, but often must operate in extreme noise and high vibration. Recently, several studies reported the potential of relatively simple tactile displays (usually consisting of no more than eight tactors in a belt around the waist) for land applications, including directional threat warning in armoured vehicles [33], dismounted soldier navigation [34], and communicating arm and hand signals [35]. Figure 1.4 displays a joint U.S. Army and TNO land navigation system.

Figure 1.4: Joint U.S. Army and TNO Tactile Array for Land Navigation.

1.2.4 Uninhabited Vehicles

Separating the operator from the vehicle means that the operator no longer receives direct sensory input from the remote environment, but only mediated information. This mediated information is usually restricted to (low quality) camera images [36][37][38]. This means that the remote operator is deprived of a range of sensory cues that are available to onboard operators, including somatosensation. According to the final report of the NATO-HFM Task Group on Unmanned Military Vehicles (UMVs), the loss of the rich supply of multisensory information often afforded to onboard operators is one of the challenges of advanced UMV operator interfaces. In the executive summary, the experts even state that *"....it could be said that the primary goal of the interface should be to reproduce the perceptual cues that are used by the operators in the real environment to perform the task"* [39].

The general belief is that tactile technology has a promising spin-off to uninhabited vehicles. There are two important arguments for this conviction. The first is that many of the crucial problems or bottlenecks

in the interfaces of inhabited military vehicles (e.g., sensory and cognitive overload) are also relevant for remote control interfaces. The second is that remote operators could benefit from the presentation of touch cues that are available onboard the vehicle but are absent in a remote control situation as stated above. The remote operator lacks valuable information, including vibration cues indicating platform and engine performance, pressure cues indicating forces acting on the platform, and environmental cues that can better be felt than seen, such as road condition in a ground vehicle and turbulence in an aerial vehicle. Van Erp [40] identified four application areas for remote control interfaces: navigation and vehicle control information, directional warning and attention allocation systems, situation awareness support systems, and reproduction of critical perceptual cues of the remote world.

1.2.5 Additional Application Areas

1.2.5.1 Telemanipulation

Beyond the previously described traditional applications of tactile display technology, emerging fields exist that expand their overall functionality and utility. Telemanipulation can be defined as the handling, operation, or utilisation of either concrete or virtual objects from a remote or otherwise detached location. For example, utilising gloves that provide tactile feedback, two individuals in different locations could jointly move or manipulate/modify virtual objects and "feel" the forces applied on the object by the other individual or object. Feedback including active touch or proprioceptive signals (e.g., force feedback, active exploration of an object) is typically referred to as haptics. Some potential applications of this technology include tactile/haptic feedback for medical applications (e.g., a surgeon performing surgery from a distant location), teaching applications (e.g., civil engineering students could "feel" the forces and stresses within a particular structure), and artistic applications (e.g., artists from a variety of regions might jointly form a virtual sculpture).

Additionally, telemanipulation could be used to control real objects while providing tactile feedback to the user. A potential application includes controlling a set of robotic arms in a variety of situations. One example involves disarming bombs and mines from a safe and distant location. Here, a robot (with mechanical arms) could be controlled by a human operator utilising gloves outfitted with haptic and tactile feedback. This would allow the human to feel the structure, wires, tools, etc. in his/her hands virtually to more easily manipulate the bomb components while maintaining safety. This expanding range of tactile/haptic feedback applications provides insight into the diversity of these displays.

