Army Research Laboratory

Remote Tactile Displays for Future Soldiers

by Richard D. Gilson, Elizabeth S. Redden, and Linda R. Elliott (editors)

ARL-SR-0152 May 2007

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of Central Florida. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of Central Florida and shall not be used for advertising or product endorsement purposes.

The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, by the sponsoring agencies, the University of Central Florida, or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copy-right notation thereon.

With respect to this document, neither the United States Government nor the University of Central Florida nor any of their employees make any warranty, express or implied, including the warranties of merchantability and fitness for a particular purpose, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

DESTRUCTION NOTICE—Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5425

ARL-SR-0152 **May 2007**

Remote Tactile Displays for Future Soldiers

Richard D. Gilson
University of Central Florida

Elizabeth S. Redden and Linda R. Elliott
Human Research & Engineering Directorate, ARL

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* May 2007	**2. REPORT TYPE** Final	**3. DATES COVERED (From - To)**
4. TITLE AND SUBTITLE Remote Tactile Displays for Future Soldiers		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) (editors) Richard D. Gilson (UCF); Elizabeth S. Redden and Linda R. Elliott (both of ARL)		**5d. PROJECT NUMBER** 62716AH70
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory Human Research & Engineering Directorate Aberdeen Proving Ground, MD 21005-5425		**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-SR-0152
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		**10. SPONSOR/MONITOR'S ACRONYM(S)**
		11. SPONSOR/MONITOR'S REPORT NUMBERS

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Address correspondence to Elizabeth Redden, U.S. Army Research Laboratory, USAIC HRED Field Element, ATTN AMSRD-ARL-HR-MW, Bldg 4, Room 332, Fort Benning, GA 31905; elizabeth.redden@benning.army.mil.

14. ABSTRACT

This report is a consolidated description of past work performed to develop the University of Central Florida's tactile belt display system and to evaluate its potential for use as a covert means of communication to the individual warfighter. Previously, the results from these evaluations were distributed as technical reports, meeting presentations, and live demonstrations spanning the past several years. This report documents the full body of work and combines it into one document. Researchers expected the use of tactile displays to reduce demands on and interference with the Soldiers' overtaxed visual and auditory channels, thereby improving overall performance capacity and mission readiness. As part of the development process, tactile system characteristics were reviewed and assessed to ensure system effectiveness. Several studies were performed to determine optimal system characteristics. After an effective system was developed, it was evaluated for military applications such as covert communication and target cuing in realistic mission context. This report contains these studies and documents the tactile belt display system's effect on Soldier performance.

15. SUBJECT TERMS

communication; hand and arm signals; Soldier performance; tactile display; tactor technology; target queing

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Elizabeth S. Redden
a. REPORT UNCLASSIFIED	**b. ABSTRACT** UNCLASSIFIED	**c. THIS PAGE** UNCLASSIFIED	SAR	85	**19b. TELEPHONE NUMBER** *(Include area code)* 706 545-5493

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

List of Tables

Foreword

This work was sponsored in part by the Defense Advance Research Projects Agency (DARPA), administered by the Tank-Automotive Research, Development, and Engineering Center under contract number DAAE07-03-C-L143; and in part by the U.S. Army Research Laboratory's (ARL's) Human Research and Engineering Directorate (HRED) as part of the Army Technology Objective (ATO) for Enhanced Unit of Action Maneuver Team Situational Understanding (SU) under contract number US000463. Direct field and personnel support was provided by the HRED Field Element, U.S. Army Infantry Center, Fort Benning, Georgia; the United States Military Academy at West Point, Behavioral Sciences & Leadership Department; the Naval Postgraduate School, Operations Research Department, Monterey, California; and the U.S. Army Sniper School at Fort Benning. Sub-contact support was provided by Engineering Acoustics, Inc., Winter Park, Florida; and RIMLine[1] LLC (Limited Liability Company), Orlando. Cooperative support was provided the Department of Defense, Multi-disciplinary University Research Initiative: Operator Performance Under Stress, grant DAAD19-01-1-0621 administered by the U.S. Army Research Office through the University of Central Florida (UCF) and the Institute for Simulation and Training. Sponsoring contract administration was provided by UCF under account numbers 11726010 and 11726010.

Today's Soldier receives information from many sources, but comprehension is limited by the constraints imposed by the equipment itself, the medium of transmission, and human information processing. Despite technological advances, the battlefield continues to overwhelm the Soldier's primary sources of input (namely, the eyes and ears) by sheer volume or by obscuring or distorting sights and sounds. In fact, display signals themselves can block environmental cues, emit signals detectable by opposing forces, or interject attention-diverting communications during the intensity of combat. Any or all these factors can place the best-equipped 21st century Soldier at a significant disadvantage on the battlefield.

Alternate sensory input may well bypass sensory losses and address these perceptual bottlenecks by providing information that would otherwise overwhelm Soldiers. The sense of touch holds special promise in this regard. Remotely conveyed touch combines a meaningful, powerful, and primal sensory channel with themes of natural compatibility and essential simplicity, while drawing on innate and learned expectancies. At its most basic level, touch invades awareness and highlights messages for fast, accurate detection and recognition breaking through sensory saturation, particularly under the stress and high workload conditions experienced by Soldiers.

Tactile transmissions add another dimension to communications, yet retain crucial independence by providing information without further overloading visual or auditory channels. There is strong

[1]not an acronym

evidence that parallel processing by parsing input among the different sensory systems opens channel bottlenecks and enables more efficient multi-tasking (Wickens, 2002). Combat operations ranging from urban warfare to engagements with remote systems provide rich and varied examples of situations when critical information, conveyed covertly, reliably, and uniquely by touch could provide Soldiers with a clear communications advantage. The use of tactile messaging is particularly relevant when other channels are degraded (e.g., night operations, heavy fog, loud noise, etc.), when cognitive capability is lessened (e.g., fatigue, stress, sustained vigilance), and when there is a need to maintain stealth, thus precluding the use of audio communications.

Although current military applications rarely use tactile displays in combat operations, touch has become routine in other settings for simple alerts. Consider the ubiquitous vibrating cellular telephone as a clear illustration of the primacy of touch to gain attention and its effectiveness during multi-modal processing. It follows that with proper development, the use of tactile displays for Soldiers should reduce demands on and interference with the overtaxed visual and auditory channels, thereby improving overall performance capacity and mission readiness.

This report expands the work initiated by DARPA and expanded by ARL, which explored the use of covert signaling by remote touch to increase Soldiers' performance. By remote touch, we refer to use of vibrotactile technology that enables communication through patterns of vibrating tactors placed on the Soldier's body. Initial efforts by UCF focused on constructing a tactile cueing system capable of withstanding expected operational demands. Once the prototype was constructed, the project transitioned to test the feasibility of a tactile language (patterns that convey message content) best suited for the Soldier. The scope of inquiry included studies of signal types and characteristics, the most effective receptor positions on the body, and the design of tactile messages for intuitive understanding and for ease of training. Dynamic testing performed under the ARL ATO for Enhanced Unit of Action Maneuver Team SU assessed tactile messaging under physiological stress and in operationally relevant field conditions. The success of the communication work led to studies that further explored potential military applications for tactile systems such as target and directional cueing.

The UCF system was designed with components for a four-Soldier "fire" team. The tactile display is worn around the waist (just above the navel) along with a small control unit (receiver/controller). The display itself consists of eight transducers (tactors), all independently capable of producing vibration. The control unit receives transmitted signals and converts them into recognizable patterns of vibration. In their present form, personal digital assistant pre-programmed buttons initiate transmission for any of six basic commands in tactile patterns designed to be analogous to standard Army arm and hand signals. The six commands (attention, halt, move out, direction to go, rally, and NBC[2]) represent only a few of the many commands and signals that could be communicated by touch.

[2]NBC = nuclear, biological, and chemical.

Experiments demonstrated that Soldiers quickly learned the system with minimal familiarization, and the use of the system resulted in significant speed and accuracy benefits. In addition, after-action reviews from these Soldiers showed that reception of tactile commands occurs naturally, accurately, and largely independently of vision and hearing.

The work thus far has explored and demonstrated a powerful but yet untapped means for rapid messaging among dismounted Soldiers using transmitted vibratory patterns. If implemented, such technology can speed and coordinate information flow to Soldiers and can ultimately assist in saving lives, achieving mission success, and asserting superiority in the various forms of conflict faced by our Armed Forces. We have disseminated the results thus far in the form of technical reports, meeting presentations, and live demonstrations spanning the past several years. This report attempts to consolidate our past work into one document.

INTENTIONALLY LEFT BLANK

Acknowledgments

The authors wish to acknowledge the following contributors:

J. Christopher Brill	University of Central Florida (UCF)
Christian B. Carstens	U.S. Army Research Laboratory (ARL), Human Research and Engineering Directorate (HRED) Field Element, Fort Benning, GA
Jeremy L. Duehring	Naval Postgraduate School
Linda R. Elliott	U.S. Army Research Laboratory, HRED Field Element, Fort Benning
Richard D. Gilson	UCF
John Graham	U.S. Army Military Academy (USMA), West Point
Karl Gunzelman	Intelligent Decision Systems, Inc./U.S. Army Col. (retired)
Peter A. Hancock	UCF, Dept. of Psychology/Institute for Simulation and Training
Timothy W. Hannen	Naval Postgraduate School
Michael D. Matthews	USMA, West Point
James Merlo	UCF/USMA
David C. Mortimer	UCF
Rodger A. Pettitt	ARL HRED Field Element, Fort Benning
Elizabeth S. Redden	ARL HRED Field Element, Fort Benning
Daniel Smith	USMA, West Point
Lawrence Shattuck	Naval Postgraduate School
Shawn Stafford	UCF
Peter I. Terrence	UCF
Daniel D. Turner	ARL HRED Field Element, Fort Benning

INTENTIONALLY LEFT BLANK

Section 1. Introduction

Chapter 1.1 In Touch (Hancock, Gilson, and Redden)

In the modern combat environment, information superiority is vital to operational success. Today's enemy seizes opportunities to execute sporadic acts of ruthless terrorism and create a constant state of fear. Countermeasures start with our ability to collect intelligence that limits the enemy's advantage as the instigator of conflict and then disseminate that knowledge for counter-actions at the right place, at the right time, and in the most effective manner. Unfortunately, for now, these two activities are disproportionate. We spend considerable time and effort on the task of gathering, coherently structuring, and synthesizing intelligence information but less in devising innovative and effective methods for conveying what we have to those who need it most.

We hold it to be a central principle that information communicated incorrectly or poorly is more than a waste of the vast resources taken to collect it. It can prove to be most detrimental, weakening the mission and the individual by producing a state of confusion that, paradoxically, we wish to promote only within the enemy forces themselves—not in our own ranks. The crucial task in combat, whether in skirmishes or in major battles, is to use the best advanced technology to quickly bridge information gaps and to eliminate unknowns in near-real time by conveying only the most critical information to the individual Soldier. Such technologies thus become "force multipliers".

Recently developed technologies can send data packets to Soldier-worn portable receivers over secure networks. The obvious advantage is that rather than the need to carry more sensing equipment, the Soldier must only receive the necessary signals, thereby decreasing the physical load while expanding the range of reception to the limits of the entire network.

Although hardware and software issues for secure signaling clearly remain, these problems are the focus of converging solutions in the commercial sectors as well as in the military. This reflects the increasing demand for communications and messaging devices by countless consumers worldwide, virtually ensuring technical advances to come. The problem for the military is that combat poses fearsome barriers to communications that can obliterate input, stifle processing, and overwhelm understanding. The overarching goal of this work was to leverage (multiply) the sense of touch as an addi-tional information pathway that can help ensure that the Soldiers receive necessary information to complete the mission at hand despite the visual and auditory noise of combat.

Technology significantly alters the role of the Soldier on the modern battlefield. One example is the use of night vision devices (NVDs). "Owning the night" has achieved its great success because it restores the capacity of vision as a major sensory channel to such a degree that a technologically inferior enemy is placed at a decided disadvantage. However, care is needed in its use. NVDs can consume so much of the capacity of vision for information processing that they have the potential to interfere with other tasks that naturally demand sight and attention, particularly in the heat of battle. Visual attention, like auditory attention, is a precious commodity that cannot be directed at two places at once without decrement.

Demands for a Soldier's attention by increasingly complex technology on the battlefield threaten the very gains expected from new designs. Of question here, can the potential benefits sought by technology for the Soldier be negated or even reversed by difficulties in use? A Soldier engaged in battle already has a demanding role, and it is unrealistic to expect that any Soldier will have much tolerance for disentangling overloaded visual and auditory channels for the additional information unless there is a clear combat advantage. Researchers concur that the need for basic cognitive processing consistently drains mental resources (e.g., Cook & Woods, 1994; Wickens, 2002). Recognizing these demands, the objective then is to determine the most critical information and how to convey it most efficiently in order to achieve operational advantages. This would allow the Soldier to focus on other ongoing tasks, such as visual surveillance, verbal communications, navigation, and tactical analysis.

Given that critical information must be communicated to the Soldier, the question we address in this report is how to best convey critical information to the user. The ever-increasing stream of information adds new demands to a bottleneck that has become more prevalent in daily operations as Soldiers struggle with awkward designs and bothersome "push technology," often embedded as unwanted information in interactive audio and video services. It is here that human abilities move to the forefront of design issues. To achieve "full spectrum" dominance over the enemy, we must consider human capabilities as well as technical limitations by providing our Soldiers with reliable and critical knowledge about their current operations. A major threat to the combat Soldier of the future is an overwhelming flood of data, much of it context irrelevant. Too much information is more than just a bothersome distraction; it induces cognitive overload and leaves the multi-million-dollar-equipped Soldier vulnerable to an inferior adversary. Live combat is about the here and now, and any information that distracts the engaged Soldier from action in the present is simply another enemy. Combat ground Soldiers do not need the same type or amount of information that higher echelons need (Redden, 2002). Therefore, in most instances, basic commands and short "bits" of information should suffice to provide the ground warriors with the information they need. Wearable tactile displays now offer another path for conveying these small but vital pieces of information to the Soldier rapidly and without additionally burdening the eyes and ears as with traditional visual and auditory displays.

Chapter 1.2 Remote Touch: Independent Covert Information (Gilson, Redden, and Hancock)

Using touch as another channel for communications circumvents many of the limitations of traditional visual and auditory displays, especially in combat or conflict environments plagued with sensory overload. The distribution of information across the various sensory systems can help overall mental workload by reducing channel competition and bottlenecks associated with modality overload. In addition, tactile communication can serve as the deciding factor in contexts where silence is necessary to ensure mission success, by allowing the rapid and accurate communication of otherwise unavailable information.

Beyond silent alerts, tactile signaling offers far-ranging capabilities yet untapped. It broadens multi-sensory communications with separately channeled transmissions, thus bringing inherent advantages to the Soldier. For example, tactile displays are non-illuminating, silent, "eyes free," and can be distinctly unambiguous—all advantages on the battlefield. Touch also invades awareness at a primary level, highlighting messages for fast, accurate responses; yet it can be intentionally disregarded in lieu of other combat demands. This suggests that at even a modest level of sophistication, remote transmission of tactile signals can potentially provide a wide variety of useful, covert, and clear communications to Soldiers under sustained stress.

The use of touch for Soldiers requires a paradigm shift since it is not normally considered a channel for communications beyond the occasional tap on the shoulder. Beyond the technical issues of remote transmission, the chief impediment to touch is limited bandwidth as compared to vision or hearing. Nevertheless, its availability can provide new opportunities for channeling signals from a variety of sources. The strategy is to glean essential information for the bandwidth and give it the natural priority that comes with touch. This requires thoughtful and careful coding tailored to intuitive touch patterns to retain the validity of signals chosen for their value.

Note that this multi-sensory approach complements traditional visual and auditory displays by highlighting and rapidly conveying salient information with minimal interference among other tasks. Thus, in the extremes of combat, touch cues may provide the winning advantage in circumstances that would render sight and sound useless for friend and foe alike. The capability for alternate signaling by touch can create an advantage over the enemy that augments effectiveness of NVDs by avoiding light-mediated systems (or auditory signals) that would otherwise "stimulate the environment" and alert the enemy.

Section 2. Brief Overview of Tactile Systems

Chapter 2.1 Touch Systems in Perspective (Gilson)

Humans, from infancy to adulthood, naturally use touch as a prime sense to verify their surroundings and later to bind communications with others (e.g., identification by feel, a meaningful nudge, or a handshake). The distinguishing characteristic of this type of interaction, besides whether it is haptic or tactile, is whether the modality is added information that verifies the other channels or is prime information in its own right in absence of other incoming signals. For centuries, tactile devices have been envisioned as an alternate means of communication for those who are visually or hearing impaired. Oddly, the success of Braille "reading" stands in triumphant isolation to many disappointing approaches from attempting to "feel" speech vibrations, or to recognize embossed letters and words by touch. The latter serves as a vivid example of unsuccess-ful applications that failed to "learn from science." In many of these applications, technology often rapidly and haphazardly forged ahead of human sensory limitations, creating problems for the user and product "dead ends" for the designers. For example, simply embossing the alphabet in paper to read by touch succumbed to Braille because subtle spatial patterns easily apparent to the eye, such as "C" versus "O" or "E" versus "B," are difficult to discern by touch with the skin's limited spatial resolution, at best in millimeters (Van Boven, Hamilton, Kauffman, Keenan, & Pascual–Leone, 2000).

Likewise, attempts to feel speech vibrations have been thwarted by the skin's limited frequency range for discrimination, at best 20 to 1000 hertz (Hz) (Goff, 1967; Gunther, Davenport, & O'Modhrain, 2002), where the informational content in speech is generally in sharp consonants well above 1000 Hz. Even attempts to create a coded alphabet with variations of simultaneously activated touch stimuli in patterns succumbed to "masking" effects, where weaker stimuli go unnoticed in the presence of stronger ones, particularly when spacing is less than a few centimeters (Gilson, 1968, 1969a, 1969b). In addition, the means of stimulating the skin (with its many different qualities) can fail (e.g., pressure fades, electricity hurts, chemicals spread, thermal stimulation neutralizes).

On the other hand, haptic devices speak the language of touch by using what the fingers do best, manipulation (Jagacinski, Flach, & Gilson, 1983; Gilson & Ventola, 1980; Gilson, 1978; Burke, Gilson, & Jaqacinski, 1980; Gilson, Ventola, & Fenton, 1975) even through gloves (Jenkins, 1947). More recently, silent yet invasive vibrating alerts have been designed for products ranging from the vibrating pagers to aircraft stick shakers to roadside "rumble strips". The important lesson here is to discover what the skin discerns best, such as movement or sequential stimulation. Pointedly, nearly half a century of research confirms that experimental data, user evaluations, or reliability testing may not support what may seem initially obvious to enthusiastic inventors and designers. With technological advances such as wireless transmission now widely available and with science directing the way, communicating by touch is literally now within our grasp. What follows is a description of experiments using increasingly sophisticated touch variables to convey useful information to Soldiers. These include (1) tactor selection, (2) tactile cueing, (3) error detection by touch, (4) tactile coding for messages, (5) tactile channeling for workload reduction, and (6) application and fielding considerations.

Chapter 2.2 Tactile Masking and Pattern Recognition (Gilson)

Stimulating various loci in different combinations can create a large number of possible patterns for cutaneous communication. In theory, the number of pattern combinations increases as a factorial (n!), where "n" is the number of loci available for stimulation. However, serious con-straints limit the usable patterns (Gilson, 1968, 1969a, 1969b; Craig, 1985).

One such constraint is that recognition falters rapidly with increases in the number of elements in the pattern, starting with as few as three (Alluisi, Morgan, & Hawkes, 1965; Geldard & Hahn, 1961). Geldard and Hahn, using vibrotactile stimuli, created patterns by simultaneously stimulating as many as six loci on the shoulders, elbows, and wrists in a manner fashioned after the six-dot Braille system. Although an alphanumeric code was mastered with surprising rapidity, one striking difficulty emerged when the wrist, elbow, and shoulder of one side were stimulated simultaneously. This pattern resulted in a complete suppression of the sensation at the elbow. However, elimination of only one point of stimulation at either the wrist or shoulder brought the elbow sensation back in full force.

Alluisi et al. (1965) found similar effects with electro-cutaneous stimulation at the same locations in a pilot experiment and found large increases in the percentage of errors with increases in the number of loci stimulated. They interpreted these findings as evidence of a masking effect (where the stronger stimulus suppresses the weaker), since nearly all the errors were those of omission. They also suggested that some central mechanism of masking might be operating because of the highly localized nature of the stimulus used (bipolar electrical stimulation) and the wide separation of loci.

Gilson (1969b) showed quite clearly that multiple maskers do produce greater suppression than does a single masker. The amount of suppression appears to be nearly equal to the sum of the individual masking effects rather than just the sheer number of maskers. These results are in accord with earlier patterning studies (Gilson, 1968; Alluisi et al., 1965; Geldard & Hahn, 1961), which show a general decrement in the identification of the full complement of pattern elements with an increase in the number of elements within a particular pattern.

Interestingly, staggering stimulation onset times by as little as 20 ms can substantially reduce these masking effects, regardless of loci (Gilson, 1969a) and therefore should increase pattern discriminability. Such signaling delays to the brain occur quite naturally because of neural signaling speed from distance loci in the order of about 100 meters per second. For example, simultaneous stimulation of the lower leg and the shoulder will introduce about a 20-ms neural arrival difference at the brain (Gilson, 1969a). Thus, if the shoulder stimulation is artificially delayed by 20 ms in relation to the lower leg stimulation, the natural offset times to the brain will be negated, substantially increasing the masking effect despite the distance (Gilson, 1969a). This suggests that artificially introducing stimulation offset times by 20 ms for equal-distant loci, such as at the waist, should allow each element in a pattern to be distinguished far better than would simultaneous activation.

Of course, there are limitations to the rather simple notion that the degree of vibrotactile masking is controlled only by differential time delays and not by masker placement. For example, despite the similar distances from the brain for the fingers and upper thighs, the degree of masking is not the same. This suggests some fundamental difference in the neural organization of the body that may be related to the amount of sensory cortex sub-serving the loci in question.

Later work by Craig (1985) concurs that masking may be a problem in pattern perception, adding that generally there is more interference when the masking stimulus follows the target (backward masking) than when it precedes it (forward masking). He states, “One of the problems encountered in conveying information to the skin by means of vibratory patterns is that presenting patterns, such as letters of the alphabet, in close spatial and temporal proximity, may result in considerable masking.”

Craig (1985) also indicates that the problem may be reduced if the temporal and spatial separation between pattern elements is increased, but he raises several concerns yet to be fully resolved:

- Temporal separations add time to each pattern, reducing the presentation rate.
- Spatially distinct sites may lead to difficulties in attending to all pattern loci at once.

We infer that asynchronous forward and backward masking may complicate attempts to achieve acceptable discrimination by temporal and spatial separations among elements within patterns. This may hamper pattern identification in the field, particularly if Soldiers are focusing on specific elements of a pattern (feature detection through perceptual learning) and not the entire pattern. Care must be used in the development of tactile patterns since elements can be lost because of masking.

