Chapter 6 – APPLIED RESEARCH REVIEW/LESSONS LEARNED

by

W. Ercoline and A. McKinley

6.1 INTRODUCTION

This chapter briefly summarizes past and current applied research with an emphasis on lessons learned. It is not intended to cover the entire database of published research articles. The taxonomy for this chapter organizes the information into the four basic topics of Air, Land, Sea, and Other.

6.2 AIR

The intricate dynamics and high speed of the modern manned flight environment can provide conflicting cues to the pilot's vestibular system regarding his/her true position in reference to the ground in the absence of out-the-window visual cues. These conflicts are often referred to as spatial disorientation and have contributed to many mishaps (see Chapter 1). Often these illusions are most prominent when the accelerations of the aircraft occur below the threshold of perception of the pilot. Tactile displays provide a method of providing orientation cues during such instances thereby mitigating the debilitating effects of the illusion. Additionally, tactile cues may be used to provide targeting location, which may reduce demands on the visual system [1].

6.2.1 Fixed-Wing Manned Aircraft

6.2.1.1 Self-Motion During Spatial Disorientation [2]

Summary: van Erp et al. investigated the effectiveness of a tactile torso display as a countermeasure to spatial disorientation (SD), and whether the display should follow an inside-out or an outside-in coding. Twenty-four subjects participated, 12 in each coding group, matched for age and gender. The researchers used a rotating chair to induce SD by spinning subjects about their yaw axis followed by a sudden stop. During the ensuing recovery phase, a random disturbance signal was added to the chair's orientation. Subjects actively controlled their orientation and were instructed to maintain a stable orientation. Statistical analyses revealed that recovery from SD was improved with support of the tactile instrument ($p < .001$, mean number of spins reduced from 8 to less than 1), but that tracking performance was reduced ($p < .001$, mean correlation between error and control signal reduced from –.87 to –.80). The effects were the same whether the instrument was available full time or during the recovery phase only. There were no differences between outside-in and inside-out coding. The present study demonstrates the potential of tactile cockpit instruments in limiting SD, even in the presence of strong, but misleading self-motion information from the vestibular sense.

Lessons Learned: There appears to be no apparent difference in performance utilizing outside-in or inside-out tactile symbology. Evidence suggests that the subject performs equally well with either method of coding given that the proper training has been accomplished. It is also important to note that prior experience may influence the preference of the individual. Hence, prior experience with inside-out visual displays may yield a greater preference for inside-out tactile displays.

6.2.1.2 T-34 Tactile Situational Awareness System (TSAS) Project

The T-34 TSAS project integrated a tactile display into a T-34 aircraft [3, 4]. A 7-event test operation was conducted to demonstrate that a pilot could maintain aircraft orientation using a tactile display during

flying operations. One United States Navy (USN) test pilot was selected to fly the flight events. Objectives of the T-34 TSAS flight demonstration (see Figure 6.1) program were to show:

- That a significant amount of orientation and awareness information can be intuitively provided continuously by the under-utilized sense of touch; and
- The use of the TSAS display to show that a pilot, with *no visual cues*, can effectively maintain effective control of the aircraft in normal and acrobatic flight conditions.

Figure 6.1: A T-34 Equipped with a Tactile Situation Awareness System during a Flight Demonstration Project.

Summary results showed that roll and pitch tactile cues could be provided via a matrix array of vibrotactors incorporated into a Tactor Locator System (TLS), a variant of the TSAS. The TLS was a torso harness of cotton and fire retardant NOMEX with elastic and velcro straps that was worn underneath the flight suit. The TLS positioned the 20 electro-mechanical tactors on the torso as an array of 4 columns of 5 tactors located 90 degrees apart on the front, left, back, and right of the test pilot. The test pilot in the rear seat was shrouded to block any outside visual cues and all flight instruments in the rear cockpit were removed. The test pilot flew the following maneuvers: straight and level for 5 minutes; climbing and descending turns; unusual attitude recovery; loops; aileron rolls; and ground controlled approaches (GCA). The test pilot successfully performed all maneuvers without visual cues, relying solely on tactile cues for attitude information.

For this flight demonstration, two different “tactile pages” were developed using variations of tactor stimulus selected from intensity and location. The first tactor page was used for fine control of the aircraft, and the second program was used for acrobatic control. The first or “fine” page had a pitch and roll range of +/- 40 degrees and used only 3 tactors per column, while the second or “acrobatic” page had a pitch and roll range of +/- 180 degrees and used 5 tactors per column. Flight performance showed that it was more intuitive and easier to distinguish between a low, middle and high tactor. As a result, during non-acrobatic maneuvers, improved performance was noted using the fine page as compared to using the 5 tactor acrobatic page. Only the acrobatic control program could be used for the acrobatic maneuvers. These results indicate that the tactile display should provide information optimized for a particular flight regime, and that the test pilot could distinguish between fine and acrobatic tactor “pages”.

Lessons Learned: This flight demonstration provided evidence that tactile displays can be utilized to intuitively provide orientation information through the somatic modality. It also demonstrated that the information provided through the tactile display allows the pilot to maintain control of the aircraft during both straight and complex maneuvers with no visual cues. However, as the flight demonstration utilized a limited number of pilots and aircraft, further investigation is warranted to ensure the intuitiveness of the

tactile displays across a general pilot population. In addition, the use of TSAS in aircraft with higher performance characteristics should be assessed.