1.2.5.2 Training, Simulation and Virtual Media, Gaming and Entertainment

Tactile displays are being explored with increasing frequency in the realms of simulation, training, and gaming. For simulated environments, tactile cues offer the potential of a greater sense of presence and improved task performance. Despite this potential, relatively little research has been done in this area. Li and colleagues [41] developed a haptic apparatus as a training aid for performing virtual catheterizations. Further, Gerling and Thomas [42] explored the use of a haptic feedback device for simulated breast examinations. They found that the use of haptic feedback resulted in improved training effectiveness, even though the sensations provided did not replicate those experienced during actual examinations. In the videogame industry, tactile feedback has become a relatively standard feature. It was first introduced in the home through force feedback steering wheels for PCs and add-on "rumble packs" for the Nintendo 64 and Sega Dreamcast controllers. Since then, vibration-based feedback has been incorporated into the controllers of several home video game consoles including Sony's Playstation 2 (see Figure 1.5), Nintendo's Gamecube and Wii, and Microsoft's X-Box and X-box 360.

Figure 1.5: Sony's Playstation 2 Controller with Vibration Feedback.

1.2.5.3 Therapeutic Applications

Applications under development outside the military environment are not within the scope of this report, although an influx of technology is possible. Therefore, we give a concise overview of therapeutic applications of tactile displays. Many applications have been developed for people with visual deficits. A successful device is the long cane used by the blind. In this case, tactile cueing can provide a natural correlation between the distal environment event and the proximal cue that is felt. Other devices include:

- A tactile vision-substitution system [43], designed to present optical patterns to the skin of the back.
- An optical to tactile converter called Optacon, developed to present patterns obtained from text registered by a camera directly to the fingertip [44]. It serves as a reading machine that provides vibrotactile spatial temporal patterns of alphabet letter shapes.
- The National Institute of Standards and Technology (NIST) has designed a refreshable tactile graphic display to allow the blind to receive information displayed on a computer screen and has developed a refreshable rotating wheel Braille display.

Similarly, numerous forms of prosthetic devices using the skin as an alternative sensing system have been developed for the deaf.

- In 1907, M. Du Pont proposed a tactile device that used direct electrical stimulation as an aid to communicate acoustic messages [45].
- Gault [46] developed a teletactor, a device that presented patterns to the fingers of the deaf.
- Tactile displays used as a hearing aid are typically based on the cochlea model of speech [47] where the acoustic signal from speech is sent through several bandpass filters that modulate the amplitudes of a corresponding array of tactors. Single and multipoint tactile aids designed to present analogues of the acoustic waveform in a one-dimensional array to the volar forearm were developed [48][49]. Both the linear electrocutaneous belt [50] and the two-dimensional multipoint electrotactile speech aid [51] displayed similar electrocutaneous patterns to the abdomen. Craig and Sherrick [52] developed dynamic arrays for tactile pattern presentation.
- Deaf students also learned to feel the vibrations of the pulsations of a balloon on the face and throat. This led to the development of vibrotactile aids (Tactaid VII Audiological Engineering Corp., Somerville, Massachusetts) that employ a linear array of tactors presenting vibration on the chest and the nape of the neck [53][54].

- The University of Sheffield is currently researching vibration elicited at the wrist to provide information from ambient sounds.
- A study by Sparks [55] used a 288 electrode tactile display to accurately provide auditory information on the abdomen. Each column referred to a band of frequencies and the subjects could identify segmental speech with 50 – 95% accuracy depending on the set of sounds used. In general, results from tactile hearing aid displays have been encouraging, but have not achieved great success or widespread use [45].

Another application to aid persons with disabilities is a sensory assistive device for those without sensation in their extremities.

- A study performed by Collins and Madey [56] used a special glove instrumented with strain gages on the fingertips. Each of the strain gages controlled the intensity of an electrode on the forehead. The results showed that subjects without sensation in their hand could distinguish rough surfaces from soft surfaces and could also detect edges and corners.
- Somatosensory displays can be used to provide proprioceptive feedback for spinal injury victims. A study performed by de Castro and Cliquet [57] introduced encoded tactile sensations relating artificially generated movements, provided by neuromuscular electrical stimulation systems, during walking and grasping activities. Paraplegics can use this sensorimotor integration to recognize artificial grasp force and to obtain spatial awareness of their legs during walking.
- Tupper & Gerhard [58] proposed the development of an electro-tactile stimulator that would provide positional and rate command feedback to motorized prosthetic arm users.
- Current applications of tactile displays include a vestibular prosthesis that provides information about body position and motion to patients with balance disorders in order to correct for body sway and to prevent falling [59][60].