There may be hope for easily attending to patterns consisting of widely spaced loci that are asynchronously stimulated. While acknowledging masking, Mahar and Mackenzie (1993) proposed a tactile “integration hypothesis” that predicts pattern perception is facilitated by a process of temporal sequencing of the individual elements in spatial and temporal proximity. To assess the relative effects, Mahar and Mackenzie (1993) measured the amount of inter-element masking and the discriminability of patterns as a whole by varying the spatial and temporal separation of pattern elements. As expected, masking among pattern elements increased as the spatial or the temporal separation between them was lessened. However, the pattern discrimination data supported the integration hypothesis in that the overall patterns were discriminated more accurately with decreasing temporal element separation, with a similar but non-significant trend in the case of spatial separation. Yuan, Reed, and Durlach (2005) were able to show remarkable discrimination of temporal order for two different frequencies (one at 50 Hz delivered to the thumb and the other at 250 Hz delivered to the index finger) with an average of 34 ms of stimulus-onset asynchrony. Taken together with other findings, these suggest that at the very least, asynchronous timing is critical to highly recognizable tactile patterns and that it may be possible to create a much wider spectrum of pattern tactile discrimination and recognition, even something akin to tactile “movies” or “melodies” (see Pasquero & Hayward, 2003; van Erp & Spapé, 2003).

Thus, with the precision of advanced technologies to manipulate timing within matrices, and perceptual learning developed by prolonged use, the ability to create, recognize, and use complex tactile patterns should improve. As an example of new technologies, Pasquero and Hayward (2003) described a tactile system capable of activating 100 laterally moving skin contactors with a spatial resolution of 1 millimeter and a refresh rate of 700 Hz. This design creates a time-varying programmable array capable of stimulating the skin surface with a variety of graphic-like representations. On the perceptual side, Braille readers learn to rapidly perceive and process what they touch quite differently than most, showing unique activity in the visual cortex triggered by tactile stimulation (Sadato, Pascual-Leone, Grafman, Ibañez, Deiber, Dold, & Hallett, 1996). Overall, many other findings suggest that even the most advanced tactile displays have not yet reached the full processing capabilities of the skin that are suggested by scientific research.

Section 3. Characteristics of Tactile Systems

Chapter 3.1 Tactor Display Selection and Configuration (Gilson and Brill)

The choice of the type of stimulator to be used is very important for effective communication. It is much more important for messaging than for simple alerts or directional cueing. This chapter explains the choices and the rationale for the choices that we made when choosing the type of tactors and the tactor attributes used in the University of Central Florida (UCF) tactile system.

As noted in the previous chapter, pressure sensations fade, electricity hurts, chemicals spread, and thermal stimulation neutralizes. Vibrotactile sensations can be well controlled and are well tolerated. Although adaptation to vibration does eventually occur, short bursts likely to be used under about 0.5 second do not appear to cause significant adaptation. Thus, vibration is usually the modality of choice (Sherrick & Cholewiak, 1986).

With the mode of stimulation determined, the type of stimulus characteristics becomes an issue, encompassing such factors as stimulation area (and depth), intensity, frequency, onset characteristics (rise time to reach full activation), reliability, weight, power, and cost. Initial work with small, lightweight, widely available cellular telephone or pager alerts (those that create a "wobble" within a cylinder or a "pancake" disk to create vibration) indicated to us inadequacies in control and likely unreliability in field use. Obviously, the inertial shaker motors used in pagers work well as designed within their housings as "event" alerts. However, they are severely limited in controlling the stimulation applied directly to the skin and in their flexibility for coding touch messages for some of the following reasons:

- Spatial attributes. Unfortunately, the entire housing vibrates, allowing unconstrained physical wave propagation along the skin. This makes the perceptual experience extensive and spreads to interact with other adjacent inertial shaker motors if activated together in patterns. The net effect is interference with point-to-point specificity and degradation of two-point vibratory discrimination.

- Intensity control. This poses additional concerns. Firm pressure on the skin is needed to keep contact and to constrain erratic shaking. However, pressure couples the shaker with body tissue mass and changes the overall impedance, thus loading the tiny motor and reducing intensity. Varying pressure such as produced under body armor, particularly during movement, alters the loading and changes attenuation unpredictably. Preliminary tests show that under normal loading needed to maintain coupling with the skin (about 15 grams), the intensity of inertial shaker motors drops by nearly 60%, with a further decrease to 80% with greater loading. Unfortunately, because of the design, adjustments that might increase vibratory frequency (spinning faster) also increase the intensity. This alters the perceptual experience and in doing so negates frequency as well as intensity as a coding characteristic.
- Frequency choice. Several operational issues are posed by inertial shaker motors normally operating at about 60 Hz. These low frequencies stimulate superficial free nerve endings more than the skin's deeper Pacinian corpuscles most sensitive to vibration at frequencies in the 200- to 250-Hz range (Kandel, Schwartz, & Jessell, 2000). Besides the obvious inefficiencies and quality of feel differences (Head, 1920), a superficial loss of sensation by conditions (e.g., cold or surface injury) is likely to affect low frequency devices more than those designed to stimulate the skin at higher frequencies. Mahns, Perkins, Sahai, Robinson, and Rowe (2006) found that surface anesthesia produced a marked impairment in vibro-tactile detection and discrimination at the lower frequencies of 20 and 50 Hz but had little effect at higher frequencies of 100 Hz and 200 Hz.
- Timing. Another concern is a slow, imprecise onset or rise time for these devices, taking roughly 50 to 100 ms to reach full activation and intensity, depending on the individual unit. This complicates the use of special perceptual attributes of the skin, known as the "Tau" effect (much like visual apparent movement or the "Phi" phenomenon) and the "Saltation" effect (phantom stimulation between stimulators). Both phenomena can be created with carefully controlled sequential stimulation of the skin with timing on the order of 100 ms or less (Geldard & Sherrick, 1972).
- Reliability. Reliability was also a problem in our evaluations of the inertial shaker motor tactors. Several of the inertial shaker motors that we were trying to test broke when outside their normal protective encasements, even during laboratory use, which suggests that field reliability may be an illusory goal.

Engineering Acoustics, Inc. (EAI) makes tactors specifically designed to stimulate the skin with vibration and designed to be rugged enough for military use, even under water. Their "C2" model (http://www.eaiinfo.com/) consists of a moving center plunger about 8 mm in diameter, actuated (with a 1-mm gap) within a stationary 31-mm anodized aluminum housing that constrains the vibratory wave propagation and localizes the perceptual signature. The center plunger can move as much as 1 mm, attenuating less than 20% when pre-loaded by the skin and is designed to withstand more loading with little loss. It has a fast rise time in the order of 3 to 4 ms and a frequency range of 0 to 300 Hz that is quite intensity independent. The optimum transducer operating range is established by skin-coupled resonance to be between 200 and 270 Hz. Because the C2 tactors ameliorate the problems associated with the inertial shaker motor tactors, we chose to incorporate this type of tactor in our system. For field use, we use and drive these C2 tactors at a frequency of 250 Hz, a value that fits well with skin sensitivity and that creates robust perception with sine wave bursts. We set intensity at about 24 db above sensory threshold (about 0.6 mm of plunger movement) with values of about 2.0 volts root mean square (Vrms) operating at about 250 milliamperes (ma).

The tactile system used for this experiment was developed under the Defense Advanced Research Projects Agency (DARPA) contract number DAAE0703CL143. Each tactile display assembly included eight of the aforementioned C2 tactors. These eight tactors and their associated wiring were fitted into an elastic belt worn securely around the torso (above the navel but below the sternum). This arrangement created a ring of equidistant stimulation loci with the first one centered just above the navel. Photographs of sample tactor are shown in figures 1 and 2. The center piston, visible with a midpoint screw, moves within the larger fixed housing. These tactors are essentially acoustic transducers that transmit 200 to 300 Hz sinusoidal vibrations onto the skin. The mass of each tactor is 17 grams.

Figure 1. Image of a single tactor, model C2, with a size comparison.

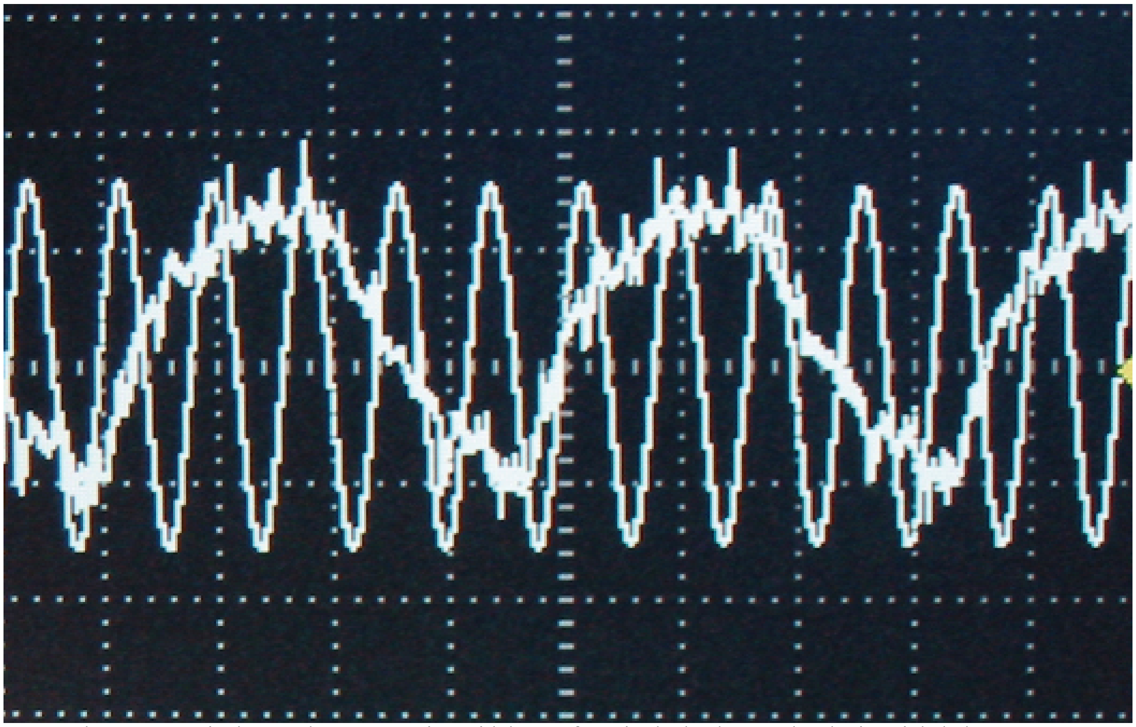
Figure 2. Close view of single C2 tactor built by EAI.

In addition to the C2 tactor's capability to operate in the 250-Hz "sweet spot," the added benefit in this technology is its precise timing, with the fascinating potential to create unique patterns from tactile arrays with fewer points (loci) of stimulation. Laboratory testing suggests that other methods of stimulation, such as staggering the onset times of individual tactors, on the order of only milliseconds, create "pseudo-sensations" that can substitute for touch without a physical stimulus at the locus. The possibility then is to enhance the communication capabilities of tactile displays with the same or even a smaller hardware set, thereby reducing the number of tactors and their associated cost, weight, wiring, power draw, etc. Given this capability and advantage, expanded investigation into these phenomena is warranted.

For comparison purposes, we equated the C2s to inertial shaker motors by having laboratory subjects match them for perceptual loudness. We then measured the values shown in table 1 using a skin compliance model, making adjustments as necessary with small-value linear assumptions.

Table 1. Parameters and data for tactor comparison.

Parameters for Equivalent Motors	Inertial Shaker	C2 Tactor Loudness
Magnitude above threshold	20 dB	20 dB
Total signal duration	300 ms	300 ms
Displacement (peak)	277 µm	228 µm
Voltage input	3.3 volts direct current (VDC)	1.0 Vrms
Amperage	11 ma	180 ma
Frequency (see tracings in figure 3)	62 Hz	250 Hz
Rise time to full intensity	40 ms	5 ms



Note. The C2 tactor is the regular 250-Hz sinusoidal waveform in the background. The inertial shaker motors' waveform is the non-sinusoidal waveform in the foreground at about 60 Hz. Time scale per large division is 5 ms. Voltage scale per large division is 20 mV.

Figure 3. Oscilloscope traces of C2 and inertial shaker motor vibration.

3.1.1 Power Usage Analysis

An electrical power analysis showed that power differences are not a major issue, regardless of the vibrating stimulator used. Bluetooth[3] wireless and the control connection create the primary power demand by 90% or more, making the C2 tactor's proportional power draw low. On the average, the Bluetooth receiver and the circuit board consume about 950 milliwatts (mw) of power. The Bluetooth receiver alone consumes about 400 mw, while the circuit board itself consumes about 450 mw for residual power. (Please note that this is an average with the current configuration of 802.11; newer control electronics have power-saving features; however, these are not available in our current hardware.)

The tactors themselves draw an average of about 45 mw based on several conservative assumptions: all eight tactors are actuated at full 500-mw power each for every pattern; the messaging duty cycle is 1% (one 600-ms message per minute), and the amplifiers that drive the tactors operate at about 88% efficiency ($8 \cdot 0.01 \cdot 500 \cdot 1.12 = 44.8$ mw). The total power draw for the C2 configuration is 950 mw + 45 mw, or 995 mw total.

A similar power analysis for inertial shaker motors with the same Bluetooth connection would yield just under a 4% savings in power, as follows:

[3]Bluetooth is a registered trademark of Atmel Corporation.

- Vibrators, operating at a slower 60 Hz or less, draw about 3 mw. That is, using the same assumptions as before, they operate at 3.3 VDC at 11 ma, consuming about 36 mw for each vibrating motor, with the total consumption about 3 mw ($8 \cdot 0.01 \cdot 36 \cdot 1.12 = 3.2$ mw).
- If inertial shaker motors were to be used in place of the C2s in the current configuration, the total draw would be 950 mw + 3 mw or about 953 mw total.
- The savings is 42 mw (995 mw - 953 mw), a value that proportionally translates to only about 4.2% savings ($42/995 \cdot 100$) in power.

Operationally, this means that despite the disparity between the tactile stimulators, the power difference is measured only in minutes for ideal battery packs capable of 10 hours of continuous operation as defined before—a trade-off that does not, in our opinion, justify the loss in percep-ual clarity.

Chapter 3.2 Placement, Fit, and Comparison of Two Types of Tactile Displays (Redden, Carstens, Turner, Brill, Stafford, and Terrence)

The previous chapter provides an engineering-based evaluation of two types of tactors, the C2 and the inertial shaker motors. In this chapter, we describe the investigation of these two tactors from an operational perspective. This investigation, which compared the utility of different types of tactor characteristics for dismounted Soldier operations, was conducted by ARL as part of the ATO for Enhanced Unit of Action Maneuver Team SU (Redden, Carstens, Turner, & Elliott, 2006).

Tactile displays have different engineering specifications, and some may be more effective than others in terms of the ability of the wearer to feel the tactile stimulation and to localize the position of the individual tactors, particularly during movement in dynamic situations (see chapter 3.1). Most previous studies in tactor localization have focused on statically mapping various parts of the body to determine how far apart tactors must be to be felt as separate (Gemperle, Ota, & Siewiorek, 2001; Cholewiak, Brill, & Schwab 2004; van Erp, 2005a). However, these studies did not address the operational effectiveness of various tactor types. Although tactor differences may be described in terms of hertz and onset times, we must also know how these differences influence effectiveness in operations. Thus, the question is raised concerning what type of tactor and what level of signal intensity would be best for imparting information in operational field environments.

After an in-depth literature review, some initial trial and error, and many pilot experiments, we determined the torso to be an acceptable body site for stimulation and spatial resolution. The torso has been found to be a stable and effective reception area and is particularly suited for cueing direction. UCF researchers tested other areas of the body such as the head, the forearm, and the hands, but these areas were dismissed for a variety of reasons ranging from vibratory propagation issues to interference with anticipated operational needs. For example, vibratory propagation with loci at the skull introduced considerable bone conduction, stimulus spread, and confusion, along with considerable negative user feedback in pilot testing to determine optimal tactor placement and two-point vibrotactile threshold (Brill & Gilson, 2006).

Several researchers have established that the waist is an effective torso area for tactors (van Erp & Werkhoven, 1999; Lindeman, Yangida, Lavine, 2003). In this study, we controlled for placement by stimulating loci around the torso just above the waist. This positioning does not appear to interfere with Soldiers' clothing and equipment or with Soldiers' abilities to perform their dismounted duties, and tactors mounted at the waist appear to stay in place (Pettitt, Redden, & Carstens, 2006). Also, since Soldiers are taught to reference direction from the center of the body mass, namely, the front of the torso, this positioning provides for intuitive directional signals (Elliott, Redden, Pettitt, Carstens, van Erp and Duistermaat, 2006; van Erp, 2005b) and for intuitive communication (Pettitt, Redden & Carstens, 2006).

The number of tactors used on the different parts of the body also had to be carefully considered. Cholewiak, Brill, and Schwab (2004) found that for the torso, a ring of eight loci of vibration is the most that could be resolved with accuracy exceeding 90%. Thus for Army operations, we chose to investigate a waist-mounted tactile system that consisted of an elasticized belt and eight tactors.. This was considered sufficient to communicate direction and basic signals. Instead of "mapping" every centimeter of the torso, we wanted to ascertain the effectiveness of each type of tactor, in the con-text of an eight-tactor array. The belt itself was fabricated in a breathable non-irritating bicycle jersey material worn securely at mid-torso around the abdomen, in a line about 10 cm above the navel.

In this work, we compared the two types of tactors most commonly used in past studies, inertial shakers and C2 tactors (Mortimer, Zetts, Cholewiak, in press). Both have been described in chapter 3.1. The prime purpose of this effort was to evaluate the tactors at different settings to determine the tactile signals that could be most easily localized. Both types of tactors were embedded in similar systems (i.e., the tactor torso belt developed by UCF).

The C2 tactors can be programmed for intensity and frequency, allowing us to compare C2s to the inertial shakers more directly by first equating their perceived loudness. These equated values in general were about 4 dB lower than the normal intensity levels used for the C2's (approximately 24 dB) (Cholewiak, Brill, & Schwab, 2004). We chose to keep the frequency of the C2s at 250 Hz, which is best suited to stimulate the main vibratory receptors in the skin, the deep Pacinian corpuscles (Verrillo, 1966). The inertial shakers were not programmable and their frequency was fixed at about 60 Hz. That frequency stimulated mostly the free nerve endings nearer the surface. Three conditions were tested, the inertial shakers and C2 tactors at equal loudness levels (20 dB), and the C2 tactors at their normally higher 24-dB "loudness" levels. We used 500-ms burst durations of vibration to assist in cue signal detection, although Gescheider, Hoffman, Harrison, Travis, and Bolanowski (1994) found that durations longer than 200 ms did not add to salience. We chose 500 ms primarily because of the functional limitations of the inertial shaker motors. They have a 50- to 70-ms rise time, whereas the C2 system has about a 2-ms rise time to full activation. As such, the inertial shaker motor stimulus would have been, in effect, 25% shorter in duration than the C2 tactors resulting in an unfair comparison. In other words, using the 200-ms stimulus would have favored the C2 tactor. With a long duration stimulus (500 ms), any failures in detection would not be attributable to stimulus duration but to some other aspect of the stimulus or system. Although it is true that sensory adaptation occurs after 400 to 500 ms of exposure to a vibratory stimulus, the interstimulus intervals were long enough to allow for recovery of the skin receptors. Moreover, the 200- to 300-ms "ideal" was born out of research conducted in pristine laboratory conditions and may not generalize to field operations.

Thirty Soldiers participated in the experiment. Each Soldier was given tactile signals while standing upright and still (static condition) and while moving through a woodland individual movement techniques (IMT) course (dynamic condition). Soldiers wore their fighting loads including interceptor body armor outer tactical vest, with front and back small arms protective insert ceramic plates; they carried their personal weapons (M4). After a short training session with the tactile systems, each Soldier completed the static and dynamic tests three times, once with each of the three tactile signals. The tactile signal manipulations were evaluated, based on objective performance data, data collector observations, and Soldier questionnaires.

A psychophysical pre-test was conducted to confirm the initial equivalence settings for the inertial shakers and C2 tactors and to assess the overall stimulation intensities. The Soldiers were asked to rate the signal intensity of all three conditions using a 0 to 100 scale, with 0 representing an undetectable stimulus, 100 a painful stimulus, and 50 the best level for stimulation. The mean ratings ranged from 15.1 to 23.6. The mean ratings for the inertial shakers and equalized C2 tactors were lower and more similar than the mean rating for the normally "louder" C2 tactor. However, all the mean ratings were much lower than 50, indicating that the signal strength of all three systems was below the level considered best by Soldiers equipped with body armor and ceramic insert plates. Further work should be performed to investigate the benefits of increasing signal strength, as well as to determine if there are any associated problems, such as desensitization after prolonged use, spurious noise generation, or appreciable increases in power consumption.

Although the findings from the static trials demonstrated similar and fairly accurate localization rates among all three systems, ranging from 86.1% to 91.8% correct, significant differences did emerge during the dynamic field trials. On the IMT course, tactor localization was best with the higher intensity C2 tactor (78.7%) and worst with the inertial shakers (48.8%). Localization was best when the Soldier was moving upright or in a kneeling firing position and worst when the Soldier's torso was in ground contact or when he was climbing an obstacle. Localization differed, depending on the position around the waist, with greatest localization accuracy at the front of the body and lowest at the sides.

Based on the previously discussed advantages of the C2 tactors in capabilities and characteristics, and codified by these findings at Fort Benning, we selected the "C2" model for all the work that follows. Although the UCF system was initially designed to be compatible with military PDA and standard radio frequency (RF) communications, for cross-system compatibility we used a Bluetooth wireless option for most of our remote communications and Windows[4] CE programming to individually control the multiple tactors. In the work that follows, Soldiers or laboratory subjects wore the UCF-designed belt embedded with eight equally spaced C2 tactors and carried a portable tactor control unit powered by an eight "AA" battery pack to receive controlling signals and to actuate individual tactors.

Beyond the directional cueing advantages, later chapters show that the C2 tactor control system provides unique and easily understood communication patterns and the capability to allow team members to send messages to any other team member(s). In a subsequent demonstration of operational capabilities for DARPA, four members of a team demonstrated they could wirelessly receive "touch messages" from as far away as 100 meters with RF transmission using pre-programmed PDA "button" options by touch alone. This demonstration highlights the potential for tactile messaging to allow covert communication between Soldiers while focusing visual and auditory attention on other combat-relevant tasks.

Chapter 3.3 Tactile Stimulus Parameters (Gilson and Brill)

Robust coding of signals, commands, or messages for touch depends on distinctive stimulus patterns that can be intuitively matched to the intended information for "icon-like" recognition (Brewster & Brown, 2004b). Such tactile icons, or tactons, represent higher level cutaneous information. At the basic level, every tacton must be uniquely identifiable (independently, not as a paired comparison) with careful and thoughtful selection of stimulus parameters (Brown, Brewster, & Purchase, 2005). The following are examples of stimuli and ranges that by themselves or together can produce a wide variety of discriminable patterns:

- Position -- Single-tactor stimulation spaced at widely distributed body locations can independently encode spatial information by position, e.g., eight tactors at mid-torso around the body (Cholewiak, Brill, and Schwab, 2004).
- Number -- Activating several tactors in various combinations can create uniquely identifiable patterns. Care is required, however, because simultaneous vibrotactile stimulations can overlap by wave propagation or perceptually fuse neural signals (Gilson, 1968). Fortunately, sequencing tactors with differential onsets by as little as 20 ms can dramatically improve pattern recognition because each tactor is perceived separately with its "head start," even if they do eventually overlap through physical wave interactions (Gilson, 1969a).
- Duration -- Pulses of different durations can encode information but usually are best when left in presentation increments of 200 ms (Gescheider, Hoffman, Harrison, Travis, & Bolanowski, 1994). In our pilot studies, most observers perceived durations of less than 200 ms as too short and durations beyond 400 ms as too long, and such durations begin to

[4]Windows is a trademark of Microsoft Corporation.

involve cutaneous adaptation (Gescheider, 1997). Kaaresoja and Linjama (2005) also found that subjects rated the optimal duration for a vibratory signal of a mobile device, such as a cellular phone, as between 50 and 200 ms. They describe durations longer than 200 ms as being "irritating".