6.2.2 Rotary-Wing Manned Aircraft

6.2.2.1 Cockpit Instrument to Support Altitude Control [5]

Summary: van Erp et al. tested the effect of a tactile torso display on maintaining an instructed altitude during low level flight. The tactile instrument consisted of 64 vibrating elements attached to the torso, shoulders and thighs of the pilot. In a helicopter simulator, 12 student pilots flew under different visual (full vision and night vision) and tactile conditions (none, a simple version, and a complex version). The simple version of the tactile display presented the direction of the desired altitude. The complex version added the current motion direction. The participants performed an additional cognitive task during half of each scenario. Performance and subjective mental effort ratings were analyzed. The results showed that the tactile instrument halved the altitude error without affecting the mental effort rating. This effect was present in full vision and in night vision conditions. There were no differences between the two versions of the tactile instrument. The authors concluded that this emerging technology is a powerful support in a low-level flight without increasing the pilot's mental workload.

Lessons Learned: This study provides evidence that tactile displays can be used in both simplistic and complex fashions to display information to a pilot without significantly increasing mental workload. In addition, the tactile modality can serve as a vehicle for sending additional information to increase the situational awareness of the pilot. This was evidenced by the significant performance improvements.

6.2.2.2 Tactile Display and Night Vision Goggles [6]

Summary: The degraded visual information when hovering with Night Vision Goggles may induce drift that is not noticed by the pilot. Researchers at TNO tested the possibility of counteracting these effects by using a tactile torso display. The display consisted of 64 vibro-tactile elements and presented information on the desired direction of motion (simple version), and also information on the current motion direction (complex version). The participants flew in a fixed-base helicopter simulator with either full vision or simulated night vision goggles. The results showed performance improvement for both tactile display variants compared to hovering without a tactile display. This improvement was present in the NVG conditions (mean reduction of the position error of 22% in the horizontal direction and of 41% in the vertical direction), and also in the full vision condition (mean reductions of 32 and 63%, respectively). Additionally, performance with a tactile display was less affected by the introduction of a secondary (cognitive) task than performance without a tactile display. The complex variant of the tactile torso display tended to be less effective than the simple variant. It is hypothesized that this effect may be due to "*tactile clutter*". This simulator study proves the potential of intuitive tactile torso displays in reducing drift during hover.

Lessons Learned: The evidence provided by this study indicates that information can be effectively communicated through surrogate sensory modalities (e.g., tactile) without increasing attentional or cognitive demands. Provided with a simple, intuitive tactile display, subjects can maintain helicopter hover, regardless of the prevalence and salience of the visual cues. However, the issue of "tactile clutter" can nullify or attenuate the benefits of the tactile display; thus the design and implementation of the system become critical considerations.

6.2.2.3 The Role of Intelligent Software in Spatial Awareness Displays [7]

Summary: This series of flight demonstrations was aimed at assessing the Tactile Situation Awareness System (TSAS) in a variety of aircraft and situations. Specifically, TSAS was utilized in an effort to

provide aircraft state information to the pilot and reduce their visual workload; its usefulness in the absence of visual cues was also assessed.

6.2.2.3.1 UH-60 TSAS Programme

The UH-60 TSAS flight demonstration project was a follow-on effort to the fixed-wing T-34 TSAS flight demonstration and integrated the tactile display into a UH-60 helicopter. A 9-event test operation was conducted to demonstrate that a rotary wing pilot could receive aircraft orientation and performance information using a tactile display during flying operations. Three US Army (USA) pilots were selected to perform the flight events. Objectives of the UH-60 TSAS flight demonstration program were to demonstrate:

- That a significant amount of orientation and awareness information can be intuitively provided continuously by the under-utilized sense of touch; and
- The use of the TSAS display to show that a pilot, with *no visual cues*, can effectively maintain control of a helicopter in the complex rotary wing environment.

The flight demonstrations showed that controlled flight maneuvers in a rotary wing aircraft using tactile information were possible. Roll and pitch tactile cues were provided via a matrix array of vibrotactors incorporated into a torso harness as used for the T-34 effort. Additionally, airspeed and heading error tactile cues were provided by tactors located on the arms and legs, respectively. The blindfolded test pilot in the right seat had no visual cues. The test pilots flew the following maneuvers: straight and level; standard rate turns; unusual attitude recovery and ground controlled approaches. The test pilots were able to successfully perform all maneuvers without visual cues, relying solely on tactile cues for the necessary attitude and performance information.

The auxiliary tactile cues from the torso caused some difficulties. Heading control remained problematic during the demonstration as pilots had some difficulties picking up the heading error signal when the other pitch and roll channels were active. This suggests that keeping the heading tactors off until the pilot approached straight and level flight would improve the ability to return to a base course following unusual attitude recovery.

Lessons Learned: This follow-on flight test illustrated the potential for utilizing tactile displays in rotary-wing applications. Available evidence indicates that the tactile cues can be sensed despite the high-vibration environment created by the revolving rotors. In addition, it was learned that providing multiple cues simultaneously can become problematic due to the fact that the stimuli were similar. This presents a recondite situation where tactile cues may overlap and provide rather confusing signals. A better approach may be to provide only one type of information at a time depending on the needs of the pilot.

6.2.2.3.2 JSF / UH-60 TSAS Programme

The Joint Strike Fighter (JSF)/UH-60 Tactile Situation Awareness System (TSAS) flight demonstration project [8] was a short-duration technology maturation and flight demonstration program funded by the JSF Program Office. The JSF-TSAS project integrated a tactile display, F-22 cooling vest, and GPS/INS technologies into a UH-60 Helicopter (Figure 6.2). A 10-event test operation was conducted to demonstrate the utility of this advanced human-machine interface for performing hover operations. Four test pilots were selected to perform the flight events.

Figure 6.2: TSAS Equipped UH-60.