1.3 HISTORICAL ASPECTS

In order to fully appreciate the myriad of tactile applications that have been described, it is useful to trace the historical aspects of tactile displays. The concept of presenting information via the sense of touch is not new. People have long ‘tapped each other on the shoulder’ to indicate their presence and the direction of their location. Also horse riders give instructions to the horse via tactile cues: the reigns pull on the horse’s head, and the feet push into the horse’s sides to give instructions to turn. Blind people have used tactile displays for many years (e.g., Braille and Moon alphabets). Also, military applications are many centuries old. In the late 1700s, Charles Barbier de la Serre, a French army captain, invented the basic technique of using raised dots and dashes for tactile reading and writing (Braille, Britannica Concise Encyclopedia). The original objective was to allow soldiers to compose and read messages/command orders silently at night without illumination. The raised dots represented words according to how they sounded rather than how they were spelled; this practice was known as sonography or “night writing”. Serre’s system was based on twelve dots. In 1824, Louis Braille further developed the method of touch reading and writing based upon conventional spelling using six dots; the Braille system as we know it today. The general concept and specific benefits of Braille remain relatively unchanged and unchallenged today, but the system has been complemented by an increase in speed and automation available through new electronics and computing power.

The attempt to employ tactile displays in aviation also has a lengthy history. As early as 1954, Ballard and Hessinger [61] proposed a vibro-mechanical tactile display system to indicate pitch and roll attitudes of the aircraft. The system consisted of four tactors mounted on the thumb. Two of the tactors provided pitch information and two provided roll information. The frequency of vibration indicated the magnitude of the deviation from the desired flight path. However, no results or further work on this system have been

reported in the open literature. Similarly, in 1961 Hirsch [62] proposed a tactile display for roll, pitch and yaw acceleration/velocity in aerospace vehicles using vibro-mechanical tactors on the thumb and forefinger. A kinesthetic and tactile aviation display consisting of an actuator mounted in the control stick that was capable of stimulating the hand (holding the control stick) was developed by Gilson and Fenton [21]. Movement of the actuator corresponded to the error (in degrees) from the desired angle of attack. Flight test results using a Cessna 172 suggested that the device allowed novice pilots to perform a tight turn about a point with less tracking error and contributed to decreased altitude and speed variations.

Morag [63] proposed a tactile display array inside the pilot's helmet to provide the spatial locations of targets or threats. He also suggested that the amplitude or frequency modulations of the tactile cues could be used to represent detailed information about the target such as the distance or urgency of the target. The part of the head that is stimulated represents the pilot's head-referenced angular direction of the target location. Gilliland and Schlegel [64] showed that the head was very sensitive to tactile stimulation. The localisation accuracy and response times varied inversely with the number of tactors available. For example, there was ninety-three percent accuracy with 6 tactor locations compared with 47% accuracy with 12 tactors. They further demonstrated that high workload (using dual memory and tracking task) did not interfere with the response time or localisation accuracy. However, performance during air combat simulation showed lower accuracy and longer response times. Zlotnik [65] proposed a matrix of electrocutaneous tactors embedded in a sleeve positioned on the forearm that would present airspeed, angle of attack, and altitude. However, no results or further work on this electrocutaneous device have been reported in the open literature.

In 1989, Rupert and colleagues renewed the idea that a tactile interface could be used as a "more natural" approach to convey position and motion perception during flight. This renewed interest resulted in many successful proofs-of-concept in rotary and fixed wing aircraft (see Chapter 6). Beneficial effects were shown over a range of circumstances including dynamic sustained acceleration, night operation, and situations of high mental workload. These successes and extensive research efforts have been responsible for bringing tactile displays to the precipice of introduction into operational cockpits. These efforts have extended to other military settings, including dismounted soldiers, remote control operators, vehicle and fast boat operators, and special forces.