- Frequency -- Vibrations ranging from 20 to 500 Hz applied to the skin are perceivable, but the 200- to 250-Hz frequency range stimulates the Pacinian corpuscles specifically associated with "fine touch" from tissue vibration (Gescheider, 1997). Nevertheless, there is good discrimination between two vibration ranges, around 50 to 60 Hz and 200 to 250 Hz (Merzenich & Harrington, 1969; Talbot, Darian-Smith, Kornhuber, & Mountcastle, 1968), thus providing at least two frequencies for encoding patterns. Vibrotactile frequency sweeps may offer other options (Kuc, 2002).
- Amplitude -- Intensity of stimulation is a poor choice for encoding patterns because weak signals may go unnoticed, especially with the natural variations introduced by body movement, and because there are masking effects with multiple activations, even with widely spaced loci (Békésy, 1963, 1967; Gilson, 1969a).
- Waveform -- The perception of wave shape is limited. Users can differentiate between sine waves (as smooth) and square waves (as rough) but not easily, and more subtle differences are more difficult yet (Brewster & Brown, 2004b).
- Onset -- As noted before, both the Tau effect and cutaneous saltation (i.e., illusory localization of a stimulus locus toward another stimulus locus) are available with careful onset manipulation beyond 50 ms to create unique tactile sensations as pattern elements (Geldard & Sherrick, 1972).
- Repetition -- Repeated patterns add urgency or can be counted or encoded as a unique pattern, although counting uses mental resources (Brewster & Brown, 2004b).
- Sequencing -- Several patterns as permutations in different sequences can change meaning to represent hierarchical message structures (Brewster & Brown, 2004b).

To illustrate how these factors might be applied to system or tactile pattern development as part of our program of research, we developed TACTICS[5], a wearable tactile display capable of presenting directional cues as well as tactile icons. For example, the display consists of eight equidistant stimulators to facilitate relatively accurate tactile localization of simple directional cues. The use of more stimulators would likely result in an increase in localization errors and confusion (Cholewiak, Brill, & Schwab, 2004). The tactile patterns are comprised of super threshold 250-Hz sinusoidal signals ranging from 100 ms to 400 ms. They are intense enough to facilitate reliable detections but short enough to minimize sensory adaptation. To further increase the likelihood of signal detection in field settings, all patterns are presented twice in succession, with a 300- to 400-ms interstimulus interval, once again to minimize sensory adaptation. These

[5]Tactile information communication system

timing parameters are adjusted, depending on the nature and urgency of the information presented. Tactile icons conveying critical commands use shorter durations, whereas those communicating non-critical commands use longer durations. In addition, some iterations of the system have incorporated artificial anchor points through frequency modulation (see Brill, Gilson, Mouloua, Concodora, & Whitehead, 2004; Cholewiak, Brill, & Schwab, 2004). Had we failed to abide by the aforementioned guidelines, the overall effectiveness of our system might have been compromised to the detriment of the end user.

Section 4. Performance Benefits With the Use of Touch With or Without Vision and Audition

Chapter 4.1 Discrete Tactile Versus Auditory Target Cueing (Brill and Terrence)

In military settings, the advantage of advanced sensors that can warn Soldiers of a threat is lost if the enemy is also alerted (e.g., by a "call-out" of the position). The assumption here is that there are sensors capable of capturing critical spatial information such as enemy position and that there are capabilities to relay the information. It is important for the Soldier to be accurately and discreetly cued as to the direction of what the unseen may harbor. The signal should be covert, easily understood, and should not tax other needed resources. Tactile cueing can provide such quiet alerts in a manner similar to cellular telephones or pagers silently alerting their users to incoming calls and messages. For example, in a military operation, the location of the vibratory alert on the body could signify the direction of the threat. Threat location has also been naturally done with three-dimensional (3-D) sound localization but with well-known errors (e.g., front/back confusion). Tactile cueing can serve as a silent alternative or as an augmentation to 3-D communications to preclude the likelihood of errors.

Accordingly, UCF researchers investigated the relative effectiveness of systems to identify the location of distant threats, using surround sound (via a binaural spatial auditory display) or their wearable vibrotactile display system. The "threat" was presented at various localizations in the azimuth, as well as below and above the horizon in order to provide differentiation in the vertical axis (24 positions around the participant; 8 azimuth x 3 elevations at, above, and below the horizon). Note, the use of more tactors to create 12 azimuth sectors presented no apparent advantage over 8 sectors (see Cholewiak, Brill, & Schwab, 2004). Details of this work are presented in Brill, Gilson, Mouloua, Hancock, and Terrence (2004).

4.1.1 Method

4.1.1.1 Apparatus and Stimuli

Auditory tones representing stimuli below, level with, and above the horizon consisted of sinusoid frequencies at 250, 440, and 800 Hz, respectively. Pilot testing of stimulus parameters indicated that it was difficult for participants to accurately discriminate the three elevation levels using a single frequency, so the stimuli recorded at each level were at different frequencies, with lower pitches corresponding to lower positions and higher pitches corresponding to higher elevations. Early testing showed that these pitch differences were easily distinguishable in isolation and that they still provided acoustical cueing for binaural localization.

For the tactile presentations, a total of ten tactors (8 for azimuth, 2 for elevation) were attached with Velcro[6] to an elasticized belt worn around the abdomen. Each participant was provided with a protective research garment, consisting of a white 100% cotton T-shirt of appropriate size. The belt placement began with the area just above the navel, with eight tactors placed at equidistant points in a horizontal ring around the torso of each participant, creating 45-degree sections along the horizontal plane. The front or ahead represented the zero-degree reference. At the immediate right and left (90 and 270 degrees, respectively) positions, low frequency tactors (EAI model C2-LF) were positioned and at all other points are model C2 tactors. These low frequency loci were incorporated to provide artificial sensory anchor points, an approach that has been found to improve localization of vibrotactile stimuli (Cholewiak, Brill, & Schwab, 2004). A Tektronix[7] AFG320 two-channel function generator provided a 250-Hz sinusoid to the C2 tactors and an 80-Hz sinusoid to the C2-LF tactors. All tactile stimuli were presented approximately 24 dB above threshold; the intensities of the respective auditory cues were matched to this magnitude with the use of cross-modal matching techniques.

To indicate the azimuth, one of these eight tactors was activated in a single burst for 200 ms. Tactors placed just above and below the 0-degree tactor indicated the elevation above, level, or below. For tactile cues representing objects above the horizon, a single azimuth pulse was presented for 200 ms. Then a directional tactile phi “arrow” was presented, consisting of three vibrotactile taps with a stimulus duration of 150 ms and an interstimulus onset interval of 50 ms. During the presentation of the tactile stimuli, the participant was presented with white noise over headphones to mask any ambient noise and any aural cues associated with the signaling equipment. This helped assure that participants responded, based on how the tactors felt.

During task performance, each participant sat on an adjustable height, padded stool, which was adjusted so that each participant’s ear was approximately at the ear height used during stimulus recording. There were two components of this target localization task: accuracy in regard to angular error and response time in seconds. Accuracy was examined for correct response in terms of azimuth and elevation position and for angular error solely along the azimuth (since elevation

---

[6]Velcro is a registered trademark of Velcro USA, Inc.
[7]Tektronix is a registered trademark of Tektronix, Inc.

determinations based on acoustics are often difficult; Blauert, 1997). Both modalities, tactile and auditory, were evaluated to determine the presence of significant differences in target localization accuracy and reaction time. Response time data were subjected to a repeated measures analysis of variance (ANOVA), with subsequent *post hoc* statistical tests. All analyses were performed with an alpha level of $p < .05$, unless stated otherwise.

4.1.2 Results

The mean number of correct responses for auditory and tactile responses for all participants across the 24 positions is shown in table 2. Note that the maximum score possible is 6. The overall mean scores, collapsed across the 24 possible positions, were 1.85 (standard deviations *[SD]* = 0.91) for the auditory and 4.76 (*SD* = 0.58) for the tactile display. A paired samples t-test demonstrated a significant difference between the tactile and auditory condition in the mean number of participants' correct responses across positions, with the tactile showing higher accuracy $t\ (23) = 13.01$, $p < .001$. Table 2 shows the total number of trials for auditory and tactile signals with the corresponding correct and incorrect responses for projecting the stimulus to the indicated direction. Table 3 shows the average number of correct responses for each participant in both the tactile and auditory conditions across the three elevations.

Table 2. Total correct and incorrect for auditory and tactile responses.

	Total Trials	**Percent**
Auditory incorrect	1993	69
Auditory correct	887	31
Tactile incorrect	593	21
Tactile correct	2287	79

Table 3. Mean correct per participant for auditory and tactile stimuli across three elevations.

	Mean Correct per Participant		**Mean Incorrect per Participant**	
Elevation	**Auditory**	**Tactile**	**Auditory**	**Tactile**
above	10.27	26.50	21.73	5.50
level	8.83	25.10	23.17	6.90
below	10.47	24.50	21.13	7.50

The median response trial for each stimulus position for each participant was averaged across participants. Median response times were used because the occasional participant did not "lock in" his response properly, thereby letting the timer continue to run and unacceptably skewing the mean response times. Absolute angle differences (AADs) were computed, based on the absolute difference between the direction indicated by the tactile or auditory stimulus and the direction the participant indicated. All analyses used an alpha value of .05, unless stated otherwise.

4.1.2.1 Response Times

A factorial ANOVA was conducted to analyze modality (tactile versus auditory), elevation (above, level, below), and stimulus position (1 through 8). The mean response time (RT) was 2736.63 ms (2.74 s; *SD* = 1584.18) for tactile and the mean RT was 3583.31 ms (3.58 s; *SD* = 1783.22) for auditory. There was a significant effect for modality, $F(1,27) = 5.72$, $p = .024$, $\eta_p^2 = .175$. We wanted to determine the RT differences for each possible stimulus position (across the three elevations). We used paired samples t-tests ($t(29)$, $p = .05$ for all comparisons) to analyze tactile and auditory differences for each of these positions. The data and results of these analyses for the three elevations (above, level, and below the horizon) are summarized in tables 4, 5, and 6, respectively.

Table 4. Response time comparison for above horizon stimuli. (Bold and italicized type indicates that a significantly shorter response time was found.)

		Tactile		Auditory	
Elevation	**Stimulus Position**	**Mean RT**	**SD**	**Mean RT**	**SD**
Above Horizon	1	***2680.85***	802.75	4074.42	1253.09
	2	***2837.78***	713.60	3470.83	986.42
	3	3924.53	3134.55	3369.82	819.12
	4	***2728.15***	741.26	3501.83	1029.84
	5	***2753.12***	810.68	4225.48	1416.37
	6	***2712.35***	860.45	4503.93	5218.62
	7	2770.62	813.55	3609.88	865.96
	8	2999.72	1137.48	3713.12	985.15

Table 5. Response time comparison for level with horizon stimuli. (Bold and italicized type indicates that a significantly shorter response time was found.)

		Tactile		Auditory	
Elevation	**Stimulus Position**	**Mean RT**	**SD**	**Mean RT**	**SD**
Level with Horizon	1	***2537.03***	730.33	3571.33	1040.83
	2	***2605.95***	797.20	3435.73	988.73
	3	***2931.52***	1288.08	3428.82	1039.89
	4	***2628.43***	801.44	3448.92	1030.55
	5	***2677.80***	800.47	3632.10	1001.34
	6	***2528.38***	642.72	3354.98	774.12
	7	***2707.52***	893.26	3393.67	881.79
	8	***2669.53***	776.97	3466.65	958.82

Table 6. Response time comparison for below horizon stimuli. (Bold and italicized type indicates that a significantly shorter response time was found.)

		Tactile		Auditory	
Elevation	**Stimulus Position**	**Mean RT**	**SD**	**Mean RT**	**SD**
Below Horizon	1	***2831.18***	1237.00	3807.13	1094.48
	2	***2763.47***	986.35	3530.17	915.89
	3	3164.82	1518.88	4290.30	4880.17
	4	***2585.17***	699.22	3463.80	850.19
	5	3202.93	2043.02	3838.57	1003.84
	6	***2633.12***	770.08	3442.43	861.74
	7	***2798.43***	860.08	3358.37	906.88
	8	***2771.78***	744.94	3653.13	947.50

4.1.2.2 AAD

A factorial ANOVA was conducted to analyze modality, elevation, and stimulus position. The mean AADs for the tactile and auditory conditions were 11.53 (SD = 5.04) and 34.28 (SD = 3.34). A significant main effect was found for modality, $F(1,29) = 795.87$, $p < .001$, $\eta_p^2 = .975$. The analyses for angular error yielded main effects for the elevations above (M = 22.251, SD = 4.00), level (M = 23.929, SD = 4.40), and below (M = 22.540, SD = 3.98), $F(2,58) = 7.37$, $p = .003$, $\eta_p^2 = .345$. Pairwise comparisons found that the Level condition yielded smaller AAD than the Above and Below elevations, which were non-significantly different from one another. There was also a main effect for stimulus position, $F(7,23) = 41.68$, $p < .001$, $\eta_p^2 = .927$. Means and standard deviations are shown in table 7 for stimulus position. Analyses yielded a significant interaction between modality (auditory versus tactile), level (above, level, below), and stimulus position (1 through 8), $F(14,406) = 17.59$, $p < .001$, $\eta_p^2 = .378$. However, analyses also yielded a significant interaction between modality (auditory versus tactile) and stimulus position (1 through 8), $F(7,23) = 30.072$, $p < .001$, $\eta_p^2 = .902$. To further analyze this interaction, paired samples t-tests ($t(29)$, $p = .05$ for all comparisons) were conducted for each position and level to compare auditory and tactile presentations (see tables 8 through 10). Additional *post hoc* tests are available to determine the significant differences within the aforementioned three-way interaction, but for our purposes, we were mainly concerned with modality differences at each position for display design guidance.

Table 7. AAD means and standard deviations for stimulus positions collapsed across modality and elevation.

Position	Mean AAD	SD
1	10.45	5.11
2	24.23	6.23
3	20.90	10.57
4	30.98	4.89
5	15.40	8.03
6	28.42	5.97
7	23.41	8.96
8	29.47	4.74

Table 8. AAD comparison for above horizon stimuli. (Bold and italicized type indicates that a significantly small AAD was found.)

		Tactile		Auditory	
Elevation	**Stimulus Position**	**Mean AAD**	**SD**	**Mean AAD**	**SD**
Above Horizon	1	***3.56***	3.06	19.66	13.57
	2	***11.31***	9.77	31.63	11.37
	3	***11.05***	10.56	22.88	14.67
	4	***8.90***	4.79	58.08	10.51
	5	***9.86***	10.01	22.27	13.47
	6	***9.39***	6.69	53.18	12.93
	7	***16.32***	10.56	23.15	13.88
	8	***18.25***	12.71	36.50	11.57

Table 9. AAD comparison for level with horizon stimuli. (Bold and italicized type indicates that a significantly small AAD was found.)

		Tactile		Auditory	
Elevation	**Stimulus Position**	**Mean AAD**	**SD**	**Mean AAD**	**SD**
Level with Horizon	1	***3.50***	2.51	11.10	8.54
	2	***11.32***	8.42	32.71	13.72
	3	***14.42***	16.80	36.08	14.41
	4	***10.74***	6.03	61.38	8.64
	5	11.92	11.09	15.69	14.18
	6	***9.24***	6.51	57.84	11.10
	7	***17.52***	11.95	35.96	15.76
	8	***17.40***	12.56	36.05	12.35

Table 10. AAD comparison for below horizon stimuli. (Bold and italicized type indicates that a significantly small AAD was found.)

		Tactile		Auditory	
Elevation	**Stimulus Position**	**Mean AAD**	**SD**	**Mean AAD**	**SD**
Below Horizon	1	***3.20***	1.91	21.64	16.43
	2	***11.59***	9.39	46.80	14.22
	3	***15.30***	15.41	25.69	14.02
	4	***9.56***	5.75	37.23	13.14
	5	***10.77***	10.56	21.87	15.38
	6	***7.99***	4.43	32.89	13.08
	7	***17.04***	11.82	30.46	15.36
	8	***16.48***	9.98	52.13	12.18

4.1.3 Discussion

The results clearly show significant and substantial improvements in perceiving the actual direction of the target with the use of tactile cues to alert an unseen referent. Projection to an unseen referent was approximately three times more accurate for tactile presentations versus auditory presentations (tactile mean AAD was 11.53 degrees; auditory mean AAD was 34.28 degrees). Moreover, front-back reversals observed in the auditory condition (a feat difficult with two ears on the sides of the head and widely recognized in the literature as the "cone of confusion") were not found in the tactile display where observers experienced minimal difficulty in discrimination between front-back cues. The cone of confusion ambiguity in the auditory signals may have contributed to the unsure and slowed response times for auditory localization (Blauert, 1997). This increased accuracy may aid Soldiers in orienting their attention more quickly and finding a visually obscured threat faster. Consistent with accuracy, tactile responses were significantly faster by nearly a second compared to the auditory condition (2.74 seconds for tactile responding; 3.58 seconds for auditory responding).

This indicates that future designs for cueing evaluation by touch should endeavor to address this issue. Nevertheless, the overall results of this experiment indicate clearly the feasibility of using tactile displays for directional cueing with important implications for dismounted Soldiers. As sensor nets improve and continue to rapidly locate enemy position, tactile displays can be used as an effective means of rapidly and accurately conveying that information to the individual Soldier.

Chapter 4.2 Tactile Localization From Different Body Orientations (Terrence and Brill)

As indicated in prior work (Brill, Terrence, Downs, Gilson, Hancock, & Mouloua, 2004), the use of tactile signals can provide salient directional cues for surrounding stimuli, thereby reducing the 360-degree visual search space to one of eight sectors in 45-degree increments of azimuth. Notably, these studies were conducted with the participant seated upright with the tactile display in the same plane of reference as the projected stimuli, signifying horizontal azimuth. In order for this display to be feasible for the dismounted Soldier, however, it must reliably and accurately convey directional cues, regardless of the Soldier's body position and orientation (Terrence, Brill & Gilson, 2005).

Accordingly, we examined the same type of directional cueing again as before but with participants in different body positions and orientations that were out of the horizontal plane of reference. The question was, would people in other positions be able to mentally translate from the ring of tactors around the torso to respond to correct directional cues in azimuth? Five body positions were selected for this study, as suggested by our subject matter experts (SMEs) regarding Soldier operational positions. All the following positions were oriented toward the 0-degree forward direction:

- Supine (lying on back with feet forward),
- Kneeling on one knee, opposite dominant hand,
- Sitting in a standard chair,
- Standing,
- Lying prone (on stomach with the head forward).

We examined these body positions for perceived angular direction and for response times with tactile and spatial auditory signals presented at 45-degree increments in azimuth. From prior work, we expected that tactile cues would still yield shorter response times and more accurate angles than spatial auditory cues but that there might be less difference because of the additional processing required for mental rotation in some of the body positions. There is evidence that it does take longer for individuals to make greater mental rotations (Cooper, 1976). This is supported by Cohen and his colleagues (1996) who found that numerous areas of the brain become more cortically active during a mental rotation task as compared to simply viewing stimuli in the same orientation. Both studies suggest that the supine and prone body orientations would require additional mental rotation translation to interpret the cue in the horizontal plane, thereby producing increased response times compared to those of other body positions, regardless of stimulus sensory modality.

4.2.1 Apparatus and Stimuli

To approach the question experimentally, tactors were fitted around the abdomen for each participant as before. The tactile stimuli consisted of 200-ms, 250-Hz sinusoidal frequency bursts at approximately 24 dB above mean threshold. These parameters were selected on the basis of pilot testing and previous experimentation of tactile stimulus parameters (Brill, Gilson, Mouloua, Concodora, & Whitehead, 2004).

The spatial auditory cues were delivered as tones that were emanating from eight equidistant points (45-degree separation) along the azimuth. The auditory stimuli consisted of clearly directional overlapping tones with frequencies of 440, 800, 1000, 4000, 7000, and 11000 Hz delivered via headphones. This arrangement provided three tones below 1.5 kHz for interaural temporal difference cues (ITDs) and above 3 kHz for interaural intensity difference (IIDs). The two highest frequencies were also within a frequency band that allowed the outer ear (pinna) to aid in providing elevation cues and resolving front-back discriminations (Blauert, 1997; Duda, 1993). Pilot testing showed that auditory stimuli of two 200-ms presentations with 50-ms interstimulus intervals afforded sufficient acoustical information for binaural localization. Cross-modal loudness matching procedures determined the appropriate amplitudes for the auditory signals. We measured angular error by taking the absolute difference between the perceived direction by the participants and the direction indicated by the auditory or tactile stimulus (one of the eight equidistant positions). Participants indicated the perceived direction by using a graphics tablet and stylus. The circle on the tablet represented a ring around the participant (top-down view), and they were instructed to indicate at which point along the circle the stimulus would indicate in extra-personal space. A custom software package recorded the stimulus that was presented, the direction indicated by the participant, and the response times from the stimulus presentation to the response capture. Trials (six for each of the eight stimulus positions) were randomly presented without replacement for each body orientation, again determined by random selection without replacement.

4.2.2 Results

The median response trial for each stimulus position (in each body orientation) was then averaged across participants. AADs were computed, based on the absolute difference between the direction indicated by the tactile or auditory stimulus and the direction indicated by the participant.

The results were analyzed with a repeated measures ANOVA and an alpha value of .05, unless stated otherwise. As before, there was a significant and substantial effect for modality showing tactile cueing superiority. The analyses for angular error yielded main effects for modality, $F(1, 29) = 424.41$, $p < .001$, and stimulus position, $F(7, 23) = 44.37$, $p < .001$, while body orientation did not reach significance. RT analyses showed a significant effect for modality, $F(1, 29) = 95.372$, $p < .001$, and a significant interaction between modality and body orientation on RTs was observed, $F(4, 116) = 3.01$, $p < .05$. *Post hoc* comparisons using Tukey's Honestly Significant Difference (HSD) test indicated that RTs for tactile signals ($M = 3.039$ sec, $SD = 1179.6$) were significantly shorter than those for auditory signals ($M = 3.785$ sec, $SD = 1340.8$) at each of the five body orientations, collapsed across the eight stimulus positions. The mean response times and AADs were then analyzed with paired sample t-tests (t (29), $p = .05$ for all comparisons) comparing the tactile and auditory presentations for each stimulus position for the five body orientations. Tables 11 through 15 show the response times and subsequent statistical analysis results. Tables 16 through 20 show the AADs and subsequent statistical analysis results.

Table 11. RTs for supine position. (Bold and italicized means indicate shorter RTs [sec] according to paired t-test [$df = 29$; $p < .05$]).