Objectives of the JSF-TSAS flight demonstration program were to demonstrate:

- The potential for TSAS technology to reduce pilot workload and enhance situation awareness (SA) during hover and transition to forward flight; and
- The use of the TSAS display to show that pilots, with no outside visual cues, can effectively hover and transition to forward flight in a vertical lift aircraft.

Summary results showed that TSAS technologies increase pilot SA and reduce pilot workload when using the tactile display, especially during simulated shipboard operations in Instrument Meteorological Conditions (IMC). Prototype hardware development showed that tactile display could be integrated into existing flight gear (Figure 6.3). The test pilots successfully performed all maneuvers with degraded outside visual cues, relying on tactile cues for the necessary information. Using TSAS, pilots demonstrated improved control of aircraft during complex flight conditions. The tactile display reduced pilot workload and provided the opportunity to devote more time to other instruments and systems when flying in task saturated conditions. These effects can potentially increase mission effectiveness. One US Army test pilot commented that “in IMC, the TSAS vest could be the difference between mission success and a mishap.”

Figure 6.3: TSAS Experiment Pilot Showing TSAS Tactor Locator System.

The awareness of aircraft velocity over the ground or “drift” without looking at a visual instrument was the biggest advantage of the JSF-TSAS. The maintenance of SA during hovering in reduced visual conditions was enhanced. Overall, TSAS decreased pilot workload and enhanced SA.

Lessons Learned: The TSAS flight tests were able to demonstrate that a pilot can maintain control of an aircraft using tactile cues and that a tactile display can reduce workload and enhance SA. However, the following issues need to be addressed:

- *The need for improved tactors*. The prototype tactors used in the flight demonstrations could only be turned on and off. The amplitude, frequency, and stimulus type (vibration, stroking) could not be controlled in the prototype system. This is analogous to a black and white vs. a color visual display. A "richer" tactile sensation that could convey compound information can be achieved with improved tactors.
- *Incorporating the absolute minimum number of tactors into existing flight gear*. Today's aviator is asked to wear an ever-increasing amount of equipment. A tactile display that has a minimum number of tactors while still providing the necessary information will be lighter, more robust, and easier to maintain than a tactile display with a large number of tactors.
- *Keeping the tactile display intuitive and easy to understand.* If the user must spend extra time cognitively processing the displays, then many of the advantages of using this modality is lost. It is also important to avoid tactile clutter and overly complex tactile coding.

6.2.2.4 Canadian Helicopter Test [9, 10]

Summary: This study investigated the effectiveness of the Tactile Situational Awareness System (TSAS) in maintaining position during a high hover maneuver and a simulated shipboard-landing maneuver in both good and degraded visual environments (see Figure 6.4). Objective flight performance and subjective evaluation of situational awareness (SA), workload and self-performance evaluation were measured. Results show that providing a combination of position and velocity signals enhanced pilot performance, eliminated low frequency drift problems, improved situational awareness, and did not increase pilot workload. In general, information based on tactile cueing is effective in reducing hover position error in the axis where the cues are presented. During high hover in degraded visual environments, the use of TSAS cues resulted in performance improvements of 59% in horizontal positioning accuracy and 67% in vertical positioning accuracy. During shipboard landing maneuvers, pilot performance was significantly better with TSAS than without TSAS. Furthermore, the provision of horizontal information via the TSAS appeared to enhance performance in the vertical axis as well. The mechanisms leading to this improvement demand further investigation.

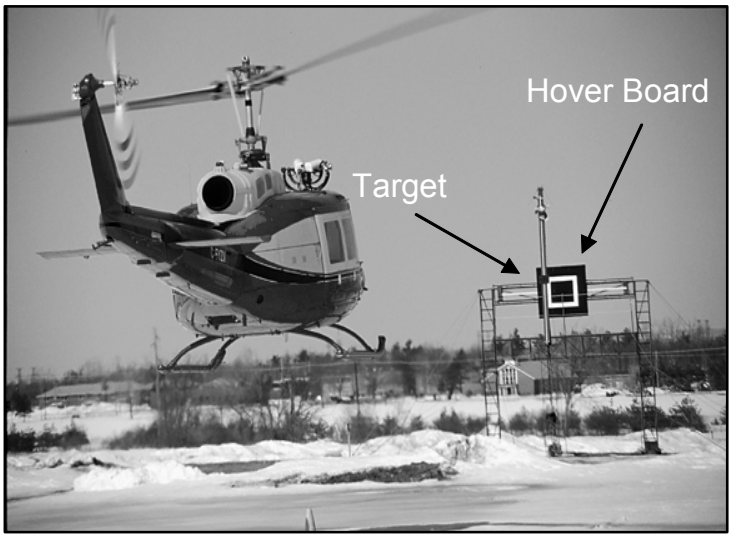

Figure 6.4: TSAS Equipped Helicopter Performing Hover Task.

The TSAS is a valuable and effective tool in improving pilot performance during precision hover maneuvers and during visually saturated tasks, particularly during degraded visual environments. With minimal training, pilots were able to reduce their RMS position error in horizontal, vertical, and lateral axes, depending on the maneuver. This performance improvement was accompanied by a concurrent improvement in subjective situational awareness ratings and subjective performance ratings. A corresponding increase in subjective workload rating is notably absent.

Aircrew members unanimously agreed TSAS was effective, reduced workload, and improved SA. One of the most promising uses for TSAS involves missile warning/tracking cues combined with terrain following (TF) climb/dive inputs. The TSAS vest provided excellent threat SA to the crew by using variable frequency directional inputs. Combined with vertical cueing from the TF radar, missile warning cues gave the crew SA on the threat as well as terrain awareness.