1.4 SET UP OF THE REPORT

1.4.1 Definition of the Tactile Sense

There seem to be as many definitions of tactile displays as there are researchers working in the field. However, we use the following nomenclature throughout this report:

- Proprioception is related to all the senses that are included in the perception of oneself in space, including the sense of touch, the vestibular system and the haptic sense.
- Haptics / sense of touch / somatosensation all refer to the sensory systems related to both active and passive touch, including the mechanoreceptors in the skin and the receptors in muscles and joints.
- Tactile / cutaneous is related to stimuli that evoke a response in the mechanoreceptors in the skin only, thus excluding receptors in joints and muscles, and excluding noxious stimuli that evoke a pain sensation and temperature stimuli that evoke a sensation of cold or warmth.
- Vibrotactile is related to vibrating stimuli, thus excluding for example pressure stimuli.

Figure 1.6 depicts the relationship of the terms defined above.

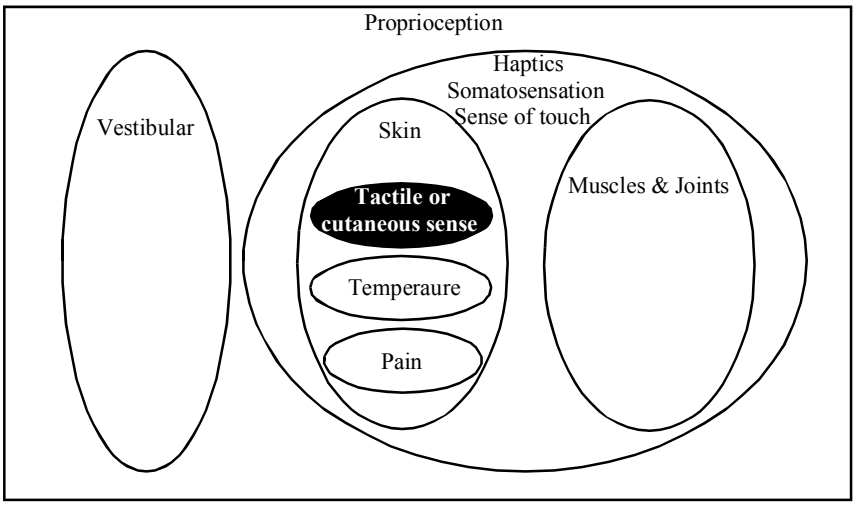

Figure 1.6: The Working Definitions of the Tactile Sense in Relation to Other Systems Used Throughout This Report.

1.4.2 The Remainder of This Report

The report is organised as follows. Chapter 2 provides a more detailed introduction of the sense of touch and its neurophysiological and psychophysical aspects. Chapter 3 presents detailed information on human factors issues and perceptual aspects relevant for military applications. Chapter 4 is focussed on (available) hardware and Chapter 5 details known hardware and system integration issues. Chapter 6 gives an overview of relevant applied research studies completed in this area, and Chapter 7 suggests future research topics.

1.5 REFERENCES

[1] Van Erp, J.B.F. and Werkhoven, P. (2006). Validation of Principles for Tactile Navigation Displays. in Human Factors and Ergonomics Society. San Francisco, CA.

[2] Van Erp, J.B.F., Carter, J. and Andrew, I. (2006). ISO's Work on Tactile and Haptic Interaction Guidelines. in Proceedings of Eurohaptics 2006. Paris.

[3] Benson, A. (2002). Technical Evaluation Report. in Spatial disorientation in military vehicles: causes, consequences and cures. La Coruna, Spain: NATO.

[4] Van Erp, J.B.F., Groen, E.L., Bos, J.E. and Van Veen, H.A.H.C. (2006). A Tactile Cockpit Instrument Supports the Control of Self-Motion During Spatial Disorientation. Human Factors. 48(2): p. 219-228.