		Tactile		Auditory	
Body Position	**Stimulus Position**	**Mean RT**	**SD**	**Mean RT**	**SD**
Supine	1	***3.34***	1.39	5.28	2.91
	2	***3.23***	1.2	4.28	1.63
	3	***3.65***	3.28	4.07	1.3
	4	***3.54***	1.74	4.14	1.63
	5	***3.07***	0.92	4.35	1.75
	6	***3.25***	1.21	4.31	1.5
	7	***3.56***	1.18	3.95	1.25
	8	***3.48***	1.79	4.22	1.22

Table 12. RTs for kneeling position. (Bold and italicized means indicate shorter RTs [sec] according to paired t-test [$df = 29$; $p < .05$]).

		Tactile		Auditory	
Body Position	**Stimulus Position**	**Mean RT**	**SD**	**Mean RT**	**SD**
Kneeling	1	***2.7***	0.92	3.82	1.29
	2	***2.7***	0.77	3.4	1.03
	3	***2.63***	0.77	3.18	0.9
	4	***2.71***	0.9	3.63	1.45
	5	***3.07***	0.86	3.56	1.55
	6	***3.25***	0.8	3.5	1
	7	***3.56***	0.79	3.4	0.93
	8	***3.48***	0.9	3.73	1.35

Table 13. RTs for sittng position. (Bold and italicized means indicate shorter RTs [sec] according to paired t-test [$df = 29$; $p < .05$]).

		Tactile		Auditory	
Body Position	**Stimulus Position**	**Mean RT**	**SD**	**Mean RT**	**SD**
Sitting	1	***2.98***	0.94	4.06	1.42
	2	***2.91***	0.88	3.73	1.32
	3	***3.01***	0.91	3.34	1.08
	4	***3.11***	1.05	3.6	1.1
	5	***3.23***	1.45	3.75	1.2
	6	***3.01***	0.98	3.7	1.01
	7	***3.31***	0.97	3.7	1.14
	8	***3.19***	0.97	3.99	1.41

Table 14. RTs for standing position. (Bold and italicized means indicate shorter RTs [sec] according to paired t-test [$df = 29$; $p < .05$]).

		Tactile		Auditory	
Body Position	**Stimulus Position**	**Mean RT**	**SD**	**Mean RT**	**SD**
Standing	1	***3.01***	1.01	3.97	1.41
	2	***2.85***	0.86	3.58	1.13
	3	***2.86***	1.1	3.3	1.18
	4	***2.91***	1.04	3.46	1.3
	5	***2.83***	0.93	3.55	1.2
	6	***2.79***	0.9	3.66	1.38
	7	***3***	0.97	3.5	1.05
	8	***3.1***	1.07	3.75	1.36

Table 15. RTs for prone position. (Bold and italicized means indicate shorter RTs [sec] according to paired t-test [$df = 29$; $p < .05$]).

		Tactile		Auditory	
Body Position	**Stimulus Position**	**Mean RT**	**SD**	**Mean RT**	**SD**
Prone	1	***2.98***	0.99	3.96	0.97
	2	***3.01***	1.16	3.66	0.95
	3	***3.03***	0.96	3.72	1.18
	4	***3.03***	1.27	3.53	0.97
	5	***2.84***	0.88	3.67	1.14
	6	***3.08***	0.93	3.78	1.02
	7	***3.25***	1.02	3.69	1.11
	8	***3.34***	1.05	3.91	0.96

Table 16. AADs for supine position. (Bold and italicized means indicate shorter AADs [sec] according to paired t-test [*df* = 29; *p* < .05]).

		Tactile		Auditory	
Body Position	**Stimulus Position**	**Mean AAD**	**SD**	**Mean AAD**	**SD**
Supine	1	***4.09***	6.46	75.74	53.53
	2	***11.96***	12.45	28.31	15.96
	3	10.31	9.13	16.17	13.10
	4	***11.27***	10.61	54.20	17.36
	5	***5.14***	7.94	45.88	61.13
	6	***11.89***	12.97	53.34	22.20
	7	19.02	20.34	13.14	15.09
	8	***13.76***	11.55	33.23	21.98

Table 17. AADs for kneeling position. (Bold and italicized means indicate shorter AADs [sec] according to paired t-test [*df* = 29; *p* < .05]).

		Tactile		Auditory	
Body Position	**Stimulus Position**	**Mean AAD**	**SD**	**Mean AAD**	**SD**
Kneeling	1	***2.67***	1.79	68.39	56.24
	2	***13.89***	15.10	28.81	21.45
	3	***12.58***	13.40	20.09	13.25
	4	***9.94***	6.51	56.51	20.78
	5	***4.14***	5.91	29.98	43.55
	6	***6.47***	5.52	43.79	24.32
	7	13.10	12.08	13.46	11.17
	8	***18.16***	17.15	35.92	21.08

Table 18. AADs for sitting position. (Bold and italicized means indicate shorter AADs [sec] according to paired t-test [*df* = 29; *p* < .05]).

		Tactile		Auditory	
Body Position	**Stimulus Position**	**Mean AAD**	**SD**	**Mean AAD**	**SD**
Sitting	1	***6.33***	14.64	67.31	56.87
	2	***14.82***	17.32	26.18	20.93
	3	14.80	13.31	20.14	16.62
	4	***9.73***	6.24	52.48	26.67
	5	***5.49***	9.98	33.40	49.56
	6	***12.38***	12.73	49.32	19.54
	7	***10.96***	8.34	19.37	16.59
	8	***11.13***	7.83	26.27	23.37

Table 19. AADs for standing position. (Bold and italicized means indicate shorter AADs [sec] according to paired t-test [*df* = 29; *p* < .05]).

		Tactile		Auditory	
Body Position	**Stimulus Position**	**Mean AAD**	**SD**	**Mean AAD**	**SD**
Standing	1	***5.92***	13.00	72.06	49.05
	2	***11.01***	7.01	32.53	21.70
	3	9.64	12.23	14.18	12.49
	4	***10.26***	5.78	54.42	25.49
	5	***3.96***	7.16	34.04	43.74
	6	***8.73***	6.76	47.19	20.57
	7	12.41	11.53	17.40	16.84
	8	***14.88***	11.61	30.93	23.07

Table 20. AADs for prone position. (Bold and italicized means indicate shorter AADs [sec] according to paired t-test [*df* = 29; *p* < .05]).

		Tactile		Auditory	
Body Position	**Stimulus Position**	**Mean AAD**	**SD**	**Mean AAD**	**SD**
Prone	1	***4.38***	7.74	67.26	51.71
	2	19.14	18.02	28.07	22.05
	3	13.10	13.22	14.98	10.80
	4	***13.41***	14.87	62.52	23.73
	5	***9.44***	20.68	45.52	52.52
	6	***8.71***	5.20	49.43	18.25
	7	18.32	14.23	12.12	12.78
	8	19.94	19.42	27.57	21.57

These results show that spatial tactile display outperforms or equals spatial auditory localization, regardless of body position and orientation. Angle difference calculations showed that participants project from proximal tactile signals better than or equivalent to auditory signals for the eight tested azimuth locations. An examination of the stimulus positions where tactile cues did not significantly outperform auditory cues reveals that auditory cues were robust when they were more lateralized to the left or the right side. This allows participants to fully use ITD and IID cues for binaural localization (Blauert, 1997). Response time data show that responses to spatial tactile cues were significantly faster than spatial auditory cues at each body position and for each point along the azimuth, with no significant effects of body orientation except a longer RT in the supine position.

These findings have robust implications for dismounted Soldiers. Tactile displays for directional cueing can improve response times to threats and offer accuracy performance equal to or better than the accuracy performance of auditory cues to reduce a 360-degree search space to a 45-degree sector, potentially benefiting the visual and auditory senses, reducing workload, and enhancing Soldier performance. (Please see Terrence, Brill, & Gilson, 2005, for the original work.)

Chapter 4.3 Tactile Channeling to Reduce Mental Workload (Mortimer and Gilson)

Undoubtedly, the Soldier of the future will sustain added communication demands, given rapidly advancing technology. These demands will involve new and different types of sensors, signals, and commands available through network-centric warfare to convey necessary information to Soldiers. Can Soldiers successfully multitask with such high attentional and task demands? Soldiers are already tasked with many critical duties demanding attention, so anticipated advances in technology must be balanced in terms of their effects on attentional limitations. Unfortunately, more information may induce processing bottlenecks, taxing not only the sensory channels themselves but also the ultimate ability of each Soldier to attend to that information, depending on the circumstances, stresses, and demands of the moment.

The objective then is to avoid negating hard-earned technological gains by overloading the Soldier with displayed information. Theoretically, parsing and channeling signals to those sensory modalities best suited for the information (spatial for vision, intensity for hearing, and now perhaps movement for touch) will help relieve channeling loads, if not processing loads (Wickens, 2002). Thus, various sensory capacities should be assessed under loads, as well as during less-than-ideal field conditions, in order to select those that will best improve throughput and performance and to determine what tasks/information can be offloaded to modalities other than vision. The following experiments were completed to address the workload aspects and appeared in Mortimer (2006).

The purpose of this two-experiment study was to determine what effect altering the difficulty of the processing of a simple targeting task in a dual task procedure would have on task performance. The simple targeting task required the subjects to use auditory and/or tactile cues to locate a target on a video shooting range. In the first experiment, the guidance cue matched the location of the target in space, i.e., if the target was on the left, the cue was delivered to the left ear or left side. In the second experiment, the guidance signal to move left came from in front of the subject, and the cue to move right came from behind the subject. This required the participants to not only locate the source of the signal but then to mentally rotate the signal before responding. Because the source of the signal was placed in front of or behind the participant, locating the signal became more difficult, especially for the auditory signal because of front-back reversal which is a common phenomenon in the location of auditory signals. Once this was located, the participant had to mentally rotate the signal to determine which way to move the cursor. The second task in the study was a shadowing task in which the subjects shadowed a series of sentences.

According to multiple resource theory (MRT) (Wickens, 2002), the response time to locate the target would have been faster in experiment 1 for the tactile cues than for the auditory cues but slower than the combination of tactile and auditory cues. Second, it was hypothesized that increasing the difficulty of the targeting task in experiment 2 would have resulted in poorer performance across all cues but that the decrement would have been greater for the auditory cues than for the tactile cues. Third, it was hypothesized that auditory cues would have caused more interference on the shadowing task than tactile cues. Fourth, it was hypothesized that participants would have rated the use of the tactile cues as requiring less workload than the auditory cues in all conditions.

4.3.1 Methods

With certain exceptions, the same procedure was used for both experiments. In each experiment, 30 participants first practiced locating the targets with each set of cues, and then a baseline was established for each set of cues. The order of targeting cues and shadowing was counterbalanced across subjects to proof against ordering effects.

The auditory targeting cue and stimulus were delivered through speakers placed to the sides of the participant at a height of 57 inches above the floor and were located 47 inches from the center of the room. In experiment 2, one speaker was placed in front of the subject, and the other was placed behind the subject at the same height. The tactile targeting cue was delivered through two custom-built tactors, which were powered by a custom-built tactor box. The auditory cue was composed of six tones, three under 1,500 Hz (440 Hz, 800 Hz, and 1,000 Hz) and three between 4,000 and 11,500 Hz (4,000 Hz, 7,000 Hz, and 11,000 Hz). The high frequency ensures the use of interaural intensity differences, and the low frequencies ensure the use of interaural temporal differences in localization. The combination of frequencies also helps prevent the signal from being completely blocked by a voice at the same frequency.

The tactile stimulus was a repetitive vibration presented at 740 Hz. The target stimulus was the target range of the video game, Ghost Recon[8]. Targets were programmed to randomly appear between 2 and 9 seconds after the offset of the previous trial. The targets appeared randomly in any one of four positions. The experimental program recorded response time from target onset to target offset.

Upon arrival, the participant was escorted into the experiment area where a research assistant placed the tactile belt around the participant's midsection. In experiment 1, the tactors were placed one on each side, while in experiment 2, one tactor was placed on the front just above the navel, and one was placed on the back.

After the tactor belt was in place, the participants were told that they would complete two tasks, first separately and then simultaneously. Participants were told that they would locate the target using only a tactile cue, an auditory cue, or the combination of the two. In experiment 1, if the cue came from the left, it meant move left. If the cue came from the right, it meant move right. In experiment 2, the cue would come from in front of or behind the participant. If the cue came from in front, the target was to their left. If the cue came from behind, the target was to their right. When the subject was on the target, the cue stopped and he clicked the left mouse button to the trial and reset everything for the next trial. If the cue jumped from one side to the other, it meant that the participant had passed over the target and had to go in the opposite direction. For each

[8]Ghost Recon, which is a trademark of GRAFF Network Services (GNS) Entertainment Services, is a series of military tactical shooter video games.

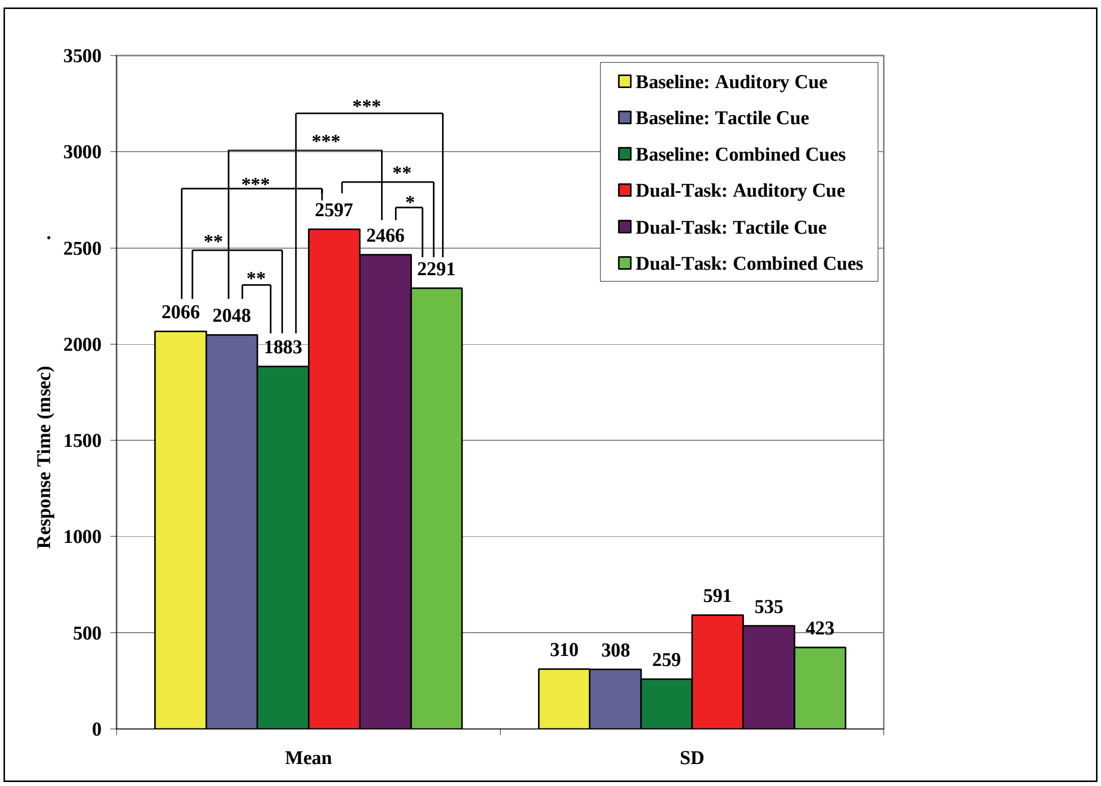
targeting cue, 10 practice trials were given, followed by 25 baseline trials. The practice trials were discarded.

The shadowing stimuli consisted of 80 sentences designed to prevent the participants from using past knowledge as an aid in reproducing the sentences (i.e., "The two men rode and rode and rode and failed to get to the shore"). Five practice sentences were presented to familiarize the participants with the pacing and length of the sentences, and the speaker's voice (e.g., "The green truck was parked outside"). For the shadowing baseline, the participants repeated a set of 15 sentences exactly as they heard them. In the dual-task conditions, the shadowing task was composed of 30 sentences for each targeting cue. Following each baseline and dual-task condition, the National Aeronautics and Space Administration task load index (NASA-TLX) (Hart & Staveland, 1988) was used to evaluate the subjective workload.

4.3.2 Results

4.3.2.1 Targeting Data Analysis

Experiment 1. According to the results shown in figure 4, the participants were slower in both the baseline and dual-task conditions when using only the auditory targeting cue than they were when they used only the tactile targeting cue, but this difference was not significant.



* The mean difference is significant at α = .05.
** The mean difference is significant at α = .01.
***The mean difference is significant at α = .001.

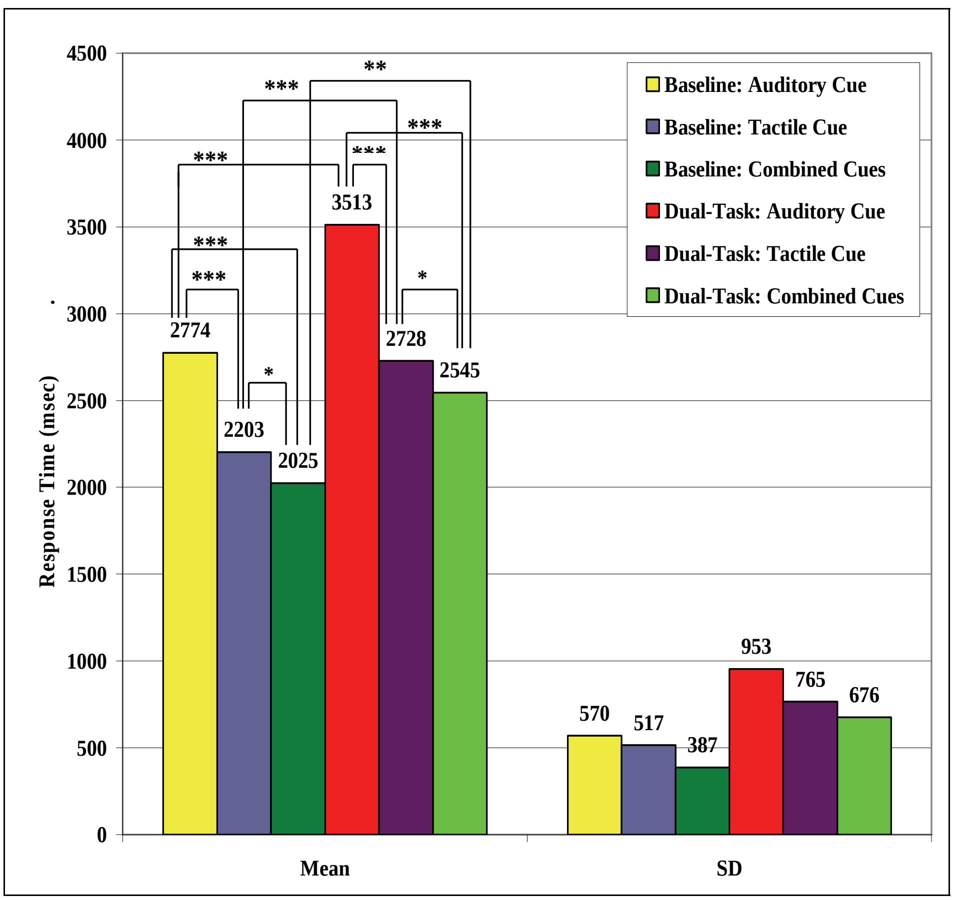
Figure 4. Mean response times and standard deviation and results of pairwise comparisons response times for experiment 1.

In both the baseline and dual-task conditions, participants were significantly faster when using the combined auditory-tactile cues than they were when using the auditory cue alone or the tactile cue alone. This indicates that the combination of targeting cues resulted in improved performance over either set of targeting cues alone.

Finally, the mean response times for all the targeting cues were significantly slower in the dual-task condition than they were in the baseline conditions, which indicated that the addition of the shadowing task significantly slowed the response times of the participants for all the targeting cues.

Experiment 2. According to the results of the analysis as shown in figure 5, in both the baseline and dual-task conditions, the participants were significantly slower to locate the target when using only the auditory targeting cue than they were when they used the tactile targeting cue or both the auditory and tactile cues together. The participants also located the target faster when they used the combined targeting cues than they were when using only the tactile targeting cue.

Finally, the addition of the shadowing task resulted in significantly slower response times for all three sets of targeting cues.



*   The mean difference is significant at α = .05.
***The mean difference is significant at α = .001.

Figure 5. Mean response times and standard deviation and results of pairwise comparisons response times for experiment 2.

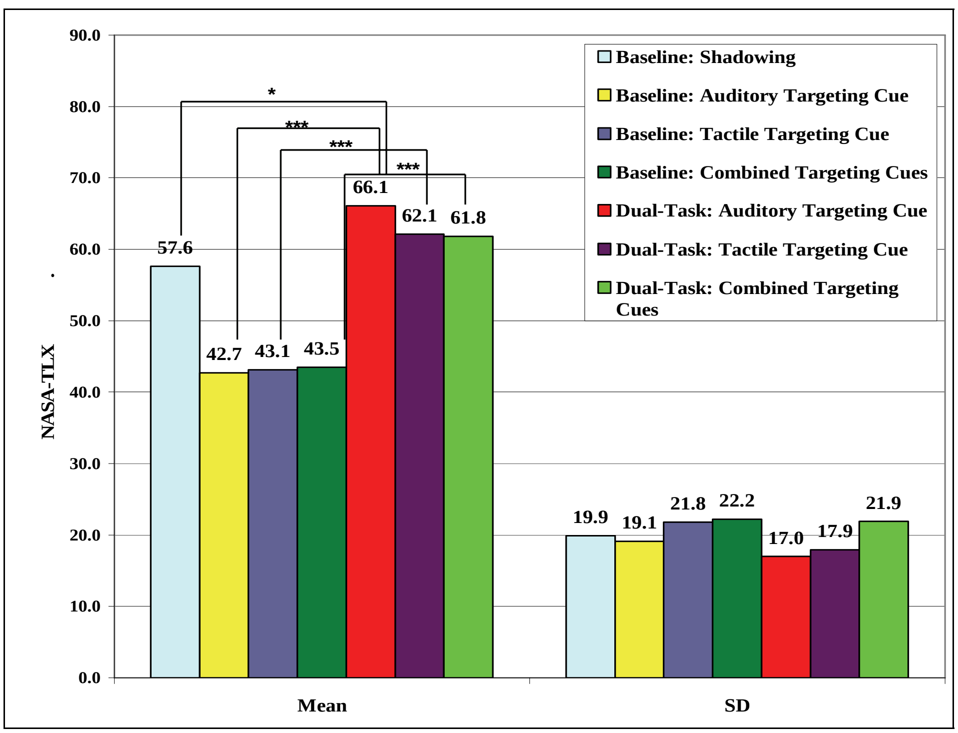
4.3.2.2 Shadowing Analysis

A repeated measures procedure was used to compare shadowing performance in terms of accuracy (the ratio of words correctly repeated to the total number of words) for the shadowing baseline and the three dual-task conditions. No significant difference was found between the four shadowing conditions in experiment 1 or experiment 2.

4.3.2.3 NASA-TLX Analysis

Experiment 1. As shown in figure 6, no difference was found in the mean perceived workload associated with the different targeting cues in the baseline portion of the experiment or the dual-task portion of the experiment.