Lesson Learned: The TSAS improves aircrew SA, reduces aircrew workload, and demonstrates potential suitability for the Air Force Special Operations Command (AFSOC) mission. The prototype TSAS, in its conception phase, is not operationally suitable for the AFSOC mission. However, with further refinement and continued testing, it can become an effective aircrew aid during critical phases of flight. Quantitative data recorded during flight and simulator sessions showed hover performance, measured as drift velocity, improved with TSAS usage.

6.2.3 Unmanned Aerial Vehicles

As the Air Force moves toward the future there will be a greater utilization of unmanned aerial vehicles (UAVs) to support the full spectrum of missions. Pilots of UAVs are faced with the difficult task of controlling the aircraft from a remote ground control station. Feedback from the UAV operating station is vital for pilots to effectively control the UAV. Many current UAV ground control stations include a monitor that shows the pilot a map and a second monitor that displays a nose camera view combined with a heads-up display (HUD). Since operators control the UAV from a ground control station that is remote from the actual aircraft, the pilot is not provided with the normal auditory, vestibular, and proprioceptive feedback they would receive in the actual aircraft. There is a larger mishap occurrence in UAVs than in manned aircraft, which may be in part due to the “out of cockpit” experience while piloting them. UAVs have on average 141 mishaps per 100,000 flight hours, while manned aircraft have one mishap per 100,000 flight hours. Twenty-two percent of these mishaps occur during the landing phase of UAV operation [11]. Tactile feedback may be a method to reduce the demand on a UAV pilot’s visual load and provide the kind of feedback needed to effectively operate the UAV in all phases of its mission.

6.2.3.1 Effect of Tactile Feedback on Unmanned Aerial Vehicle Landings [12]

The purpose of this study was to assess the potential for a vibrotactile vest to provide tactile feedback to UAV pilots during landing. All tests were performed on a UAV synthetic task environment (STE) simulator, which is derived from the Predator workstation. Thirty participants were recruited from United States Air Force Academy cadets in an upper-division leadership class. The subjects were divided into two groups of fifteen. The first group used the UAV simulator as it is currently employed with no tactile vest. The second group used the UAV simulator while also using the tactile vest. The learning performance of each group was examined by measuring the number of trials required to obtain a passing landing score for the initial condition each participant is assigned. After obtaining a passing score, the participant switched to the other condition (vest or no vest) and completed an additional three trials. The root mean square (RMS) error from an optimal flight path was used to analyze the impact of initial training with and without the tactile vest. The results are displayed in Table 6.1 below.

Table 6.1: Overall Performance Results of Participants by Condition (Mean ± SD)

	Vest	No Vest
# of Trials to Obtain Passing Score	3.53 ± 1.41[a]	7.13 ± 2.72[b]
Glideslope RMS Error	38.57 ± 12.18[a]	54.53 ± 23.82[b]
Post-trial Glideslope RMS Error (three trials)	31.04 ± 10.40[b]	25.82 ± 10.49[a]

[a]Group 2: Wore vest first, then no vest [b]Group 1: No vest first, then vest.

Lessons Learned: The performance of the vest condition significantly outperformed that of the no-vest condition in number of trials until the landing task was successfully completed. This supports the possibility that tactile feedback can be used in training novice pilots to fly UAVs, and that tactile cues may be useful for operational UAV pilots.

6.3 LAND

Soldiers have specific and sometimes unique requirements for operation and often operate in extremely demanding physical environments. Information systems may demand visual attention and can occupy the soldier's hands to carry the display. Soldiers may therefore be particularly interested in the hands-free, eyes-free, and mind-free aspects 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. Soldiers in tanks or other ground moving vehicles must often operate in extreme noise and high vibration and also need to focus their visual attention on the outside world. Here also, tactile displays may improve information transfer.

6.3.1 Navigation [13]

Summary: Presenting waypoint navigation on a visual display is not suited for all situations. The present experiments investigate if it is feasible to present navigation information on a tactile display. An important design issue of the display is how direction and distance information must be coded. Important usability issues are the resolution of the display and its usefulness in vibrating environments. In a pilot study with 12 pedestrians, different distance-coding schemes were compared. The schemes translated distance to vibration rhythm while the direction was translated into vibration location. The display consisted of eight tactors around the user's waist.

Lessons Learned: The results show that mapping waypoint direction on the location of vibration is an effective coding scheme that requires no training, but that coding for distance does not improve performance compared to the control condition with no distance information.

6.3.2 Vehicle Navigation [14]

Summary: A vibrotactile display, consisting of eight tactors mounted in a driver's seat, was tested in a driving simulator. Participants drove with visual, tactile and multimodal navigation displays through a built-up area. The time to react to navigation messages and the workload were measured for normal and high workload conditions. The results demonstrated that the tactile navigation display reduces the driver's workload compared to the visual display, particularly in the high workload group. The fastest reaction was found with the multimodal display.

Lessons Learned: This study quantitatively supports the claims that a localized vibration or tap is an intuitive way to present direction information, and that employing the tactile channel may release other heavily loaded sensory channels, therefore potentially providing a major safety enhancement.

6.3.3 Land Navigation [15]

Summary: TNO Netherlands developed a wearable system to allow land waypoint navigation, designated as the Personal Tactile Navigation system (PTN) [16]. Eight tactors are equally spaced on a torso belt connected to a digital compass and GPS system. Waypoints can be programmed into the system and the wearer is then guided to each of these positions through tactor-based guidance. This provides the individual with critical directional information without having to consult the usual visual-based navigation systems (e.g., compass, GPS devices). The PTN was evaluated, along with other navigation systems, by US Army Infantry soldiers in a collaborative effort between TNO Netherlands and the US Army Research Laboratory [17]. Other systems included traditional map and compass, the current operational Army GPS device (analogue display), and the prototype head-mounted map display in the Army Land Warrior system. Experimental field evaluations in operationally realistic and demanding multi-task scenarios enabled assessment of each navigation system for many performance indices, including waypoint achievement, navigation time, deviation from route, avoidance of terrain obstacles, and avoidance of off-limits areas. Performance on secondary tasks such as response to radio communications and detection of targets was also assessed, and soldier-based evaluations were collected. Soldiers achieved 100% of the waypoints with the PTN in daytime and also in night operations, and tended to detect more targets and/or move more quickly.