[5] Van Erp, J.B.F. and Van Veen, H.A.H.C. (2006). Touch down: The effect of artificial touch cues on orientation of microgravity. NeuroScience Letters. 404: p. 78-82.

[6] Ercoline, W.R., et al. (2000). Post-roll effects on attitude perception: The Gillingham illusion. Aviation, Space, and Environmental Medicine. 71(5): p. 489-495.

[7] Braithwaite, M., et al. (1998). Spatial disorientation in U.S. Army rotary-wing operations. Aviation, Space, and Environmental Medicine. 69: p. 1031-1037.

[8] Braithwaite, M., Groh, S. and Alvarez, E. (997). Spatial Disorientation in US Army Helicopter Accidents: An Update of the 1987-92 Survey to include 1993-95. US Army Aeromedical Research Laboratory: Fort Rucker, Alabama.

[9] McGrath, B.J., Gierber, G. and Rupert, A.H. (2005). Spatial Disorientation in Naval Aviation Mishaps. in Aerospace Medical Association Meeting. Kansas City, KA.

[10] Adams, D., McGrath, B.J. and Rupert, A.H. (2007). Tactile Situation Awareness System; H-60 Cost Benefit Analysis (submitted). NAMRL: Pensacola, FL.

[11] European Commission, Commission recommendation of 21 December 1999 on safe and efficient in vehicle information and communication systems: a European statement of principles on human machine interface. Recommendation 2000/53/EC, European commission, Brussels. 2000.

[12] ISO, Human-centred design processes for interactive systems. (1999). International Standards Organisation.

[13] Spence, C. and Driver, J. (1997). Cross-modal links in attention between audition, vision, and touch: Implications for interface design. International Journal of Cognitive Ergonomics. 1(4): p. 351-373.

[14] Parkes, A. and Coleman, N. (1990). Route guidance systems: A comparison of methods of presenting directional information to the driver., in Ergonomics – setting standards for the '90's, E. Lovesey, Editor. Taylor & Francis: London. p. 480-485.

[15] Streeter, L.A., Vitello, D. and Wonsiewicz, S. (1986). How to tell people where to go: comparing navigational aids. International Journal of Man-Machine Interaction. 22: p. 549-562.

[16] Forbes, T. (1946). Auditory signals for instrument flying. Journal of Aeronautical Science. 13: p. 255-258.

[17] Wickens, C.D. (1992). Engineering psychology and human performance. New York: Harper Collins.

[18] Rupert, A.H., Guedry, F.E. and Reschke, M. (1993). The use of tactile interface to convey position and motion perceptions. in NATO Advisory Group for Aerospace Research and Development. Lisbon.

[19] Sklar, A.E. and Sarter, N.B. (1999). Good vibrations: tactile feedback in support of attention allocation and human-automation coordination in event-driven domains. Human Factors. 41(4): p. 543-552.

[20] Fenton, R. (1966). An improved man-machine interface for the driver-vehicle system. IEEE Transactions on Human Factors in Electronics. HFE-7(4): p. 150-157.

[21] Gilson, R. and Fenton, R. (1974). Kinesthetic-tactual information presentations-Inflight studies. IEEE Transactions on Systems, Man, and Cybernetics. SMC-4(6): p. 531-535.

[22] Van Erp, J.B.F. and van Veen, H.A.H.C. (2004). Vibrotactile in-vehicle navigation system. Transportation Research Part F -. Traffic Psychology and Behaviour. 7(4-5): p. 247-256.

[23] Browse, R. and McDonald, M. (1992). Using tactile information in telerobotics. IEEE Transactions on Systems, Man, and Cybernetics. 22(5): p. 1205-1210.