A significant difference was found between the mean perceived workload for each targeting cue in the baseline and the same cue in the dual-task condition. Participants perceived the targeting task to be more difficult when the shadowing task was added for all targeting cue conditions. They only perceived a significant increase in the workload associated with the shadowing task when the targeting task was added when they were using the auditory cue.

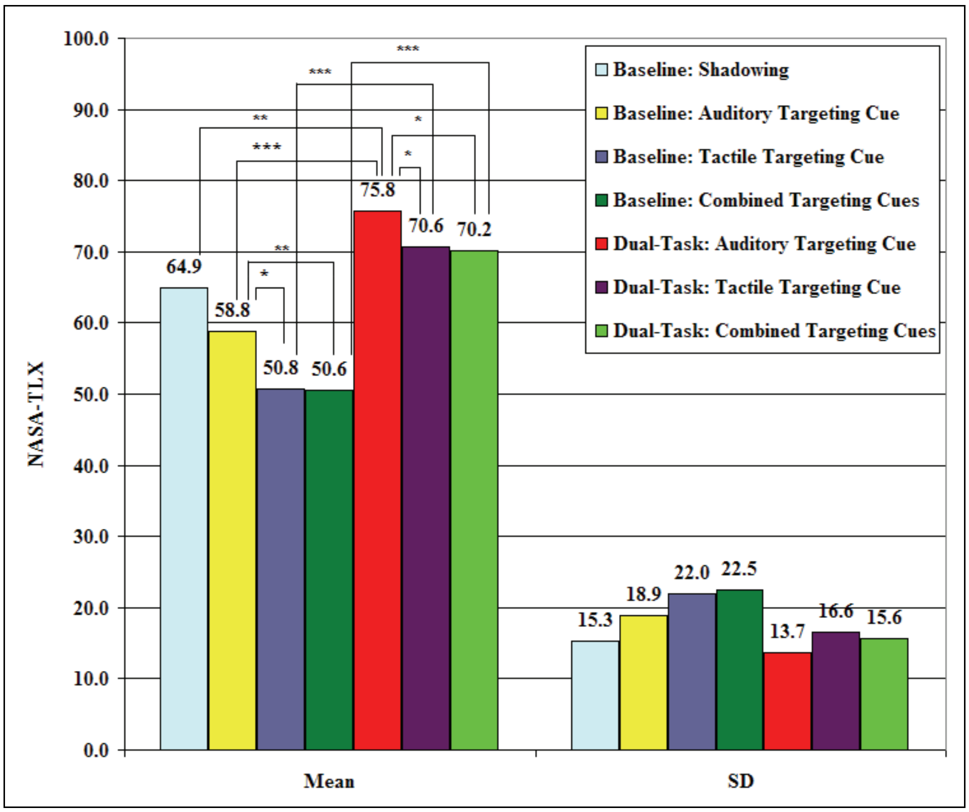


* The mean difference is significant at α = .05.
***The mean difference is significant at α = .001.

Figure 6. Means and standard deviation and results of pairwise comparisons response times for the NASA-TLX, experiment 1.

Experiment 2. As shown in figure 7, the results show that when performing only the targeting task, the participants perceived the task to be more difficult when using the auditory cue than when using the tactile cue or the two cues combined. The results were the same when the shadowing task was added in the dual-task condition.

When comparing baseline conditions with dual-task conditions, the participants believed that the workload increased significantly with the addition of the shadowing task no matter which targeting cue they were using. However, they only perceived a significant increase in the workload associated with the shadowing task when the targeting task was added when they were using the auditory cue.



* The mean difference is significant at α = .05.
** The mean difference is significant at α = .01.
***The mean difference is significant at α = .001.

Figure 7. NASA-TLX means and standard deviation and results of pairwise comparisons response times for the NASA-TLX, experiment 2.

4.3.3 Results of the Cross-Experimental Analysis

A multivariate analysis of the variance was conducted to compare the participants' performance of all measures across the two experiments. The alpha level was set to .05 to distinguish significant effects.

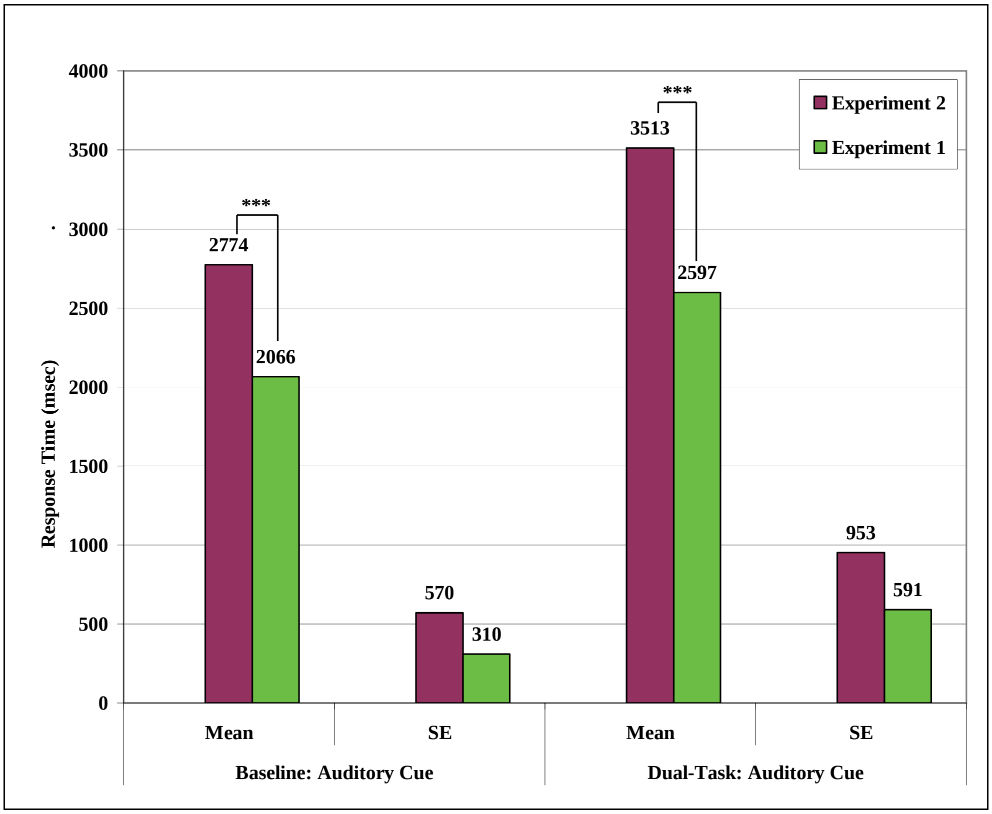
4.3.3.1 Targeting Analysis

As shown in table 21, only the response times for the baseline and dual-task auditory cues were significantly different across the two experiments. No significant difference was found in the participants' response time in the baseline of dual-task conditions with the tactile cue alone or the two cues combined. As figure 8 shows, participants were slower when using the auditory cue in experiment 2 in both the baseline and dual-task conditions.

Table 21. Results of multivariate analysis of targeting measures for both experiments.

	F	df1	df2	Sig.	Partial η^2
Baseline: Auditory Cue Only	10.929	2	87	.000***	.208
Baseline: Tactile Cue Only	.985	2	87	.378	.023
Baseline: Auditory/Tactile Cues Combined	2.009	2	87	.141	.046
Dual-Task: Auditory Cue Only	21.654	2	87	.000***	.343
Dual-Task: Tactile Cue Only	.976	2	87	.381	.023
Dual-Task: Auditory/Tactile Cues Combined	1.663	2	87	.196	.039

***The mean difference is significant at $\alpha = .001$.



***The mean difference is significant at $\alpha = .001$.

Figure 8. Comparison of auditory cue for experiments 1 and 2.

4.3.3.2 Shadowing Analysis

As seen in table 22, no significant difference was found in the performance of the shadowing task across the two experiments.

Table 22. Results of multivariate analysis of shadowing task for both experiments.

	F	df1	df2	Sig.	Partial η^2
Baseline: Shadowing	2.573	2	87	.082	.058
Shadowing for Dual-Task with Tactile Cue	1.574	2	87	.213	.036
Shadowing for Dual-Task with Auditory Cue	2.614	2	87	.079	.059
Shadowing for Dual-Task with Auditory/Tactile Cues Combined	1.870	2	87	.161	.043

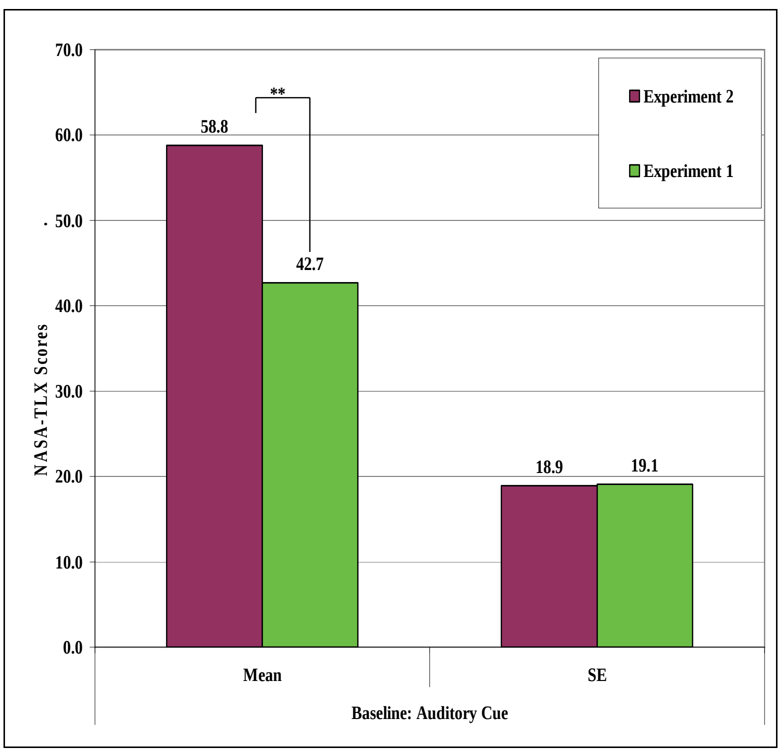
4.3.3.3 NASA-TLX Analysis

As shown in table 23, no significant difference was found in perceived workload except in the baseline auditory condition. As shown in figure 9, the participants in experiment 1, who considered using only the auditory cues in the targeting task, required significantly less effort than the participants in experiment 2.

Table 23. Results of multivariate analysis of NASA-TLX for both experiments.

	F	df1	df2	Sig.	Partial η^2
Baseline: Shadowing	1.340	2	87	.267	.030
Baseline: Auditory Cue Only	5.772	2	87	.004**	.118
Baseline: Tactile Cue Only	2.335	2	87	.103	.052
Baseline: Auditory/Tactile Cues Combined	1.593	2	87	.209	.036
Dual-Task: Auditory Cue Only	3.051	2	87	.052	.066
Dual-Task: Tactile Cue Only	2.677	2	87	.075	.059
Dual-Task: Auditory/Tactile Cues Combined	2.253	2	87	.111	.050

**The mean difference is significant at α = .01.



**The mean difference is significant at α = .01.

Figure 9. Comparison of NASA-TLX means for baseline auditory cues.

4.3.4 Discussion

The purpose of this two-experiment study was to determine what effect altering the difficulty of the processing of a simple targeting task in a dual-task procedure would have on task performance. According to MRT, the response time to locate the target would be faster in experiment 1 for the tactile cues than for the auditory cues but slower than the combination of tactile and auditory cues. The results, however, did not completely support this finding. Although the combination of cues did result in faster response times than for either targeting cue alone, no significant difference was found between the auditory and tactile targeting cues. There are two possible explanations for this finding. First, the shadowing task and the auditory targeting task are familiar tasks that we perform every day, separately and in combination. As a result, we are practiced enough to perform these two tasks together without experiencing decrements in performance of either task. Second, structural features of the auditory system may allow for the performance of the two tasks used in these studies without interfering with each other. Wickens proposes a similar idea concerning vision. He suggests that vision may actually have two resource pools, one for focal vision and one for ambient vision (Wickens, 1992). Similarly, the auditory system may also have two resource pools, one for speech and one for spatial location. Since the shadowing task is a speech task and the targeting task is a location task, they may have been using resources from separate resource pools instead of drawing on resources from the same pool. In this case, the results are probably attributable to a combination of these two explanations.

This suggests that the difference in the sensory systems affects the allocation of resources and that differences within a sensory system may influence the allocation of resources across tasks using that same sensory system.

The results of the second study support the hypothesis that increasing the difficulty of the targeting task would result in poorer performance across all cues but that the decrement would be greater for the auditory cues than for the tactile cues. Again, the explanation for these results is likely because of the differences in the sensory systems used. The targeting task in the second experiment required the participant to determine whether the targeting signal came from in front or from behind. This is the most difficult auditory localization task because of front-back reversal, which is a common problem when we try to locate something auditorily. However, our sense of touch does not suffer from front-back reversal because it is a proximal sense and the stimulus is in contact with the skin. As a result, locating the direction of the signal is simple.

The finding that the tactile cues were not as affected by the increase in task difficulty as auditory cues suggests that even though the tactile and auditory cues were processed spatially, the use of tactile cues enabled the subject to adjust to the increase in task difficulty, thus resulting in only a small decrease in performance. This also resulted in better performance of the second task when the tactile cues were used. This suggests that specific characteristics of the different sensory systems make them more or less resistant to the decrements in performance that result from an increase in task difficulty.

The results also suggest that the interference does not occur at the level of the sensory input for simple spatial cues but instead occurs at the processing level. This may seem unlikely because the assumption can be made that the targeting task requires spatial processing, no matter whether the guidance cues are auditory or tactile. However, this may not be the whole story. The difference in performance between the tactile and the auditory cues may be attributable to differences in the senses themselves. First, touch is a more basic sense than hearing. Second, the tactile cues are delivered directly to the body, whereas auditory cues originate away from the body. This results in a smaller perceptual world for the tactile cues, which can be processed quickly. The auditory cues, however, occur in a larger perceptual world that takes longer to process. These two factors together suggest that the adjustments that the participants needed to make to locate the target in experiment 2 may have been more intuitive and thus easier to make for the tactile cues than for the auditory cues which resulted in the differences in performance and in perceived workload. Thus, when one is developing new systems, the strengths and weaknesses of the sensory modalities to be used should be taken into account.

Chan, MacLean, and McGrenere (2005) looked at the detectability of vibrotactile "icon" cueing by studying their intrusiveness during other multi-sensory tasks. They found that the average detection time with no other task took 1815 ms; with a visual task, it took 3507 ms; and with visual plus auditory tasks, it took 4269 ms. When we compare the most intrusive to the least intrusive vibrotactile icons, respectively, detection times ranged from 2500 to 6000 ms with a visual distractor and from 3000 to 6600 ms with a visual plus auditory distractor. The most intrusive vibrotactile icons used the tactile equivalent of a two-tone sound made when a Personal Computer Memory Card International Association is inserted into and removed from a Windows laptop, i.e., a short buzz followed by a stronger buzz, and vice versa. The least intrusive vibrotactile icons used "pulses" (two quick light taps, delivered periodically), suggesting a person tapping or drumming fingers while waiting in line. Clearly, the design of the vibrotactile icon makes a large difference in "intrusiveness" and should be studied thoroughly and "controlled".

Mahar, Mackenzie, and McNicol (1994) suggested that tactile icon design is improved when the patterns are characterized by changes across time, akin more to audition than vision's spatially distributed patterns. Van Erp and Spapé (2003) essentially used this type of approach to create 59 tactile "melodies" by transforming pieces of music from the auditory domain to the vibrotactile domain. Participants judged these tactile melodies on characteristics such as "melodious," "tempo," "alarming," and intrusiveness. They interpreted these results as supporting the creation of more distinguishable and recognizable tactile signals for single-point tactile displays such as in mobile phones and computer mice. As tactile displays grow in signal complexity, it will be vital for the Soldier in the field to focus on vibrotactile parameters that allow proper identification of a tactile message amid the visual and auditory fog of combat.

In the case of mounted Soldiers, these results are highly encouraging for future display design. Mounted Soldiers must often rely on visual displays for information presentation, but Soldiers within a vehicle are often required to already perform a number of visually based tasks (e.g., driving, navigating a route, maintaining local security). Mounted environments also impose detrimental levels of auditory noise (engine, terrain, etc.). This type of environment does not provide a pristine environment for traditional visual and auditory displays. A tactile display may offer advantages in the mounted context to rapidly provide salient signals that can enhance situation awareness without degrading information pathways for existing combat task demands.

Chapter 4.4 Multi-Modal Information Processing With Touch (Gilson)

Tactile displays have proved to be workload relievers in numerous settings. Tactile haptic displays (those that depend on manipulation) have been shown to be effective in multi-tasking situations, suggesting that touch systems in general can add greater bandwidth for information channeling, aiding both vision and audition. Several American patents of kinesthetic-tactual (KT) (haptic) displays are held by Gilson et al. (U.S. Patents 4,195,802 and 4,093,159) and Fenton (U.S. Patent 3,478,351) and have been extensively studied in multi-tasking situations *in situ* in cars and airplanes (Gilson, Ventola & Fenton, 1975; Gilson & Fenton, 1974). Experiments have shown performance gains for dual tasks using two sensory channels (tactile and visual) over dual tasks that use the same information channel (visual and visual) input (Jagacinski, Flach, & Gilson, 1983; Burke, Gilson, & Jagacinski, 1980; Jagacinski, Miller, & Gilson, 1979; Gilson & Fenton, 1974).

For example, in an early experiment, a critical tracking task was used to examine performance with a uni-dimensional KT display embedded in a joystick control or an equivalent visual display. The participants were asked to control an increasingly unstable system until they lost control. The results indicate that this method was a feasible and a reliable technique for assessing tactual tracking and that both displays demonstrated approximately equal performance, highlighting the ability of KT displays to provide information as robustly as visual displays, allowing visual attention to be directed to other critical locations (Jagacinski, Miller, & Gilson, 1979).

In later experiments, two KT displays (one in each hand) were compared to two visual displays and were intermixed, with one display serving as the primary task and one serving as the secondary task (Jagacinski, Flach, & Gilson, 1983). In the mixed modality situation, tactile and visual, the KT display resulted in superior cross-modality performance (Burke, Gilson, & Jagacinski, 1980). Comparisons of various combinations of primary and secondary visual displays in integrated or separated formats indicate that the superiority of the KT display was not simply attributable to the elimination of visual scanning but to some modality influence. The clear suggestion in these studies is that manual tracking with a KT (haptic) display can be an effective alternative or supplement to visual displays and that similar effects could be possible for other touch displays if they were implemented as intuitively.

Section 5. Tactile Messaging

Chapter 5.1 Constructing Tactile Messages (Stafford, Gunzelman, Terrence, Brill, and Gilson)

Shifting from simple alerts, cueing, and directional guidance to the viability of remote touch as a real-time communication system for Soldiers is an important leap. Clearly, a system akin to Braille is impractical for Soldiers using their hands for other tasks, but the success of Braille suggests the intriguing possibility of using a type of specialized dynamic tactile lexicon. Braille has not superseded print, and full dynamic tactile "literacy" undoubtedly will not supersede other forms of military communications. Moreover, various notable research endeavors over decades have attempted but failed to produce a viable tactile system for language (Brewster & Brown, 2004a).

Nevertheless, although a full conversational language may not be feasible because of hardware, physiological, or psychological limitations, a practical tactile lexicon clearly does have potential for improved response times, accuracy, and verification for Soldiers. The key is to identify and develop intuitive means to convey critical information. The creation of a functional command system could serve the dismounted Soldier well in certain operational settings, where silence must be maintained and visibility is low, making traditional arm and hand signals difficult. Several studies with Soldiers now show that limited bandwidth touch messaging is quite possible with only a modest level of sophistication (e.g., encoding tactor activation; Brewster & Brown, 2004b).

We began developing the tactile lexicon by asking Soldiers what was needed to develop a viable tactile communication system to overcome current line-of-sight and need-to-be-silent limitations. Their response was to avoid creating a completely new language but instead focus on adopting existing communications (e.g., remotely communicating U.S. Army arm and hand signals). Soldiers are well versed in these signals, and any tactile analogy that could potentially convey equivalent information would benefit from transfer of existing training.

Our approach to development of a tactile lexicon started with a focus group of SMEs (with Special Operations experience) to suggest how to convey a sampling of standard Army hand and arm signals as tactile icons or tactons. Based upon their suggestions, we tested the concept by first emulating and then conveying each message. Tactons are structured messages encoded tactually by the manipulation of cutaneous stimulation parameters (e.g., place, timing, temporal sequencing, etc.) to represent specific information. The encoding is similar to that of icons for vision or earcons for sound where musical parameters (e.g., frequency, timbre, rhythm, intensity, register) are varied to create concise, easily understood, and rapid ways of communicating information (see Blattner, Sumikawa, & Greenberg, 1989; Brewster & Brown, 2004a; Lemmens, Bussemakers, & de Haan, 2001). Likewise, similar parameters can be used for tactons, although their relative importance may be different.

5.1.1 The Signals

The six key signals that our original SME focus group suggested were intended to correspond to their visual hand and arm signal counterparts and were created in the laboratory based upon known scientific techniques. For the most part, they worked well, but each could be improved as indicated below:

- **Visual Halt** or stop is simply signaled by a raised hand, palm forward. **Tactile Halt** was originally envisioned as a surround of simultaneously activated tactors "holding the Soldier in place". It could have been a more impressive and easily distinguishable signal but was restricted to the simultaneous activation of only four opposing tactors (2, 4, 6, and 8) because of current technical limitations. The SMEs suggested that actuating all eight tactors at the same time would improve HALT and further that the command be repeated several times, as it is, for emphasis. As an option, we could use two belts and activate offset tactors (in two groups of four) to produce a much more distinct and powerful "holding" sensation than four tactors alone. This potential solution will require additional testing with specific foci on comfort and power requirements.
- **Visual rally** is signaled by a raised arm, circling overhead. **Tactile rally** simulates this wave by sending a traveling pulse around the body clockwise, for a total of three iterations. What we used for the skin motion was the "Tau" effect that works well in a laboratory setting but sometimes can be confused in an applied setting with other motion commands that also use a traveling pulse, such as "move out" and "attention" if the Soldier focused more on the feeling of motion rather than the combination of the feeling of motion and the number of tactors involved in that motion. Most Soldiers correctly understood this command as the signal completely "played out"; nevertheless, the SMEs suggested that the sensation go around the body several times. The subject would then have more exposure to distinguish which signal was activated and to self-correct if necessary.
- **Visual move out** is signaled by first facing the direction of movement with the arm held overhead and behind, then swinging the arm forward to the horizontal and pointing toward the direction of movement. **Tactile move out** correspondingly starts by signaling the rear tactor (5) and then sends simultaneous pulses traveling along both sides of the body toward the front. After the signal reaches the front tactor (1), it pulses five times. Currently, the command appears to start with motion and ends at a point with stimulation. To make this signal more distinguishable from rally, we need to repeat the beginning of this signal, perhaps by two taps at tactor (5) "to push the Soldier from behind" and thus better emphasize the feel of the motion forward.
- **Visual attention** starts with the arm extended forward just above the head with the palm facing forward and is signaled with a hand-arm waving motion. **Tactile attention** attempts to simulate that wave by sending a moving pulse left to right through the front three tactors (8, 1, and 2) sequentially, then repeating the motion three times by alternating the motion

right to left with tactors (2, 1, and 8). Attention was intended to create an "attention-grabbing" sense of motion across the front as a preparatory signal to be followed by another command, but it also could initially elicit the "rally" response if the motion feature were the main focus. Our SMEs suggested simply having the three front tactors buzz at the same time as "a pause for attention".