Lessons Learned: Soldiers indicated high levels of approval for the PTN system, particularly for aspects such as ease of use. The majority of soldiers preferred the PTN system first, and the head-mounted visual map display second. The head-mounted visual map display was rated higher than other systems for providing location information. Comments emphasized that the PTN system was “hands-free, eyes-free, and mind-free,” thus freeing the soldier to move with their weapon at the ready with their attention focused on terrain and enemy threats.

6.3.4 Army Platoon Leader Decision Making [16 – 18]

Summary: This study investigated effects of visual, audio, and tactile alerts on command decision-making of a Platoon Leader (PL) during a computer-based simulation of a mounted attack mission. An Army infantry command and control research platform (AEDGE- Agent Enabled Decision Group Environment) presented each PL with three equivalent scenarios. In one condition, cues regarding level of importance of incoming information and direction of threat were presented through a visual icon (red flashing symbol). In the second and third conditions, cues were audio (beeping noise) and tactile (arm-mounted tactors), respectively. Multi-modal conditions (visual and audio; visual and tactile) were also investigated.

Lesson Learned: Results indicated that audio and tactile cues were more effective than visual cues, particularly in reducing time to respond; the PLs could be alerted effectively without having to constantly monitor the screen for visual alerts. PLs reported that tactile cues were less annoying and therefore more manageable.

6.3.5 Tactile Support of Shooting Performance in Computer-Based Army Simulation [16 – 19]

Summary: This study investigated effects of tactile, visual, and auditory cues about threat location on target acquisition and attention to visual and auditory communications. Army soldiers participated in computer-based shooting simulations, where the task was to search and shoot hostile targets on the

computer screen. Alerts were provided in the form of visual icon (clock display) that matched the targeting control dial, spatial language (audio speech indicated by "target at one o'clock", etc.), and 3D audio and tactile alerts from tactors on a torso belt. All cues provided location information on each target. The visual icon produced the fastest and most accurate response.

Lessons Learned: The favourable result for the visual display may be due to congruence between icon and task (e.g., the shooter is always looking at the screen, and the icon is thus easy to see). Also, in the test setup used, there was no visual load; soldiers were allowed to look at the visual display and had no other visual task than to detect the target.

6.3.6 Auditory and Tactile Threat Cueing in Combat Vehicle 90 [20, 21]

Summary: This experiment investigated the performance of 3D audio and vibrotactile technologies to indicate horizontal directions of threats to the driver of the light armored tank Combat Vehicle 90 (CV 90) Technology Demonstrator. Delivered by the warning and countermeasure system (WCS) with an in-vehicle PC connection, threat cueing was made by either 3D audio sound in headphones or tactile vibration from a single-row of 12 tactors onto the torso, or both in combination. Ten male CV 90 drivers from the Swedish Army Combat School participated in the task, which was to determine the direction of each threat and then turn the vehicle toward it as quickly and accurately as possible. Compared with the auditory and visual threat cueing currently employed, the 3D audio and vibrotactile technologies were considered superior for immediate detection of horizontal threat directions. The drivers had an excellent overall performance in reacting to and positioning the vehicle toward threats. It was noted that the 3D audio used needs improvement with regard to front-back confusion if it is not combined with tactile cueing.

Lessons Learned: Employing 3D audio and tactile cueing could enhance the utility of not only the individually functioning CV 90 WCS but also the WCS network for a unit of CV 90s.

6.3.7 Ground Navigation Tests [22]

Summary: During ground tests, a 5-minute, 1.6 mile, 3-leg course was mapped. Each subject navigated the course using the TSAS-Special Forces (TSAS-SF) tactile display, and then using the visual display on the GPS. For this preliminary investigation, no attempt was made to minimize order effects. For additional visual tasking, a number of small objects (10 green and 10 black) were placed along the route. A count of the number of objects of each color observed on each run was taken. Preliminary data collected showed that the number of objects correctly identified was higher with TSAS-SF than with visual displays.

Lessons Learned: Preliminary results, both qualitative and quantitative, suggest that the use of the TSAS-SF for ground navigation allows the subject more "heads up" time. This "heads up" capability can improve search capability of both hostile and friendly factors. When combined with an additional visual task, tactile cues show the potential to be an effective alternative or enhancement to visual displays. The majority of subjects felt that TSAS was easier to use, provided enhanced navigation, and was preferred over the visual only display. This would be invaluable to Special Forces operators in increasing mission effectiveness.

6.4 MARITIME

The tactile display has the potential to enhance maritime operational effectiveness and safety. A number of trials have been successfully undertaken either in the maritime environment, or are such that they can be directly related to the marine environment. Many of these were highlighted by Dobbins and Samways [23] at the NATO RTO symposium on spatial disorientation. These have primarily been designed for

navigation/orientation cues, although other specific applications have been identified. The following sections highlight the results of maritime related trials, and recommend where future development work may be focused to enhance performance and safety.