[24] Massimino, M. and Sheridan. T.B. (1992). Sensory substitution for force feedback in teleoperation. in 5th IFAC Symposium on Analysis, Design, and Evaluation of Man-Machine Systems. The Hague, The Netherlands.

[25] Van Erp, J.B.F. (2001). Tactile displays in virtual environments, in What is essential for virtual reality systems to meet military performance goals? RTO NATO: Neuilly-sur-Seine, France.

[26] Carsten, O., and Nilsson, L. (2001). Safety assessment of driver assistance systems. European Journal of Transport and Infrastructure Research. 1: p. 225-244.

[27] ECMT. Statement of principles of good practice concerning the ergonomics and safety of in-vehicle information systems. In New Information Technologies in the Road Transport Sector: Policy Issues, Ergonomics and Safety. in The European Conference of Ministers of Transport. 1995.

[28] Rumar, K. (1990). The basic driver error: late detection. Ergonomics. 33: p. 1281-1290.

[29] Dobbins, T. (2002). The use of tactile navigation cues in high-speed craft operations. in Royal Institute of Naval Architects; High Speed Craft: Technologies and Operation. London.

[30] Van Erp, J.B.F., van Veen, H.A.H.C., Jansen, C. and Dobbins, T. (2005). Waypoint Navigation with a Vibrotactile Waist Belt. Transactions on Applied Perception. 2(2): p. 106-117.

[31] Chiasson, J., McGrath, B.J. and Rupert, A.H. (2002). Enhanced situational awareness in sea, air and land environments. in NATO RTO symposium on spatial disorientation in military vehicles: causes, consequences and cures. La Coruna, Spain.

[32] Samways, S. (2005). Diver trials of a tactile information display. Portsmouth, UK.

[33] Carlander, O. and Eriksson, L. (2006). Uni- and Bimodal Threat Cueing with Vibrotactile and 3D Audio Technologies in a Combat Vehicle. in Proceedings of the HFES 50th Annual Meeting. San Francisco, CA: Human Factors and Ergonomics Society.

[34] Redden, E.S. (2006). Findings from a multi-year investigation of tactile and Multi-modal displays. In Human Factors and Ergonomics Society. San Francisco, CA.

[35] Merlo, J., et al. (2006). The effects of physiological stress on tactile communication. In Human Factors and Ergonomics Society. San Francisco, CA.

[36] McCarley, J.S. and Wickens, C.D. (2005). Human factors implications of UAVs in the national airspace. University of Illinois, Aviation Human Factors Division: Savoy, IL.

[37] Van Erp, J.B.F. (1998). Trade-offs between spatial and temporal resolution on driving an unmanned ground vehicle. in Human Factors and Ergonomics Society. Chicago Illinois.

[38] Van Erp, J.B.F., Kappé, B. and Korteling, J.E. (1996). Visual Support in Operating Unmanned Aerial Vehicles. in XV European Annual Conference on Human Decision Making and Manual Control. Delft, The Netherlands.

[39] NATO, Executive Summary, in Unmanned Military Vehicles (UMVs): Human Factors issues in augmenting the force. 2006.

[40] Van Erp, J.B.F. (2006). Tactile Displays: Spin-off From the Military Cockpit to Uninhabited Vehicles. in NATO HFM Symposium “Human Factors of Uninhabited Military Vehicles as Force Multipliers”. Biarritz, France.

[41] Li, Z., Chui, C. and Anderson, J.H. (2001). Computer environment for interventional neuroradiology procedures. Simulation & Gaming. 32(3): p. 404-419.

[42] Gerling, G. and Thomas, G. (2005). Augmented, Pulsating Tactile Feedback Facilitates Simulator Training of Clinical Breast Examinations. Human Factors. 47(3): p. 670-681.

[43] Bach-Y-Rita, P. (1970). Neurophysiological basis of a tactile visuo-substitution system. IEEE Transactions on Man-Machine Systems. MMS-11: p. 108-109.