- **Visual NBC** (nuclear, biological, chemical) attacks are signaled by extending both arms to horizontal and then quickly bending the arms toward the shoulders repeatedly as the command for donning protective gear. **Tactile NBC** is signaled by pulsing the two side tactors (3 and 7) simultaneously for five iterations as an intuitive emulation of tapping the shoulders with the fingertips.
- **Visual direction** is not a command per se but is implied by the way the body is facing in the "move out" command. **Tactile direction** is signaled only after the "tactile move out" command by activating the tactor that signifies the direction of the movement. Our SMEs suggested that the direction might be repeated.

Experimental work to date has shown that we have successfully used position, onset timing, and repetition to develop tactons into a simple language that easily and intuitively associate with basic U.S. Army hand signals such as attention, halt, move out, rally point, etc. What has been so effective and intuitive about these tactile signals is their similarity to standard Army hand and arm signals that were so well known for the commanded action required. Substantiation will be apparent in the next part of this chapter. Repetition currently adds only emphasis, i.e., as the command becomes more urgent or requires more immediate compliance, tacton activation is repeated rapidly in order to convey this insistence. Amplitude can be distinguished, but subjects in the field do not detect signals easily when the frequency decreases. When this occurs, subjects report that they can only slightly feel the signal and can barely detect what is occurring. Observationally, the subject "stills" his body and shows the same behavior of a person who is trying to listen to a quiet whisper. More work is needed to refine and expand the tactile lexicon.

Chapter 5.2 Tactile Recognition Experiments at West Point (Matthews, Graham, Smith, and Terrence)

The experiments reported in this chapter were conducted at West Point, U.S. Army Military Academy (USMA) as a part of West Point Cadets' research experience. Cadet research groups used different techniques to evaluate UCF's prototype tactile system and signal designs. Our observation of this work is that it was independently and professionally conducted and that the evaluations revealed that

- The original UCF tactile patterns needed some minimal training but could be learned quickly (with substantial improvements in as few as 5 minutes).
- The UCF tactile patterns were rated as highly intuitive and generated thinking about new tactile commands, some of which in turn proved to be just as intuitive.

- The preparatory tactile alert envisioned by UCF may be an unnecessary step that only adds itself as a delay.

Team 1 examined training effects on tactile accuracy and response times. Long training times (well beyond 5 minutes) and significant improvements would have suggested less intuitiveness on the part of the tactile signal designs or at least would imply less transfer of training from previously learned standard Army hand and arm signals upon which the tactile patterns were based.

For this study, the training group received 5 minutes of instruction with the tactile arm and hand signal patterns using the UCF prototype systems. The control group did not receive any instruction with the tactile display but were told how the system worked and of its intended purpose to present signals via remote touch. Participants were then fitted with the display, and each received two sets of the five tactile signals. All participants were instructed to verbally call out the tactile arm and hand signal as quickly and accurately as possible.

An ANOVA was performed for accuracy and response times, with an alpha level of 0.05 for all analyses. Training did significantly improve accuracy, $F(1, 36) = 13.660$, $p = .001$, partial $\eta^2 = .275$, but there were no significant differences in terms of response times between the training and the control groups. Conversely, although accuracy did not improve from the first set to the second set, there was a practice effect in that response times did improve significantly over time, $F(1, 36) = 8.390$, $p = .006$, *partial* $\eta^2 = 0.18$.

Evidently, one short 5-minute training session is effective in improving the accuracy of tactile signal recognition. This suggests that the tactile patterns are not so intuitive that they can be readily identified without any training; nevertheless, only 5 minutes of training was sufficient to significantly boost accuracy from 51% to 75% across all signals. The Cadet group also noted that the decrease in response time from set 1 to set 2 may indicate that although Cadet participants may not be sure of a signal's intended meaning, they may quickly adopt a meaning and respond with increasing speed with repeated presentations. If so, this would suggest a recognition, not a tactile detection issue. The group closes with the suggestion that additional training, perhaps combined with feedback of performance, may prove beneficial, but only 5 minutes of training do offer substantial gains.

Team 2 examined the intuitiveness of UCF-designed tactile arm and hand signals, and eight more Cadet-proposed tactile patterns (based on four arm and hand signals with two versions of each). The four Cadet signals chosen for conversion to a tactile pattern were "enemy in sight," "double time," "danger area," and "take cover". This Cadet group hypothesized that one alternative of each of their newly developed signals will be subjectively rated more intuitively than the other and expected that the more highly rated patterns would fall into the intuitiveness range established by the five original UCF patterns.

In this study, 21 Cadet participants were presented each of the five original UCF tactile patterns and were asked to rate its level of intuitiveness with the arm and hand signal on a 7-point Likert scale (extremely unintuitive to extremely intuitive). The participants were then presented with the new tactile patterns for the arm and hand signals and were asked to rate them in the same manner as the original five. Patterns were presented in a counterbalanced fashion to avoid potential order effects on the subjective ratings:

- **Visual take cover** is commanded by extending the arm out from the side above the horizontal at a 45-degree angle with the palm down, and then lowering the arm to the side. **Tactile take cover** patterns were tested by

    1. A "racheting" sequence with tactors 1, 4, and 6 vibrating first, followed by tactors 2, 5, 7, then tactors 3, 6, and 8 and ending with vibrations on tactors 4, 7, and 1, or by
    2. "Half motion" sequences, starting first with tactors 1 and 5 vibrating simultaneously and then activating the pattern to travel clockwise along the display from tactor 1 to 5, repeating twice to complete two separate half circles of movement.

- **Visual double time, or Rush** is commanded by raising the fist to the shoulder and thrusting the fist upward to the full extent of the arm and back to shoulder level, rapidly several times. **Tactile double time** patterns were tested by

    1. Starts from the rear tactor 5 and traveling along both sides to tactors 3 and 7, respectively, and then moving back to tactor 5. The pattern concludes by immediately starting again at tactor 5 and traveling along the sides to tactor 1, or
    2. Tactors 3 and 7 vibrate simultaneously, followed by tactors 2, 4, 6, and 8. The pattern concludes with tactors 1 and 5 vibrating simultaneously.

- **Visual danger area** is commanded by drawing the right hand, with palm down, across the neck in a throat cutting motion from left to right. **Tactile danger area** patterns were tested by

    1. The pattern originates at left front tactor 7 and travels left to right across tactor 1 to tactor 3 then returns along the same path right to left, back to tactor 7, and then repeats.
    2. The pattern originates at tactor 7 on the left side of the body and then travels across the body adding by activation tactors 8, 2, and 3 as it "zooms" to the right until all tactors 7, 8, 2, and 3 are simultaneously activated. The pattern then "returns" by traveling back to the left deactivating each of the four tactors in reverse order.

- **Visual enemy in sight** is commanded by holding and pointing the weapon in the ready position at shoulder level in the direction of the enemy. **Tactile enemy in sight** patterns were tested by

    1. A crosshair-type sensation created but activating tactors 3 and 7 followed by tactors 1 and 5. This pattern then repeats, leaving the operator in the center of the crossing patterns.

2. Starting at tactor 1 and then simultaneously traveling left and right around to tactors 3 and 7 respectively. The pattern then repeats once more.

An ANOVA was performed for accuracy and response times, with an alpha level of 0.05 for all analyses. The results show that alternatives for "enemy in sight" and "take cover" were not rated significantly different from one another. However, alternative 1 for double time and alternative 2 for danger area were rated significantly higher than their respective alternatives. Each of these alternatives fell within the range of subjective ratings established by the five original UCF tactile patterns for arm and hand signals.

This Cadet group concludes that "the tactile patterns developed for double time and danger area with the highest subjective ratings may be useful additions to the growing tactile pattern lexicon." Further, while additional testing with performance measures in field settings would be needed to corroborate these findings, this subjective rating method for intuitiveness may prove to be a useful starting point for developing tactile patterns for Soldier populations.

Team 3 examined whether a tactile preparatory "attention" alert before a tactile command would significantly facilitate responses under the distraction of a dual-task experimental paradigm. They expected that receiving a preparatory command would result in shorter response times and increased response accuracy, reasoning that a Soldier could be better prepared to receive incoming information and thereby be able to divert some of his attention to the subsequent tactile pattern.

5.2.1 Method

In this study, Cadet participants were randomly assigned into one of two groups: a preparatory alert group (attention) before each tactile command signal or a no-preparatory command before each tactile signal group. Each participant was fitted with the display and was then instructed to play a first-person shooter game (Halo 2[9]) and to verbally respond with the arm and hand signal as quickly and accurately as possible. The experimental protocol introduced an average time interval of 35 seconds in between commands to allow the participant to become immersed in the game task.

An ANOVA was performed for accuracy and response times, with an alpha level of 0.05 for all analyses. Although no significant differences were found for accuracy of identifying the vibro-tactile patterns, the mean response times of the two-step group were significantly longer than those for the one-step group, $F(1, 17) = 9.525$, $p = .007$, *partial* $\eta^2 = .359$. This is not unexpected since the preparatory command requires time to administer in itself and does account for the increased time. When the time required for the preparatory alert was subtracted from the two-step responses, the reanalyzed data yielded no significant differences in the response time means for the one- and two-step groups.

[9]Halo 2 is a registered trademark of Microsoft Corporation.

This Cadet group concluded that the use of a preparatory alert does not significantly improve response times or accuracy regarding a subsequent tactile command even while subjects are performing another attention-demanding task. They suggest that tactile displays may differ in attention sharing with a visually demanding task and thus may not impact perception of a tactile command. If so, "field units may not need to issue the preparatory command, a move which will reduce power consumption during use in combat settings."

These cadet projects fulfilled three research objectives. First, the importance of training with tactile arm and hand signals. While the signals are not immediately recognized, approximately 5 minutes of training was enough to drastically improve the identification accuracy for tactile signals. The second group helped to develop a subjective method for evaluating new tactile encoded arm and hand signals. Third, the utility of the "attention" command in a secondary task paradigm was not found to improve identification performance for the following command. Transferring these findings to field applications, it will remain important to consider the training needed for the current and any expanded tactile lexicon of arm and hand signals. Subjective rating methods will need to be combined with additional performance-based metrics for new tactile commands. The use of attention as a pre-cursor signal to additional tactile commands will need to be evaluated in closer-to-field conditions to determine if it is needed to ensure reception of the tactile command while the Soldier is performing combat-related tasks.

Chapter 5.3 Physiological Stress Messaging Studies (Merlo, Stafford, Gilson, and Hancock)

Physiological stress studies were conducted at West Point in advance of Soldier field IMT experiments at Fort Benning. Before the Fort Benning experiments, we wanted to identify any system or procedural weakness and to correct what was necessary before involving major investments of ARL resources. We worked to stress the participants and to challenge the capabilities of this tactile display system to convey cues, signals, and messages, while testing for ease of use, reliability, and accuracy.

The specific purpose of this study was to determine if this prototype tactile display would result in accurate reception of tactile localization and messages during vigorous body motion and physiological stress. The experiments and evaluations fall into two parts. First, we required participants to run on a treadmill within a controlled environment and then tested them for tactile cue recognition accuracy under the induced physiological load. To accomplish this, each of 10 Cadet participants first ran on a treadmill to increase heart rate to 80% of his theoretical maximum. When achieving their individual stress criterion level and while still running on the treadmill, they were tested in their ability to identify tactile localization and messaging of tactile arm and hand signals across three blocks of experimental trials.

Block 1 consisted of directional cues, meaning that two short stimulations were presented from one of eight tactors on the display. In this block, each tactor was presented three times for a total of 24 total directional presentations. Block 2 consisted of each of the four messages being presented on the tactical display. The messages were each presented five times for a total of 20 messages.

Block 3 consisted of both directional cues and message presentation intermixed. Each directional cue was presented twice for a total of 16 signals, and each message was presented twice for a total of eight signals.

Of the total 680 tactile signals presented to the ten Cadet participants (68 to each), none of the messages were missed, and only four signaled directions were misidentified by 45 degrees (i.e., Soldier reported west when it was a southwest tactor; see figure 10).

The overall 99.4% accuracy rate displayed by the participants is highly encouraging to the current tactile display design. The accuracy of the messages and the reported intuitiveness with which they were received is also a testament to the utility of the SME information and the present "language" transformation format. The results showed that USMA cadets running hard on a treadmill had almost error-free performance, demonstrating that messaging and localization of tactile signals during these conditions was unaffected by physiological arousal or stress and unaffected by strenuous movement and whole body locomotion. Even more striking, these results occurred with only minimal training on the system, fewer than 10 minutes. These findings further validated current location and message cues; no further modifications of the current system were suggested by participants during the course of this study. This suggests that regular Soldiers could recognize various tactile signals quickly and accurately while moving about strenuously in the field.

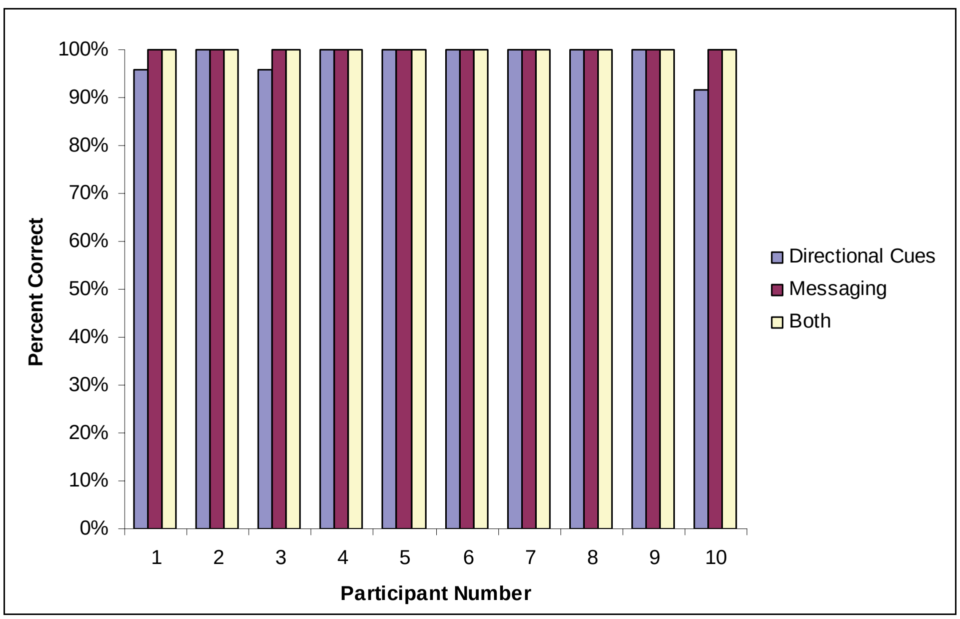


Figure 10. Percent correct by block. (The only four errors made in the 680 trials were directional cues.)

Chapter 5.4 Tactile Distance Experiments at the Naval Postgraduate School (Shattuck, Duehring, and Hannen)

The experiment reported here was conducted at the Naval Postgraduate School (NPS) as a part of the students' research experience. Student research groups developed different means to assess and to use UCF's prototype tactile system and signal designs. We are most thankful for their work and dedication.

A study by NPS students examined UCF's prototype tactile system with the objective of presenting distance information as well as new types of directional cueing to a target. This group devised and evaluated four methods to communicate distance and two methods of communicating direction, one quantitative and one qualitative. This effort augments prior UCF research and shows that tactile cues are an effective means to communicate both direction and distance.

Van Erp, van Veen, and Jansen (2005) discussed tactile navigating with a vibrotactile belt of eight tactors, each of which represented a cardinal direction (e.g. N, SE, NW, etc.). Van Erp (2005a) and van Erp and Verschoor (2004) use the phrase "tap on the shoulder" to describe the effect of tactile cues when directionality is communicated. They also used a variety of methods to attempt to communicate distance, including varying intensity (e.g., greater intensity for closer distances) and varying the "off" time between consecutive vibrations (e.g., different tactor time "off" intervals to indicate different relative distances). Their research shows that tactile communications can be used to indicate distance as well as direction, although they do state that some of their methods for communicating distance may have been confusing.

Lindeman, Sibert, Mendez-Mendez, Patil, and Phifer (2005) studied the use of tactile cues to locate objects within a virtual building. These researchers also used an eight-tactor belt fastened around the participants' waist. In this study, participants were instructed to do a sweep to find items located within a virtual building. Their results showed that the use of tactile cues reduced the time spent in locating objects during the virtual building sweep. The study also suggests that the torso is a good location for tactile communication; the torso belt design keeps the participants' hands free. Lindeman et al. (2005, p. 278) concluded that "a torso-mounted vibrotactile display can provide effective cuing."

Ho, Tan, and Spence (2005) used vibrotactile cues to alert car drivers to critical dangers presented from the rear or the front of the vehicle. Their work showed a significant improvement in participants' recognition of events in front of the car and behind the car. This improvement in sensing allowed participants to avoid an impending collision (Ho et al., 2005). Although these researchers only used tactors attached to participants in front and behind, they were able to show that tactile communication of impending danger is effective, especially when compared to participants who did not have the additional cues to assist them while driving. This research, when considered with other research in multiple resource theories of attention, suggests that a combination of tactile and visual cues will improve operator's performance or at least will not negatively detract from performance based solely on visual sensory input (Van Erp & Verschoor, 2004).

Multiple-resource theory states that individuals can acquire information via multiple modes of sensory input (Wickens, 2002). This means that very generally speaking, given two simultaneous input under high workload, people are usually better able to understand both if information is delivered via different senses than via a single channel. Of course, there are many contingencies in the theory that specify what kind of information, under what type and level of cognitive workload, in order to make specific situational predictions. This theory and the work of many researchers (Lindeman et al., 2005; Ho et al., 2005; van Erp, 2005a; Terrence et al., 2005; van Erp et al., 2005; van Erp & Verschoor, 2004) led this group to the conclusion that tactile cues could be effective at providing distance cues, as well as direction cues, with regard to target location relative to a Soldier in the field.

The research by Duehring and Hannen presented here used UCF's eight-tactor belt and four methods to communicate direction and distance to potential targets. There were four methods of providing distance information (all in the direction of an actuated tactor):

- **Method 1** Patterns of long and short pulses indicating discrete distance to indicate distance.
- **Method 2** Timed pulses that indicated distance, where longer pulses represented greater distances.
- **Method 3** Variable intensity of tactile cues where greater intensity represented a closer distance.
- **Method 4** Variable frequency between successive pulses where shorter time between pulses indicated a distance closer to the target.

Eight subjects, two female and six male, participated in a counterbalanced within-subject study. Each person participated in all four methods of communicating distance as described previously. Only the method for communicating distance varied from trial to trial.

Participants were instructed to respond verbally and to indicate direction and distance to the indicated target. They were seated for the duration of the experiment. Each of the eight tactors represented a compass direction (N, SW, E, etc.), with the front tactor representing north. One researcher transmitted the distance and direction information via the Bluetooth dongle and recorded the participants' response directly into an Excel[10] spreadsheet. In all trials, the tactors vibrated along the intended direction. Fifteen target distances were communicated for each of the four methods for a total of 60 targets per participant.

An ANOVA and pairwise comparison t-tests showed a statistically significant difference for the four methods of communicating distance, $F(3, 21) = 15.685$, $p < .001$. There were significant differences between the following pairs of Methods: 1 - 2, 1 - 3, 2 - 4 and 3 - 4, but not when Method 1 was compared to Method 4 or when Method 2 was compared to Method 3. Simply put, Methods 1 and 4 yielded significantly more accurate responses. The mean correct responses for the four methods are as follow (of a possible 15):

[10]Excel is a trademark of Microsoft Corporation.

- **Method 1** = 10.3
- **Method 2** = 4.8
- **Method 3** = 6.6
- **Method 4** = 12.4

Although each of these methods was expected to convey some scale of distance to potential targets, it was predicted that Method (1) with its combinations of long and short pulses would provide the most accurate quantifiable metric for distance. It was a surprise then to find that Method 4 was just as accurate in communicating both distance and direction. Members of the cadet research group explain the results in the follow-ing manner:

- **Method 1** provided discrete long and short pulses to indicate distance to target. It may only have achieved the same performance as the relative distance used in Method 4 because of any potential misinterpretations of short and long pulses. This could easily result in a miscalculation of distance. Mental arithmetic has also been found to be a difficult task, consuming central executive resources in working memory (Logie, Gilhooly, & Wynn, 1994). This may explain equivalent performance with Method 4, despite providing discrete distance information.
- **Method 2** required participants to perceive pulse time to within 0.5 second, without a timing device. Accurate perceptions of elapsed time are difficult (Block, 1990), particularly when multiple presentations must be remembered. Accurately perceiving the temporal durations and processing them may have entailed too high of cognitive burden to be useful as a distance display.
- **Method 3** was a categorical, not a scalable, measure, relying on only three categories of near, intermediate, or distant levels for 15 target distances. Furthermore, the low intensity pulse indicating distant targets in Method 3 was not felt by many participants, resulting in missed cues with respect to distant targets, and many could not distinguish the difference between medium and high intensity pulses making near, and intermediate distance judgments difficult.
- **Method 4** yielded performance equivalent to that of Method 1. Method 4 always had at least two different distances to compare (i.e., increasing versus decreasing frequency for distance). This gave the participant a reference that he could feel intuitively but still omits precise distance. The success of this stimulus design may be found in its similarities with perceived urgency alarm design, with more rapid pulses indicating a close target. This design parameter is often used in auditory alarm design (Hellier, Edworthy, & Dennis, 1993) and may translate easily to tactile display design. As stated previously, precise distances may prove difficult in a counting task, regardless of alternative modality. Method 4 is described as a good qualitative method when in the general vicinity of a target, but more precise distances will require refinements.

Future research plans include modification of Method 1 to establish a clearer indication of long and short pulses. Additional research is necessary in order to determine the factors yielding equivalent performance for Methods 1 and 4 and how to modify stimulus parameters to increase accuracy in distance perception with tactile displays.

Section 6. Application and Fielding Considerations of Tactile Systems

---

Chapter 6.1 Sniper Soldiers' Evaluations (Elliott, Stafford, Brill, Terrence, and Gilson)

In this chapter, we describe a preliminary evaluation of the prototype UCF tactile system for covert communications that was conducted by ARL and UCF researchers under contracts to DARPA at the Sniper School at Fort Benning. UCF and ARL research teams met with instructors and students at the Fort Benning Sniper School to obtain informal user input while the system and signals were in development, in order to gain the operational perspective of Soldiers.

The sniper Soldier is an obvious source for input in this process because of direct relevance of covert communications to the conditions of his usual missions, which include exposure to adverse conditions, need for mobility and stealth, and limited audio communications. In addition, Sniper School instructors and students are well qualified for these evaluations, including extensive in-service time and high average mental and physical abilities. Participants ranged from E-4 to Captain, and all had previous combat experience in Iraq. Approximately 50% of the students tried the tactile system, and none received training before using the system, other than a 5-minute explanation of use.

The research team observed sniper Soldiers engaged in two days of actual training exercises that ranged from classroom to field and urban stalking exercises. The following are the results of an informal evaluation of the UCF tactile prototype performed by ARL. The questionnaire was administered after demonstration of the tactile system to ten of these Soldiers.