6.4.1 Surface Operations

The advent of GPS navigation technology has dramatically improved the ability to navigate successfully at sea. Such systems now provide the capability to develop tactile display systems that can enhance the performance and safety of the coxswain and their craft. Navigation in poor visibility (e.g., in fog and at night) is dangerous and can be exceptionally hazardous when operating in poor sea conditions where the craft have to maneuver through large waves/swell. In these poor weather conditions, the coxswain's attention needs to be focused on multiple information sources: the sea, the required heading, the craft/engine condition, operational/tactical information, and audio communications. The tactile display has the ability to intuitively display the required craft heading while allowing the coxswain to pilot the craft safely around waves and obstacles, and attend to other tasks such as audio communications.

There are a number of examples of successful tactile navigation/orientation. These often use different methodologies to display the direction of travel or a correction to a course travelled. These display methodologies have advantages and disadvantages depending on the specific application.

6.4.1.1 The Use of a Navigation Tactile Interface System in Establishing the Blind World Water Speed Record [24]

Summary: The QinetiQ Centre for Human Sciences developed a Navigation Tactile Interface System (NTIS) that displays navigation cues through the highly intuitive sense of touch. The system was used to assist in establishing a blind world water speed record. The NTIS allowed the boat to be autonomously navigated by the blind driver between pre-determined waypoints with minimal input from a sighted passenger. The display was designed to operate as a virtual corridor so as to minimise course errors. This resulted in continual feedback to the driver and provided the ability to navigate a straight line course at high speed with no visual cues. As a result, a world record speed of 73 mph was established, which was ½ mph less than the sighted record for the make of boat used.

Lesson Learned: Navigation cues were successfully delivered to allow a blind person to drive a boat at high speed between predetermined positions. This suggests that tactile displays can provide craft heading cues to boat drivers in poor visibility conditions and at night.

6.4.1.2 The Use of Tactile Navigation Cues in High-Speed Craft Operations [25, 26]

Summary: Currently three methods of displaying directional cues have been successfully demonstrated on high speed craft. The first two are based on a two tactor system with the tactors placed on the arms, hands or torso and display a virtual corridor or a direction to the selected waypoint (refer to Figure 6.5 for a graphical representation of the systems effectiveness). This system demonstrated mean cross-track-error values of < 0.12 %.km^{-1} of the distance traveled between way-points. The third method uses a multiple tactor system where the tactors are placed in a ring around the torso [26] to provide an indication of the direction of the selected waypoint.

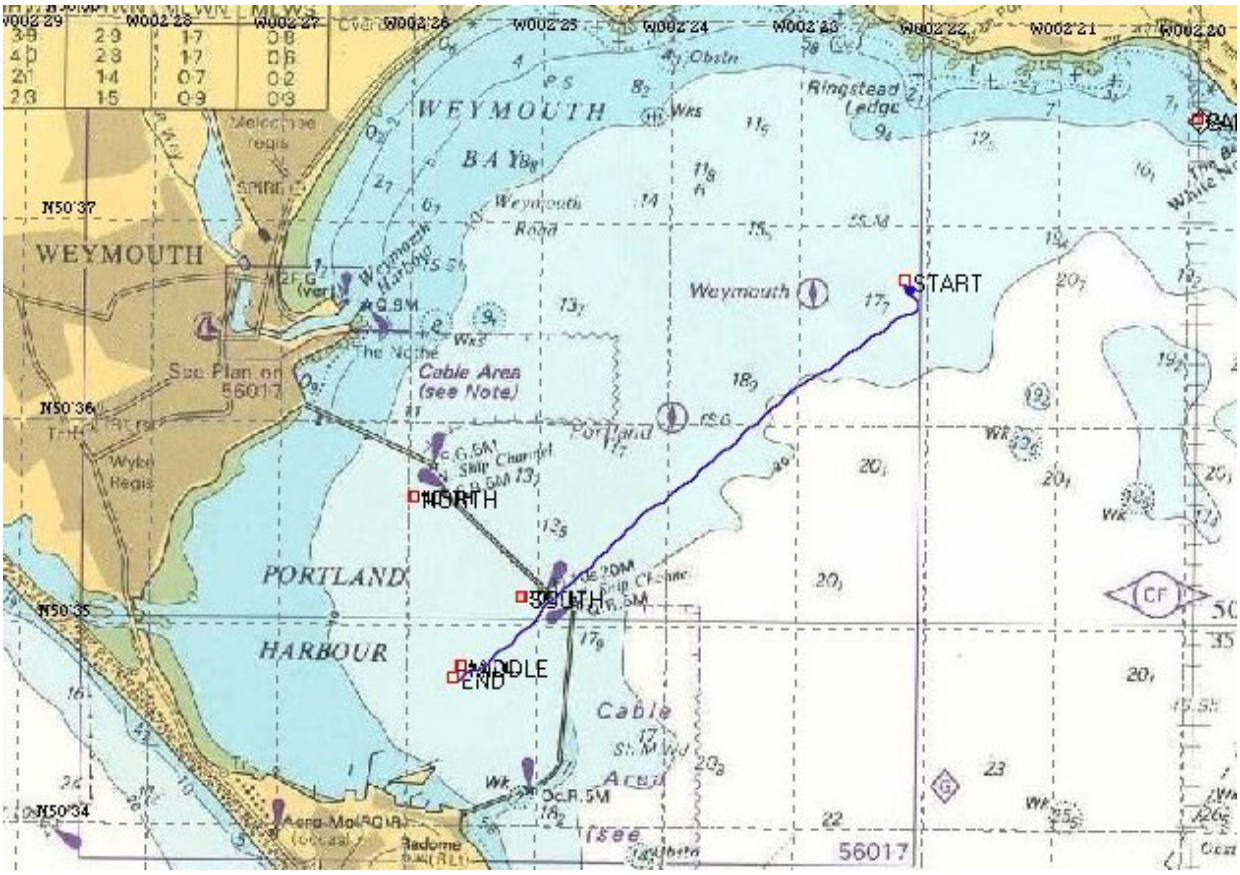

Figure 6.5: Example of Navigation Track Using a Tactile Navigation System Based on a Two Tactor Display.