[44] Bliss, J.C., Katcher, M.H., Rogers, C.H. and Shepard, R.P. (1970). Optical-to-Tactile image conversion for the blind. IEEE Transactions on Man-Machine Systems. 11(1): p. 58-64.

[45] Sherrick, C.E. (1984). Basic and applied research on tactile aids for deaf people: Progress and prospects. Journal of Acoustical Society of America. 75(5): p. 1325-1342.

[46] Gault, R. (1927). Hearing through the sense organs of touch and vibration. Journal of Franklin Institute. 204: p. 329-358.

[47] Békésy, G.V. (1955). Human skin perception of travelling waves similar to those on the cochlea. J Acoust Soc Am. 27: p. 830-841.

[48] Brooks, P. and Frost, B. (1983). Evaluation of a tactile vocoder for word recognition. Journal of the Acoustical Society of America. 74: p. 34-39.

[49] Engelmann, S. and Rosov, R. (1975). Tactual hearing experiment with deaf and hearing subjects. Journal of exceptional children. 41: p. 245-253.

[50] Saunders, F.A. (1974). Electrocutaneous displays, in Cutaneous communication system and devices, F.A. Geldard, Editor. Psychonomic Society: Austin Texas. p. 20-26.

[51] Sparks, D.W., et al. (1978). Investigating the MESA (Multipoint Electrotactile Speech Aid): The transmission of segmental feature of speech. Journal of Acoustical Society of America. 63: p. 246-257.

[52] Craig, J.C. and Sherrick, C.E. (1982). Dynamic tactile displays, in Tactual perception: A sourcebook, W. Schiff and E. Foulke, Editors. Cambridge University Press: Cambridge, England. p. 209-223.

[53] Robbins, A., Hesketh, L.J. and Bivins, C. (1993). Tactaid 7 reference guide and orientation. Somerville, MA: Audiological Engineering Corp.

[54] Weisenberger, J.M. and Percy, M.E. (1995). The transmission pf phoneme-level information by multichannel tactile speech perception aid. Ear and Hearing. 16: p. 392-406.

[55] Sparks, D.W., et al. (1979). Investigating the MESA (Multipoint Electrotactile Speech Aid): The transmission of connected discourse. Journal of Acoustical Society of America. 65: p. 810-815.

[56] Collins, C. and Madey, J. (1974). Tactile sensory replacement. in San Diego Biomedical Symposium. San Diego, CA.

[57] de Castro, M. and Cliquet, A. (2000). Artificial Sensorimotor Integration in Spinal Chord injured Subjects Through Neuromuscular and Electrotactile Stimulation. Artificial Organs. 24(9): p. 710-717.

[58] Tupper, C. and Gerhard, G.C. (1989). Dynamic tracking delays using high resolution electro-tactile feedback. in International Conference of the IEEE Engineering in Medicine and Biology Society.

[59] Schmidt, P.B., et al. (1999). An evaluation of a single-axis balance prosthesis prototype with normal subjects. in Mid-Winter Meeting Assoc Res Otolaryngol. Tampa Bay, FL.

[60] Kadkade, P.P., et al. (1999). Optimizing vibrotactile cues for application to a balance prosthesis. In Mid-Winter Meeting Assoc Res Otolaryngol. Tampa Bay, FL.

[61] Ballard, J.W. (1954). Human-engineered electromechanical tactual sensory control system. Electrical Manufacturing. 54: p. 118-121.

[62] Hirsch, J. (1961). Apparatus and method for communication through the sense of touch. U.S.

[63] Morag, M. (1987). Information display system. U.S.

[64] Gilliland, R.D. and Schlegel, R.E. (1994). Tactile stimulation of the human head for information display. Human Factors. 36(4): p. 700-717.

[65] Zlotnik, M.A. (1988). Applying electro-tactile display technology to fighter aircraft – flying with feeling again. IEEE 1988 National Aerospace and Electronics Conference. Dayton, OH.