Before the demonstration, UCF researchers explained to the Soldiers that the goal of their research was to create another communication channel using touch for messages. The requirement was for a rugged design that would not interfere with other equipment and would allow full access to natural sight and sounds. After receiving the demonstration, the Soldiers were asked to complete a questionnaire, which was developed and provided by ARL. Each item was rated on a six-point numerical scale. Participation in the evaluation was completely voluntary, and the only instructions given were to be objective and honest.

The overall outcome was a clear message to proceed with development, along with several specific recommendations that are now being considered. The first part of the questionnaire began with two "global" questions asking students to evaluate the overall usefulness of the system from a conceptual perspective. The first question asked about using the system for target detection, and the second asked about its utility for covert communications. The response to the questionnaire was judged favorably by the ARL team.

The second part of the questionnaire contained several items pertaining to operational relevance (again rated on six-point scale from 1 = not at all, to 6 = extremely relevant). The results are displayed in the following graph (figure 11), with regard to relevance for wooded reconnaissance, MOUT (military operations in urban terrain) reconnaissance, wooded overwatch, MOUT overwatch, and patrol. Results were high for all situations and highest for the reconnaissance missions.

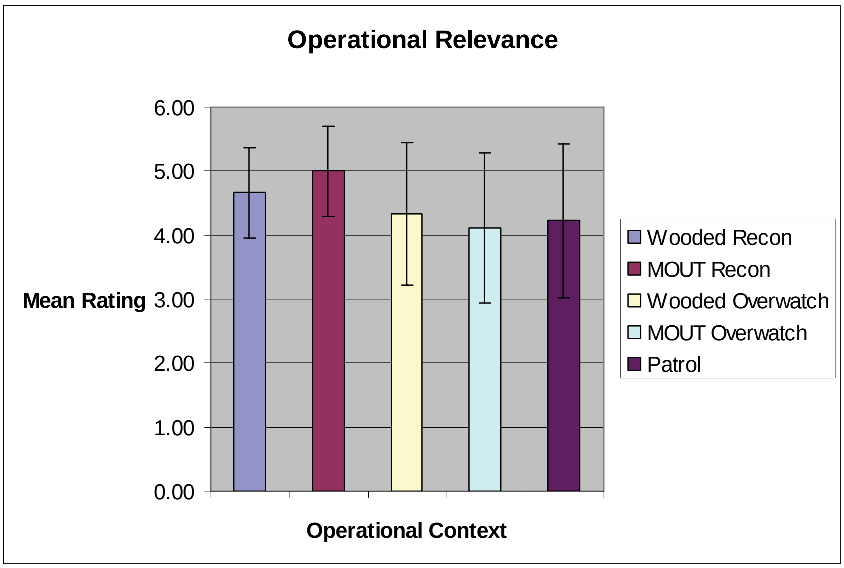


Figure 11. Soldier ratings of operational relevance.

The third part of the questionnaire concerned operational considerations. Each item was rated on a six-point scale, with higher ratings indicating greater relative importance (1 = not at all important, 6 = extremely important). The information in table 24 was arranged, following the analysis, from highest to lowest score ratings.

Table 24. Sniper ratings of design issues.

Design Issues	Mean Ratings
Waterproof	5.9
Dustproof	5.9
Easy to send signals	5.3
Easy to use at night	5.3
Battery life	5.2
Comfort during operations	5.1
Weight	4.9
Easy to tell if working	4.9
Easy to program signals	4.7
Easy to change intensity	4.4
Ability to move tactors	3.2
Integration with scope	2.9

The last part of the questionnaire concerned ratings of the importance of integrating potential sniper-specific commands into the system. Table 25 shows the mean scores arranged lowest to highest for the commands.

Table 25. Ratings of importance of sniper commands.

Potential Commands	Mean Ratings
Assigning firing arc	3.3
Countdown sequence	3.6
Enemy spotted	3.7
General alert	5.0
Halt	5.0
Enemy (primary) spotted	5.4

Additional items (table 26) asked students to rate the perceived utility of alternate input devices.

Table 26. Ratings of perceived utility of input device.

Input Device	Mean Ratings
Thumb joystick	2.6
PDA	2.9
Glove	3.6

The survey results and verbal feedback from the Soldiers indicated high evaluations for the concept of tactile covert communications as being very relevant to their operations. The signals that were demonstrated were perceived as relevant and intuitive. Soldiers expressed concern for issues regarding operational readiness of the equipment and listed many factors that need to be addressed in order to bring the equipment to operational readiness, such as ruggedness, weight, battery life, and resistance to water and dust. Overall, their evaluation of the tactile concept and the signals provided rationale to proceed further with development and validation experiments.

As noted before, the tactile input selected for this effort is only representative of some of the many possible types of information that can be conveyed with tactile displays. These sample messages (pre-selected by Soldier SMEs based on operational importance) have been shown to be as easily understood as visual arm and hand signals and could now be available as supplements to or in place of visual or auditory input. This provides the Soldier of the future with the capability of processing information from multiple or independent sources, contingent upon the immediate circumstances.

Chapter 6.2 Live Fire Experimental Demonstration (Stafford, Brill, and Terrence)

To further highlight the effectiveness of discrete (unvarying) tactile cueing for directional location and navigational guidance, UCF showed the capability for target direction cuing for Soldiers with a practical live fire experimental demonstration. The video-recorded live fire demonstration shows shorter response time with tactile cueing, compared to verbal cues. This concept was tested with vibrotactile or verbal cueing to detect targets placed left-center-right of the shooter.

Two experienced shooters, both military trained and with tours of duty in Iraq, identified and engaged specific targets when commanded by verbal instructions or by tactile cueing. The three target choices represented the location of threats as identified by color (black, yellow, or red) or were signaled by triggering “tactors” on the torso (left, forward, or right). Four shooting sequences were recorded with targets commanded by

- Verbal call-outs identifying the target by color.
- Coded verbal call-outs that required translation, as with multi-national forces, where the named color represented another color (the Stroop effect), e.g., a yellow command represented the red target, etc.
- Tactile cueing that augmented the coded verbal commands.
- Tactile cueing alone.

Average response times for both shooters were measured from initiation of the signal (verbal or tactile) to the smoke discharge from the muzzle of the rifle. The results show an average of approximately 1.2 seconds to respond for touch cueing from the tactile signal to trigger pull, versus 2.2 seconds for verbal cueing (i.e., experimenter “call-out” of the target’s position), and 4.4 seconds for verbal cueing when a confusion matrix was added (i.e., the “Stroop effect”; Stroop, 1935; Bower, 1992), again to emulate multi-cultural interactions. Interestingly, combinations of touch and verbal cueing showed that response times ranged from 1.2 to 1.6 seconds; in essence, the shooters ignored the less obvious coded verbal localization cues when tactile cues were available. These live fire conditions findings strongly suggest that tactile systems can intuitively alert the presence of threats and accurately cue their location, without initial sight (and presumably without hearing). For example, a Soldier in dust or smoke may not easily localize a target at first, but once target is detected with the aid of tactile cues, visual recognition and verification is quite feasible. Covert vibrotactile cueing does not draw enemy attention because it remains non-illuminating, virtually silent, and is available without the need for movement.

Apparent in both data (i.e., shorter response times) and in the video recording of performance is the remarkably sharp and consistent responding to tactile cues, with or without verbal call-outs, an obvious precursor to avoiding “friendly fire” incidents. In contrast is shooter hesitation to coded verbal commands, such as might be found with multi-national forces. These Soldiers, as well as others who have tried this unique system, frequently refer to tactile cueing as “natural” and “obvious”—a meaningful remark in light of the fact that this demonstration was literally completed without prior training.

Chapter 6.3 A Tactile Communication Field Experiment at Fort Benning (Redden, Carstens, Pettitt, Merlo, Stafford, Terrence, and Gilson)

Many challenges are involved in conveying battlefield information to dismounted Soldiers in a manner that enhances their ability to manage that information and increase their situation awareness (SA). Improvements in Army combat communications because of enhanced wireless network capabilities could bring greater complexity to the Soldier along with the potential for information overload. Distributing tasks and information across various sensory modalities might be an effective display intervention in situations when individuals have multiple demands for attention (Wickens, 2002).

As an example, when demands on audition and vision are high (i.e., a dismounted Soldier listening to sounds announcing the enemy's approach while looking for signs of enemy ambush), it may be beneficial to include the tactile sensory modality for intra-squad communication. Allocation of information and tasks among three different senses is expected to reduce bottlenecks and processing limitations, thus enhancing information management and SA of Soldiers. With proper implementation, the use of tactile displays for the Soldier could reduce demands on and interference with the Soldiers' visual and auditory channels, thereby improving overall performance.

6.3.1 Issues

To test this concept, a field investigation conducted by ARL at Fort Benning studied the efficacy of conveying to Soldiers standard Army hand and arm signals via tactile commands in a dynamic environment (Pettitt, Redden, & Carstens, 2006). The tactile prototype display and patterns were developed by the tactile research team at the UCF. The design of this experiment was to evaluate Soldiers' abilities to interpret and respond to tactile commands compared to their abilities to interpret and respond to visual hand and arm signals given from noncommissioned officer (NCO) leaders in the front and rear of them during movement. The following issues were addressed:

- Can Soldiers quickly learn a limited vocabulary of tactile signals?
- Can Soldiers easily distinguish one tactile command from another?
- How quickly and accurately can Soldiers understand and respond to tactile commands compared to standard visual hand and arm signals?
- Will performing IMT in a dynamic environment interfere with the detection of tactile signals?

6.3.2 Task Synopsis

The evaluations were conducted with infantry Soldiers who negotiated a woodland IMT obstacle course. Tactile and visual hand and arm signals were delivered to the Soldiers as they negotiated the course while wearing their standard uniforms and carrying their personal weapons. Accuracy of signal interpretation and response times were documented.

The IMT course requires Soldiers to use urban and field tactics, to assume a variety of positions, and to execute a variety of individual movements while maneuvering through, over, under, and around obstacles. Obstacles from four obstacle categories were used: patrolling, crawling, firing, and climbing. Initially, Soldiers walked through the course while each obstacle and position was explained to them. In addition, before the first recorded trial, all Soldiers completed one familiarization trial wearing their uniforms, tactile vests and belts, including elbow and knee pads, while carrying a simulated M4 rifle.

Even these conditions are not equivalent to combat situations. Note, the IMT course made it much easier to see the hand and arm signals than would have been possible if the experiment had been conducted in wooded terrain where distance, vegetation, and terrain features could have masked the leader's signals. Also the experiment was conducted during daylight conditions, which made it easier to see hand and arm signals compared to night operations. The IMT course does not produce equivalent demands for attention and stress. However, the course reproduces standard Army IMT in a controlled manner.

The purpose of this experiment was to determine whether Soldiers can detect and understand tactile signals while completing a physically and attentionally demanding obstacle course, thus validating the concept within a more applied setting than that used in the West Point laboratory study discussed in the previous chapter.

6.3.3 Tactile System

The tactile system used for this experiment was described in the earlier chapter by Gilson and Brill. Each tactile display assembly included the eight custom-built electro-mechanical vibro-tactile devices with their associated wiring fitted into an elastic belt worn securely around the torso. This arrangement created a ring of equidistant stimulation loci with the first one centered just above the navel. The center piston, visible with a midpoint screw, moves within the larger fixed housing.

The tactor controller box (TCB), designed by EAI, is powered by a 9.6-volt rechargeable battery (or six AA replaceable batteries). The TCB initiates sequences of tactors in pre-coded patterns (specified by UCF) and actuates the individual tactors according to predetermined stimulus parameters (specified by UCF). The sequences used for the ARL experiment were programmed and stored in the hardened TCB. The TCB wiring connects to the tactor belt through a cable. The Soldiers stored the entire TCB and its battery pack in their right cargo pocket of their uniforms. The sequences were activated remotely by means of a wireless Bluetooth PDA. The software used to send signals to the TCB was designed by RIMLine, LLC, in conjunction with and under the direction of UCF researchers. A photograph of the actual equipment is shown in figure 12.

For this experiment, the system used programmed buttons on the PDA to initiate transmission of four basic commands as tactile patterns that were designed to be analogous to standard Army hand and arm signals. The four commands (attention, halt, move out, and rally) represent only a few of the many commands and types of information that can be conveyed by this system. The tactile representations of these signals were designed in a collaborative effort of scientists at UCF and a consultant group of SMEs consisting of former U.S. Soldiers (a Navy Seal, a Marine Force Reconnaissance Marine, an Army Ranger, and an Army Special Forces Soldier). These sequences were then developed by laboratory testing at UCF.

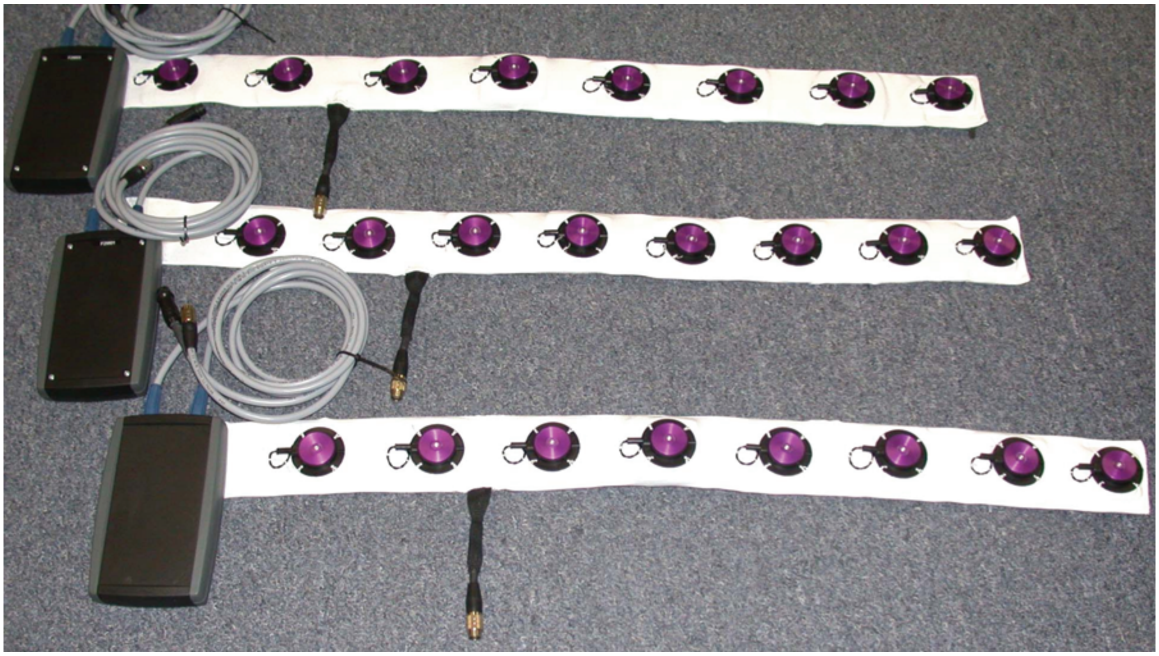


Figure 12. Three tactile displays belt assemblies are shown with their TCBs.

6.3.4 Tactile Signals

A brief description of the signals is as follows:

- Attention – sequenced side-to-side activation of front tactors, creating a “wave-like” motion.
- Halt – four tactors simultaneously actuated.
- Move Out – sequenced back-to-front activation of tactors, creating movement around each side of the body to converge in the front.
- Rally – sequenced activation of all tactors, creating a circular motion around the body.

Note, the signals were presented individually to assess their pattern reliability independently, not as they were originally intended as grouped patterns in operational sequences.

The following protocol was designed and directed by ARL personnel. UCF provided equipment and support.

6.3.5 Tactile System Training

A representative from UCF fit the tactile system to the Soldiers and trained them how the tactile signal was to be interpreted. Each Soldier was given 7 to 10 minutes of familiarization with the tactile system before completing the obstacle course. Familiarization consisted of approximately 17 repetitions of the four tactile signals: three repetitions without equipment, four times with equipment, and two times each in the kneeling, prone, combat roll, walk, and run positions/actions.

By the end of training, all Soldiers achieved 100% accuracy on all signals. Upon completion of the training, the Soldiers were given a questionnaire designed to assess their perception of the training adequacy. All the Soldiers rated the training as being "good" to "extremely good". Very little time was required to train the Soldiers to become sufficiently accurate in interpreting the tactile signals. Soldiers rated them as easier to learn than the standard hand and arm signals they already knew.

6.3.6 Obstacle Course Protocol

Thirty male Soldiers from the infantry training brigade participated four times through the IMT course for a total of 120 trials. Before the start of each trial, Soldiers were presented with the tactile signals again for review, with signals presented according to a counterbalanced matrix. The first trial was for practice only, and the next three included recorded data collection. The entire study took three days. Note, when Soldiers were not running the IMT course, they were kept out of view of the course so that they did not learn the sequence and location of signals.

During each trial, Soldiers were led through the IMT course by an NCO, who walked approximately 10 paces in front (simulating a team leader) and were followed by an NCO about 10 paces behind (simulating a squad leader). These positions are consistent with a Soldier acting as a member of a squad in a wedge formation. The team leader was designated to communicate visual hand and arm signals from the front and the squad leader from the rear, at predetermined positions. Tactile commands were communicated to the Soldier at other predetermined positions by a researcher remotely operating the PDA transmitter at a non-interfering distance from the squad member.

The Soldier's mission was to respond to the signals while negotiating each obstacle. Nine signals (three per condition, front, rear, or tactor) were given at different predetermined locations on the course and changed for each trial. At the same time, the Soldier was to maintain his scan of the woods for targets and to call out if he spotted one of three shoulder badges/tabs (Airborne, Ranger, Special Forces) that were placed on the ground at various locations on the course to serve as a visual scanning task. Typically, a Soldier was able to spot one of the three badges during the 7 minutes (on average) that it took to complete the entire obstacle course.

6.3.7 Data Collection

Dependent variables included the time from the initiation of the respective signal to the time the Soldier called out that signal and the accuracy of that verbal response. At the completion of each course trial, a subjective questionnaire was administered.

The questionnaires were designed to elicit Soldiers' opinions concerning their performance and observations, both in receiving and understanding visual and tactile communications while negotiating obstacles, and to rate the utility of the tactile system. Questionnaires were administered to each Soldier at the completion of each trial on the course.

6.3.8 Results

An overview of findings is given here with more detailed results presented in Pettitt, Redden, and Carstens (2006). As a predicate, note that the response time data are highly skewed because of a "floor effect," i.e., some minimal time is needed to respond to signals, and because of a self-imposed upper limit of 20 seconds, coded as such when there was no response to signals at all. Since an ANOVA is based on the assumption that the data are approximately normally distributed, all ANOVAs and ensuing comparisons reported here were done with log transformed data. None-theless, as a check, when the statistics were run on both the log transformed data and the untransformed data, the results were virtually identical in all cases.

Shown below are the average response times and standard deviations for the three methods of signaling, across all three IMT data trials. A repeated measures ANOVA for the log response times showed a statistically significant effect for signal modality: $F(2,58) = 80.3$, $p < .001$. Ensuing pairwise comparisons were made with a Holmes-Bonferonni to control for family-wise error, which showed that response times were significantly faster ($p < .05$, two-tailed test) with the tactile signals than with the hand signals and that response times were significantly faster when the hand signals came from the Soldier's front rather than the rear. Note that the same pattern is reflected in the variance, with the smallest standard deviation for the tactile signals and the largest standard deviation for hand signals coming from the Soldier's rear.

Signal Modality	Mean (sec)	*SD* (sec)
Hand signals – rear	4.65	2.02
Hand signals – front	2.93	1.17
Tactile signals – only	1.81	0.64

The accuracy of Soldier responses was analyzed for signal presentation. There was a significant difference in correct responses among the three presentation types: $\chi 2$ ($df = 2$) = 24.0, $p < .001$. The correct response rate was lower in the "hand-rear" condition relative to the other two signal conditions: $\chi 2$ ($df = 1$) = 20.6, $p < .001$. There was no significant difference in the proportion of correct responses between the "hand-front" and "tactile" conditions.

6.3.9 Soldier Questionnaire Responses

Soldiers rated the "hand signals" and the "tactile signals" as being very easy to learn. Soldiers also rated the "tactile commands" and the "front hand commands" as very easy to detect and to inter-pret, while the "rear hand signals" were rated as being more difficult. One Soldier stated that the tactile system seemed to become progressively easier to interpret as the trials progressed. By the third trial, he stated that the "tactile belt was easier and quicker to understand than clearly visible hand and arm signals".

Suggestions for improvement of the tactile system included reduction in the battery and receiver unit size and reduction in battery consumption (primarily drained by the continuous Bluetooth connection), which made it more difficult to interpret tactile signals when the signal strength weakened.

6.3.10 Conclusions

The tactile signal patterns were found to be intuitive and easy for the Soldiers to understand. Very little training time (fewer than 10 minutes) was required for Soldiers to become accurate in interpreting the four tactile signals used during the experiment. Results demonstrated that Soldiers performing IMT were able to receive, interpret, and accurately respond to the tactile commands faster than when the information was passed by a leader using conventional hand and arm signals. Soldiers also commented they were better able to focus more attention on negotiating obstacles and on local area SA when receiving tactile signals than when maintaining visual contact with their leaders in order to receive standard hand and arm signals.

The prototype systems proved rugged enough to allow 30 Soldiers to complete 120 trials through the 400-yard course with challenging obstacles. Different connections (perhaps wireless) between the TCB and tactile display should be considered to increase overall field worthiness. Timing modifications of the tactile patterns should be explored to determine whether they would facilitate or hinder identification of message patterns. Additional experiments should be conducted comparing the need for preparatory commands in the field, when surrounded by contextually rich environments, versus in the laboratory where preparatory commands may not be as essential.

The use of a tactile communication system could improve infantry team performance beyond what was documented in this experiment. During this experiment, leaders in the front and rear of the Soldiers were not obscured by terrain, vegetation, or light level. In other words, the conditions of this experiment were optimal for the Soldiers' abilities to see the conventional hand and arm signals. In actual wooded terrain with more vegetation and fallen debris on the ground, Soldiers would be scanning the ground more to prevent tripping and may not have as much time to observe their leaders for hand and arm signals. During combat situations, larger dispersions and obscurants could greatly inhibit reception of visual hand and arm signals. Visual barriers in an urban combat situation could impair hand and arm signaling. Also, hand and arm signals are traditionally passed along throughout the squad so that the time that the first squad member receives the signal could be much quicker than the time that the signal is passed to and received by the last squad member. A tactile communication system would allow simultaneous reception of signals by all squad members. For example, a "halt" signal sent by visual signals could result in a wave effect so that the last squad member to receive the signal could still be moving long past the time when the squad needed to stop. A "halt" signal sent by a tactile system could be received by all squad members in less than 2 seconds. A further benefit provided by a tactile system is the increased local SA experienced by the squad because the tactile system would free their eyes from having to watch for visual signals. A third benefit of adding a tactile system is the fact that Soldiers would have two means of receiving communication because the visual hand and arm signals would still be available for use.

Section 7. Summary and Future Work

The overarching goal for this continuing program of research is to provide Soldiers operating in today's complex, multi-threat environment, with an effective way to receive the critical information they need to enhance their performance and survival. Tactile communications offer inherent advantages to the Soldier, ranging from added channel capacity for multi-sensory communications to an alternate channel when other sensory capacities are limited or lost (e.g., night operations, dust storms, loud discharges, etc.).