Anecdotal feedback from experienced high speed craft coxswains has indicated that these tactile displays have the potential to provide intuitive direction cues. These methods of providing craft heading cues may be advantageous when the coxswain has a high cognitive workload in poor environmental conditions (e.g., elevated sea-states, poor visibility and at night). The use of the tactile display allows them to concentrate their attention on the sea and therefore not have to continually look down to obtain directional cues from a compass or chart plotter.

Lessons Learned: Tactile navigation displays have the potential to enhance both situational awareness and safety in high-speed craft operations by reducing operator workload and by providing intuitive navigation cues in adverse weather conditions.

6.4.2 Diving Operations

Humans operate in the underwater environment either as free swimming divers, submersible operators, or as Unmanned Underwater Vehicle (UUV) operators. All of these roles can result in the operator having limited situational awareness, and expose them to the risk of spatial disorientation.

The diver(s) responsible for the safe operation and navigation of small submersible vehicles (e.g., the US Navy SEAL Delivery Vehicle (SDV), refer to Figure 5.1) have to maintain an effective level of situational awareness and spatial orientation. This is achieved through the use of computerised sensor systems. Tactile displays offer an effective solution to maintaining and enhancing the performance (i.e., navigational accuracy and obstacle avoidance) of the vehicle.

It should be noted that in the underwater environment it is imperative to keep the divers equipment simple and robust because if the equipment can break – it will break. Therefore the decision to use complex electronic equipment underwater should not be taken lightly.

6.4.2.1 Enhanced Situation Awareness in Sea, Air, and Land Environments [22]

Summary: In the last few years divers have had the opportunity to utilise computerised navigation and sensor systems. As well as providing the diver with enhanced situational awareness, it has also provided the opportunity to overload the diver with information, therefore potentially compromising their performance. To determine the feasibility of using tactile navigation in an underwater environment in an attempt to offload the visual channel, a test was conducted with the Very Shallow Water (VSW) Mine Counter Measure (MCM) unit. A similar unit is displayed in Figure 6.6. Divers conducting VSW MCM operations navigated using the Swimmer Inshore Navigation System (SINS) while simultaneously monitoring mine detection sensor displays. TSAS was integrated into the SINS to provide underwater tactile navigation data. The subjects navigated a triangular course and navigation cues were provided visually via the SINS display or via tactors attached to the divers' wrists. The results demonstrated that tactile cues, utilising a virtual corridor concept, can be used to provide effective directional instructions to underwater divers and submersible operators.

Figure 6.6: The QinetiQ Driver Reconnaissance System (DRS) with the Display Screen Showing a Sonar Image.

Lesson Learned: Results of the underwater tests and subjective evaluations showed that tactile cues were an effective alternative or enhancement to visual displays. Cross track error was insignificant for both the visually-based SINS and the tactile integrated SINS. The majority of subjects felt that TSAS was easier to

use, provided enhanced navigation, and was preferred over the visual-only display. All divers indicated that operational navigation capabilities could be enhanced with tactile technology.

6.4.3 Uninhabited Marine Vehicles

The use of uninhabited vehicles (UVs) for littoral maritime applications has grown rapidly in the last few years. The design of UVs can be broken down into those which are autonomous, those which are remotely piloted, and those with a degree of autonomy. As with divers operating submersibles, operators of Unmanned Underwater Vehicles can become spatially disoriented. Tactile displays can be utilised for orientation and warning cues, which may enhance orientation by allowing the operator to concentrate on the camera/sensor display. Unmanned Surface Vehicles (USVs) are very similar to boats with enhanced auto-pilot systems. If the USV is equipped with surveillance systems that are monitored by a remote operator, a tactile display can again be utilised for the provision of orientation and warning cues. These potential tactile displays have yet to be field tested.

6.5 SPACE

6.5.1 Orientation Awareness in Microgravity [27, 28]

Summary: This study investigates if an astronaut's orientation awareness can be improved by providing a vibration on the torso that indicates the direction of 'down'. A Tactile Orientation Awareness Support Tool (TOAST) was tested in the International Space Station (ISS). A European Space Agency astronaut performed orientation tasks in different sensory conditions, such as with his/her eyes opened or closed. The main results showed that TOAST improves orientation performance. Task completion was faster, better, and easier with TOAST support, even so when visual cues were available. This case study confirmed the potential of providing orientation information by the sense of touch. Questionnaires used to assess subjective evaluation showed that the tool supported the astronaut in orientation tasks and has potential in challenging situations, but is not needed during daily operations. Although the comfort of the vest was rated as adequate, the somewhat bulky equipment of the demonstrator reduced its wearibility, and changes in body form during microgravity reduced the fit at the upper and lower ends of the vest.

Lessons Learned: Maintaining a good sense of one's orientation in a microgravity environment such as the ISS is difficult because information from the vestibular and the proprioceptive system is lacking. Tactile cues can support orientation awareness.

6.6 CONCLUSION

The experiments presented above form a large body of evidence indicating the potential of tactile displays in a diversity of military applications. Although most studies presented have been proofs-of-concept, favourable effects were found for a wide range of military operators. These include fixed and rotary wing pilots, vehicle drivers, dismounted soldiers, divers, unmanned vehicles, and even astronauts. The positive effect of tactile displays is evident, especially in circumstances of degraded vision or high workload. However, there have not been conducted extended experiments under real operational circumstances and for extended periods (i.e., weeks or months).

6.7 REFERENCES

[1] Eriksson, L., van Erp, J.B.F., Carlander, O., Levin, B., van Veen, H.A.H.C. and Veltman, H. (2006). *Vibrotactile and visual threat cueing with high G threat intercept in dynamic flight simulation. Iin Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

[2] 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.

[3] Raj, A.K., et al. (1996). *From Benchtop to Cockpit: Lessons learned from the vibrotactile orientation system prototype development and flight test program*. Aviation, Space, and Environmental Medicine. 67(A9): p. 48.

[4] Rupert, A.H., et al. (1996). *Tactile Interface to Improve Situation Awareness*. Aviation, Space, and Environmental Medicine. 67(A10): p. 53.

[5] Van Erp, J.B.F., Veltman, J.A. and Van Veen, H.A.H.C. (2003). *A tactile cockpit instrument to support altitude control. In Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting*. In *Human Factors and Ergonomics Society*. Santa Monica, Ca.

[6] Van Erp, J.B.F., Veltman, J.A., Van Veen, H.A.H.C. and Oving, A.B. (2002). *Tactile Torso Display as Countermeasure to Reduce Night Vision Goggles Induced Drift*. In *NATO RTO HFM panel symposium "Spatial disorientation in military vehicles: causes, consequences and cures"*. La Coruna, Spain.

[7] McGrath, B.J., Suri, N., Carff, R., Raj, A.K. and Rupert, A.H. (1998). *The Role of Intelligent Software in Spatial Awareness Displays*. In *3rd Annual Symposium and Exhibition on Situational Awareness in the Tactical Air Environment*, 2-3 June 1998. Piney Point, MD.

[8] McGrath, B.J., Estrada, A., Braithwaite, M.G., Raj, A.K. and Rupert, A.H. (2004). *Tactile situation awareness systems flight demonstration final report*. US Army Aeromedical Research LABORATORY Report 2004.

[9] McGrath, B., Schultz, K; Cheung, B.S., Jennings, S., Craig, G. and Rupert, A.H. (2004). *In-Flight Evaluation of TSAS during a Simulated Ship-borne Landing*, in *75th Annual Scientific Meeting of the Aerospace Medical Association*. Anchorage AK.

[10] Schultz, K., McGrath, B., Cheung, B.S., Jennings, S., Alberts, T.E. and Rupert, A.H. (2004). *In-Flight Evaluation of TSAS in High Hover*. In *75th Annual Scientific Meeting of the Aerospace Medical Association*. Anchorage AK.

[11] Tvaryanas, A.P., Thompson, B.T. and Constable, S.H. (2005). *U.S. Military unmanned aerial vehicle mishaps: Assessment of the role of human factors using Human Factor Analysis and Classification System*.

[12] Aretz, D., et al. (2006). *Effects of Tactile Feedback When Performing Flying Tasks in an Unmanned Aerial Vehicle (UAV) Simulator*. In *Interservice/Industry Training, Simulation, and Education Conference (IITSEC)*. Orlando, FL.

[13] 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.

[14] 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.

[15] Elliott, L.R., Redden, E., Pettitt, R., Carstens, C., van Erp, J. and Duistermaat, M.E.S. (2006). *Tactile guidance for land navigation. Technical Report (No. ARL-TRL-3814). Aberdeen Proving Ground, MD: Army Research Laboratory, Human Research and Engineering Directorate*.

[16] Van Erp, J.B.F. (2005b). *Presenting Directions with a Vibro-Tactile Torso Display*. Ergonomics. 48: p. 302-313.

[17] Elliott, L.R., Redden, E., Krausman, A. and Carstens, C. (2005). *Multi-modal displays to support Army Infantry Decisionmaking and performance*. In *Seventh International Conference on Naturalistic Decisionmaking, June 2005*. Amsterdam, NL.

[18] Krausman, A., Elliott, L.R., Redden, E. and Petrov, P. (2005). *Effects of Visual, Auditory, and Tactile Cues on Army Platoon Leader C3 Decision Making*, in *Paper presented at the 10th International Command and Control Research and Technology Symposium*. MacLean, VA.

[19] Glumm, M., Kehring, K. and White, T. (2006). *Effects of tactile, visual, and auditory cues about threat location on target acquisition and attention to visual and auditory communications*. Aberdeen Proving Ground, MD: Army Research Laboratory.

[20] Eriksson, L., Carlander, O., Borgvall, J., Dahlman, J. and Lif, P. (2005). Division of Command and Control Systems: Linköping, Sweden.

[21] Carlander, O. and Eriksson, L. (2006). *Vibrotactile and 3D audio cueing of horizontal directions to threats in an army combat vehicle*. In *Manuscripts in preparation for HFES 50th Annual Meeting + article with two additional experiments*.

[22] 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.

[23] Dobbins, T. and Samways, S. (2002). *The use of tactile navigation displays for the reduction of disorientation in maritime environments*. In *NATO RTO symposium on spatial disorientation in military vehicles: causes, consequences and cures*. La Coruna, Spain.

[24] Dobbins, T., et al. (2001). *The use of vibro-tactile cues in establishing the world blind water speed record*. In *36th United Kingdom Group Meeting on Human Response to Vibration*. QinetiQ, Farnborough, UK: Centre for Human Sciences.

[25] Dobbins, T. and Samways, S. (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.

[26] Van Erp, J.B.F., Jansen, C., Dobbins, T. and Van Veen, H.A.H.C. (2004). *Vibrotactile waypoint navigation at sea and in the air: two case studies*. In *Eurohaptics 2004 conference*. Munchen, Germany.

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

[28] Van Erp, J.B.F., Van Veen, H.A.H.C. and Ruijsendaal, M. (2008). *More than a feeling: bringing touch into astronauts' spatial orientation*. Microgravity Science and Technology. (In press).