Often described as "natural" and "obvious" by those who use them, displays by touch appear to invade awareness at a primary level, highlighting messages for fast, accurate response(s), yet they remain non-illuminating, virtually silent, and available without movement, looking, or listening. Such display capabilities can enhance mission success by presenting the most relevant threat information to the individual Soldier while not impinging upon other visual and auditory task demands.

Combat operations ranging from urban warfare to remote interaction with unmanned vehicles provide rich and varied examples of where critical information can be conveyed covertly, reliably, and uniquely by touch without drawing enemy attention. The work thus far suggests that at even a modest level of sophistication, tactile communication could provide an omni-directional communication capability for the next generation of combat Soldiers.

Our approach has been to investigate the overall utility of what tactile communications can and cannot do before we look at specific applications. For example, we determined the most workable stimulus presentation and best range of parameters for easy cueing and recognition of discrete events before applying them to alerts and alarms, to the variables and their preferred waveforms most amenable to tracking signals for navigation or targeting, and to the most intuitive sequences of patterns for messaging. At the same time, we looked at important collateral issues such as effects of body orientation, tactile memory, physical and mental workload, and collateral task performance.

By knowing the larger utility of tactile displays as well as their inherent costs, we can confidently generalize to a myriad of yet untried applications and provide reliable estimates as to their likely outcomes. By doing so, we can avoid "shotgun" testing, providing informed choices to best target applications for study that are likely to have benefits.

We plan to expand our tactile messaging into a simple Lexicon and to investigate the further use of the "C2" tactor (or similar type) into an input device or even into a physiological sensing unit for the Soldier. Clearly, tactile stimulation has the potential to provide a wide variety of useful capabilities to meet the needs of Soldiers and others in society.

We would like to extend a special thanks to those Soldiers who performed as participants, many of whom are preparing to enter the operational Army to defend our nation. A blessing to them and to their families for all that they do.

Section 8. References

Alluisi, E. A.; Morgan, B.; Hawkes, G. Masking of Cutaneous Sensations in Multiple Stimulus Presentations. *Perceptual and Motor Skills* **1965**, *20*, 39–45.

Békésey, G. V. Interaction of Paired Sensory Stimuli and Conduction in Peripheral Nerves. *Journal of Applied Physiology* **1963**, *18,* 1276–1284.

Békésey, G. V. *Sensory Inhibition.* Princeton, NJ: Princeton University Press, 1967.

Blattner, M. M.; Sumikawa, D. A.; Greenberg, R. M. Earcons and Icons: Their Structure and Common Design Principles. *Human-Computer Interaction* **1989**, *4*, 11–44.

Blauert, J. *Spatial Hearing: The Psychophysics of Human Sound Localization.* Cambridge, MA: MIT Press, 1997.

Block, R. A. (Ed.) *Cognitive Models of Psychological Time.* Hillsdale, New Jersey, Lawrence Erlbaum, 1990.

Bower, B. Brother Stroop's Enduring Effect: A Mental Task Devised Nearly 60 Years Ago Still Intrigues Psychologists. *Science News* **1992, May 9**, *141*, 312–314.

Brewster, S. A.; Brown, L. M. Non-Visual Information Display Using Tactons. *Extended Abstracts of ACM CHI (Vienna, Austria), ACM Press* **2004a**, 787–788.

Brewster, S. A.; Brown, L. M. Tactons: Structured Tactile Messages for Non-Visual Information Display. *Proceedings of Australasian User Interface Conference*, Dunedin, New Zealand, Australian Computer Society, 15-23, 2004b.

Brill, J. C.; Gilson, R. D. Tactile Technology for Covert Displays. *Proceedings of the 50th Annual Meeting of the Human Factors and Ergonomics Society*, San Francisco, CA, 2006, in press.

Brill, J. C.; Gilson, R. D.; Mouloua, M.; Concodora, S A.; Whitehead, K. D. Tactile Phi for Directional Cueing. *Paper presented at the annual meeting of the Southeastern Psychological Association*, Atlanta, GA, 2004, March.

Brill, J. C.; Gilson, R. D.; Mouloua, M.; Hancock, P. A.; Terrence, P. I. Increasing Situation Awareness of Dismounted Soldiers Via Directional Cueing. In D. A. Vincenzi, M. Mouloua, & P. A. Hancock (Eds.), *Human Performance, Situation Awareness, and Automation: Current Research and Trends, 1*, 130). Mahwah, NJ: Lawrence Erlbaum Publishers, Inc, 2004.

Brill, J. C.; Terrence, P. I.; Downs, J. L.; Gilson, R. D.; Hancock, P.A.; Mouloua, M. Search Space Reduction Via Multi-Sensory Directional Cueing. *Proceedings of the 48th Annual Meeting of the Human Factors and Ergonomics Society*, New Orleans, LA, 2004.

Brown, L. M.; Brewster, S. A.; Purchase, H. C. A First Investigation Into the Effectiveness of Tactons. *Proceedings of WorldHaptics 2005*, Pisa, Italy: *IEEE Press*, 167–176, 2005.

Burke, M. W.; Gilson, R. D.; Jagacinski, R. J. Multi-Modal Information Processing For Visual Workload Relief. *Ergonomics* **1980**, *23* (10), 961–975.

Chan, A.; MacLean, K. E.; McGrenere, J. Learning and Identifying Haptic Icons Under Workload. *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, WHC 2005, Pisa, Italy, 2005.

Cholewiak, R. C.; Brill, J. C.; Schwab, A. Vibrotactile Localization on the Abdomen: Effects of Place and Space. *Perception and Psychophysics* **2004**, 66 (6), 970–987.

Cholewiak, R. W.; Schwab, A.; Brill, J. C. Vibrotactile Localization on the Abdomen: Effects of Place and Space. Princeton, NJ: The Cutaneous Communication Laboratory at Princeton University, 2004.

Cohen, M. S.; Kosslyn, S. M.; Breiter, H. C.; DiGirolamo, G. J.; Thompson W. L.; Anderson, A. K.; Bookheimer, S. Y.; Rosen, B. R.; Belliveau, J. W. Changes in Cortical Activity During Mental Rotation: A Mapping Study Using Functional MRI. *Brain* **1996**, *119* (1), 89–100.

Cook, R. I.; Woods D. D. Operating at the Sharp End: The Complexity of Human Error. In M. S. Bogner (Ed), *Human error in medicine*. Hillsdale, NJ: Erlbaum, 1994.

Cooper, L. Demonstration of a Mental Analogy of an External Rotation. *Perception and Psychophysics* **1976**, *19*, 296–302.

Craig, J. C. Tactile Pattern Perception and its Perturbations. *Journal of the Acoustical Society of America* **1985**, *77* (1), 238–46.

Duda, R. O. Elevation Dependence of the Interaural Transfer Function. In R. H. Gilkey & T. R. Anderson (Eds.), Binaural and spatial hearing in real and virtual environments (pp. 49-75). Manwah, NJ: Lawrence Erlbaum Associates, 1993.

Elliott, L. R.; Redden, E. S.; Pettitt, R. A.; Carstens, C. B.; van Erp, J.; Duistermaat, M. *Tactile Guidance for Land Navigation;* ARL-TR-3814; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006.

Geldard, F. A.; Hahn, J. F. Charlottesville, VA: Virginia Cutaneous Project (Progress Report No. 45) at the University of Virginia, 1961.

Geldard, F. A.; Sherrick, C. E. The Cutaneous ‘Rabbit’: A Perceptual Illusion. *Science* **1972**, *178,* 178–179.

Gemperle, F.; Ota, N.; Siewiorek, D. Design of a Wearable Tactile Display. *Proceedings of the International Symposium on Wearable Computers (ISWC'01)*, IEEE, Zurich, Switzerland, 5-12, 2001.

Gescheider, G. *Psychophysics: The Fundamentals*. Mahwah, NJ: Lawrence Erlbaum Associates, 1997.

Gescheider, G. A.; Hoffman, K. E.; Harrison, M. A.; Travis, M. L.; Bolanowski, S. J. The Effects of Masking on Vibrotactile Temporal Summation in the Detection of Sinusoidal and Noise Stimuli. *Journal of the Acoustical Society of America* **1994**, *95*, 1006–1016.

Gilson, R. D. Some Factors Affecting the Spatial Discrimination of Vibrotactile Patterns. *Perception and Psychophysics* **1968**, *3* (2B), 131–136.

Gilson, R. D. Vibrotactile Masking: Some Spatial and Temporal Aspects. *Perception and Psychophysics* **1969a**, *5* (3), 176–180.

Gilson, R. D. Vibrotactile Masking: Effects of Multiple Maskers. *Perception and Psychophysics* **1969b**, *5* (3), 181–182.

Gilson, R. D. Semi-Automatic Aircraft Control System, U.S. PAT. No. 4,093,159, 1978.

Gilson, R. D.; Fenton, R. E. Kinesthetic-Tactual Information Presentations – In-flight Studies. *IEEE Transactions on Systems, Man and Cybernetics* **1974**, *4* (6), 531–535.

Gilson, R. D.; Ventola, R. W. Kinesthetic Tactile Display System, U.S. PAT. No. 4,195,802, 1980.

Gilson, R. D.; Ventola, R. W.; Fenton, R. E. A Kinesthetic-Tactual Display for Stall Deterrence. *NASA Ames Research Center, 11th Annual Conference on Manual Control*, Moffett Field, California, 440-451, 1975.

Goff, G. D. Differential Discrimination of Frequency of Cutaneous Mechanical Vibration. *Journal of Experimental Psychology* **1967**, *74* (2), 294–299.

Gunther, E.; Davenport, G.; O'Modhrain, S. Cutaneous Grooves: Composing for the Sense of Touch. *Proceedings of C*onference on New Instruments for Musical Expression, Dublin, Ireland, 1-6, 2002.

Hart, F. G.; Staveland, L. E. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research, in P.A. Hancock and N. Meshkati (eds), *Human Mental Workload* (Amsterdam: North-Holland), 139 ± 183, 1988.

Head H. *Studies in Clinical Neurology*. London: Hodder & Stoughton, 334–728, 1920.

Hellier, E., J.; Edworthy J.; Dennis I. Improving Auditory Warning Design: Quantifying and Predicting the Effects of Different Warning Parameters on Perceived Urgency. *Human Factors* **1993**, *35* (4), 693–706.

Ho, C.; Tan, Z. T.; Spence, C. Using Spatial Vibrotactile Cues to Direct Visual Attention in Driving Scenes. *Transportation research part F: Traffic Psychology and Behavior* **2005**, *8* (6), 397–412.

Jagacinski, R. J.; Flach, J. M. *Control Theory for Humans*. Mahwah, NJ: Lawrence Erlbaum Associates, 2003.

Jagacinski, R. J.; Flach, J. M.; Gilson, R. D. A Comparison of Visual and Kinesthetic-Tactual Displays for Compensatory Tracking. *IEEE Transactions on systems, man, and cybernetics* **1983**, *13* (6), 1103–1112.

Jagacinski, R. J.; Miller, D. P.; Gilson, R. D. A Comparison of Kinesthetic-Tactual and Visual Displays Via a Critical Tracking Task. *Human Factors* **1979**, *21* (1), 79–86.

Jenkins, W. O. The Tactual Discrimination of Shapes for Coding Aircraft Type Controls. In: P. M. Fitts (Ed.), *Psychological research on equipment design* **1947**, *19*, U.S. Army Air Force Aviation Psychology Program.

Kaaresoja, T.; Linjama, J. Perception of Short Tactile Pulses Generated by a Vibration Motor in a Mobile Phone. *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'05)*, Vol. 00, IEEE Computer Society, 471-472, 2005.

Kandel E. R.; Schwartz J. H.; Jessell T. M. *Principles of Neural Science* (4th ed.). McGraw-Hill: New York, 2000.

Kuc, R. Binaural Sonar Electronic Travel Aid Provides Vibrotactile Cues for Landmark, Reflector Motion and Surface Texture Classification. *IEEE Transactions on biomedical engineering* **2002**, *49* (10), 1173–1180.

Lemmens, P. M. C.; Bussemakers, M. P.; de Haan, A. (2001). Effects of Auditory Icons and Earcons on Visual Categorization: The Bigger Picture. *Proceedings of the 2001 International Conference on Auditory Display*, 117-125, Espoo, Finland.

Lindeman, R. W.; Sibert, J. L.; Mendez-Mendez, E.; Patil, S.; Phifer, D. Effectiveness of Directional Vibrotactile Cuing on a Building-Clearing Task. *CHI 2005*, 271-280, Portland, Oregon, 2005.

Lindeman, R.; Yangida, Y.; Lavine, R. Effective Vibrotactile Cueing in a Visual Search Task. *Proceedings of the ninth IFIP International conference of human-computer interaction (INTERACT 2003),* 2003.

Logie, R. H.; Gilhooly, K. J.; Wynn, V. Counting on Working Memory in Arithmetic Problem Solving. *Memory & Cognition* **1994***, 22*, 395–410.

Mahar, D. P.; Mackenzie, B. D. Masking, Information Integration, and Tactile Pattern Perception: A Comparison of the Isolation and Integration Hypotheses. *Perception* **1993***, 22* (4), 483–96.

Mahar, D. P.; Mackenzie, B.; McNicol, D. Modality-Specific Differences in the Processing of Spatially, Temporally, and Spatiotemporally Distributed Information. *Perception* **1994***, 23* (11), 1369–86.

Mahns, D. A.; Perkins, N. M.; Sahai, V.; Robinson, L.; Rowe, M. J. Vibrotactile Frequency Discrimination in Human Hairy Skin. *Journal of Neurophysiology* **2006***, 95* (3), 1442–1450.

Merzenich, M. M.; Harrington, T. The Sense of Flutter-Vibration Evoked By Stimulation of the Hairy Skin of Primates: Comparison of Human Sensory Capacity With the Responses of Mechanoreceptive Afferents Innervating the Hairy Skin of Monkeys. *Experimental Brain Research* **1969***, 9,* 236–260.

Mortimer, B.; Zetts, G.; Cholewiak, R. (in submission). Vibrotactile Transduction. Submitted to *Journal of the Acoustical Society of America*.

Mortimer, D. C. Effects of Task Difficulty on Target Guidance Using Auditory and Tactile Cues. *Proceedings of the 50th Annual Meeting of the Human Factors and Ergonomics Society,* San Francisco, CA, 2006, in press.

Pasquero, J.; Hayward, V. STRESS: A Practical Tactile Display With One Millimeter Spatial Resolution and 700 Hz Refresh Rate. *Proceedings of EuroHaptics 2003*, 94–110, 2003.

Pettitt, R. A.; Redden, E. S.; Carstens, C. C. (). *A Comparison of Hand and Arm Signals to a Covert Tactile Communication System in a Dynamic Environment*; ARL-TR-3838; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006.

Redden, E. S. *Virtual Environment Study of Mission-Based Critical Information Requirements;* ARL-TR-2636; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2002.

Redden, E. S.; Carstens, C. B.; Turner, D. D.; Elliott, L. R. *Localization of Tactile Signals as a Function of Tactor Operating Characteristics;* ARL-TR-3971; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006.

Sadato N.; Pascual-Leone A.; Grafman J.; Ibañez V.; Deiber M. P.; Dold G.; Hallett M. Activation of the Primary Visual Cortex by Braille Reading in Blind Subjects. *Nature* **1996***, 380* (6574), 526-528.

Sherrick, C. A.; Cholewiak, R. W. Cutaneous Sensitivity. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds), *Handbook of perception and human performance,* 12-1–12-57. John Wiley and Sons: New York, 1986.

Stroop, J. R. Studies of Interference in Serial Verbal Reactions. *Journal of Experimental Psychology* **1935***, 18,* 643–662.

Talbot, W. H.; Darian-Smith, I.; Kornhuber, H. H.; Mountcastle, V. B. The Sense of Flutter-Vibration: Comparison of the Human Capacity With Response Patterns of Mechanoreceptive Afferents From the Monkey Hand. *Journal of Neuroscience* **1968***, 20,* 5503–5515.

Terrence, P. I.; Brill, J. C.; Gilson, R. D. Body Orientation and the Perception of Spatial Auditory and Tactile Cues. *Proceedings of the 49th Annual Meeting of the Human Factors and Ergonomics Society*, Orlando, FL, 2005.

Van Boven, R. W.; Hamilton, R. H.; Kauffman, T.; Keenan, J. P.; Pascual–Leone, A. Tactile spatial Resolution in Blind Braille Readers. *Neurology* **2000***, 54*, 2230–2236

Van Erp, J. B. F. Vibrotactile Spatial Acuity on the Torso: Effects of Location and Timing Parameters*. Proceedings of World Haptics*, pp. 80–85. Los Alamitos, CA: IEEE Computer Society, 2005a.

Van Erp, J. B. F. Presenting Directions With a Vibrotactile Torso Display. *Ergonomics* **2005b, February***, 48* (3), 302–313.

Van Erp, J. B. F.; Spapé, M. M. A. Distilling the Underlying Dimensions of Tactile Melodies. *Proceedings of Eurohaptics*, TNO Human Factors, 2003.

Van Erp, J. B. F.; Van Veen, H. A.; Jansen, C. Waypoint Navigation With a Vibrotactile Waist Belt. *ACM Transactions on applied perceptions* **2005***, 2* (2), 106–117.

Van Erp, J. B. F.; Verschoor, M. H. Cross-Modal Visual and Vibrotactile Tracking. *Applied Ergonomics* **2004***, 35*, 105–112.

Van Erp, J. B. F.; Werkhoven, J. P. Spatial Characteristics of Vibro-Tactile Perception on the Torso. *TNO Report TM-99-B007*. Soesterberg, Netherlands: TNO Human Factors, 1999.

Verrillo, R. T. Investigation of Some Parameters of the Cutaneous Threshold for Vibration. *Journal of the Acoustical Society of America* **1962**, *34*, 1768–1773.

Verrillo, R. T. Vibrotactile Sensitivity and the Frequency Response of the Pacinian Corpuscle. *Psychonomic Science* **1966***, 4*, 135–136.

Wickens, C. D. Attention, Time-Sharing, and Workload. In L. Pearson, and C.M. Caterer (Eds.), *Engineering Psychology and Human Performance,* (364-411). HarperCollins Publishers, Inc.: New York, 1992.

Wickens, C. D. Multiple Resources and Performance Prediction. *Theoretical Issues in Ergonomic Science* **2002**, *3* (2), 159–177.

Yuan, H.; Reed, C. M.; Durlach, N. I. Temporal Onset-Order Discrimination Through the Tactual Sense. *The Journal of the Acoustical Society of America* **2005**, *117* (5), 3139–3148.

NO. OF COPIES	ORGANIZATION
1 (PDF ONLY)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FORT BELVOIR VA 22060-6218
1	US ARMY RSRCH DEV & ENGRG CMD SYSTEMS OF SYSTEMS INTEGRATION AMSRD SS T 6000 6TH ST STE 100 FORT BELVOIR VA 22060-5608
1	DIRECTOR US ARMY RESEARCH LAB IMNE ALC IMS 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CI OK TL 2800 POWDER MILL RD ADELPHI MD 20783-1197
2	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CS OK T 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR M DR M STRUB 6359 WALKER LANE SUITE 100 ALEXANDRIA VA 22310
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR ML J MARTIN MYER CENTER RM 2D311 FT MONMOUTH NJ 07703-5601
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MZ A DAVISON 199 E 4TH ST STE C TECH PARK BLDG 2 FT LEONARD WOOD MO 65473-1949
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MD T COOK BLDG 5400 RM C242 REDSTONE ARSENAL AL 35898-7290

NO. OF COPIES	ORGANIZATION
1	COMMANDANT USAADASCH ATTN AMSRD ARL HR ME A MARES 5800 CARTER RD FT BLISS TX 79916-3802
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MO J MINNINGER BLDG 5400 RM C242 REDSTONE ARSENAL AL 35898-7290
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MM DR V RICE-BERG BLDG 4011 RM 217 1750 GREELEY RD FT SAM HOUSTON TX 78234-5094
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MG R SPINE BUILDING 333 PICATINNY ARSENAL NJ 07806-5000
1	ARL HRED ARMC FLD ELMT ATTN AMSRD ARL HR MH C BURNS BLDG 1467B ROOM 336 THIRD AVENUE FT KNOX KY 40121
1	ARMY RSCH LABORATORY - HRED AVNC FIELD ELEMENT ATTN AMSRD ARL HR MJ D DURBIN BLDG 4506 (DCD) RM 107 FT RUCKER AL 36362-5000
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MK MR J REINHART 10125 KINGMAN RD FT BELVOIR VA 22060-5828
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MV HQ USAOTC S MIDDLEBROOKS 91012 STATION AVE ROOM 111 FT HOOD TX 76544-5073
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MY M BARNES 2520 HEALY AVE STE 1172 BLDG 51005 FT HUACHUCA AZ 85613-7069
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MP D UNGVARSKY BATTLE CMD BATTLE LAB 415 SHERMAN AVE UNIT 3 FT LEAVENWORTH KS 66027-2326

NO. OF COPIES	ORGANIZATION
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MJK J HANSBERGER JFCOM JOINT EXPERIMENTATION J9 JOINT FUTURES LAB 115 LAKEVIEW PARKWAY SUITE B SUFFOLK VA 23435
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MQ M R FLETCHER US ARMY SBCCOM NATICK SOLDIER CTR AMSRD NSC SS E BLDG 3 RM 341 NATICK MA 01760-5020
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MY DR J CHEN 12423 RESEARCH PARKWAY ORLANDO FL 32826
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MS MR C MANASCO SIGNAL TOWERS 118 MORAN HALL FORT GORDON GA 30905-5233
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MU M SINGAPORE 6501 E 11 MILE RD MAIL STOP 284 BLDG 200A 2ND FL RM 2104 WARREN MI 48397-5000
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MF MR C HERNANDEZ BLDG 3040 RM 220 FORT SILL OK 73503-5600
10	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MW E REDDEN BLDG 4 ROOM 332 FT BENNING GA 31905-5400
1	ARMY RSCH LABORATORY - HRED ATTN AMSRD ARL HR MN R SPENCER DCSFDI HF HQ USASOC BLDG E2929 FORT BRAGG NC 28310-5000
1	ARMY G1 ATTN DAPE MR B KNAPP 300 ARMY PENTAGON ROOM 2C489 WASHINGTON DC 20310-0300

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARMY INFANTRY SCHOOL ATTN ATZB CD COL RADCLIFF ROOM 304 FORT BENNING GA 31905
1	PRESIDENT NAVAL POSTGRADUATE SCHOOL ATTN COL LAWRENCE SHATTUCK 234 GLASGOW HALL 1411 CUNNINGHAM ROAD MONTEREY CA 93943
1	UNITED STATES MILITARY ACADEMY ENGINEERING PSYCHOLOGY PROGRAM DEPT OF BEHAVORIAL SCI & LEADERSHIP WEST POINT NY 10996
12	UNIV OF CENTRAL FLORIDA ATTN DR RICHARD GILSON INST OF SIMULATION AND TRAINING 3100 TECHNOLOGY PKWY SUITE 332 ORLANDO FL 32826
1	DIRECTOR SPATIAL ORIENTATION SYSTEMS TACTILE RSCH GROUP NAVAL AEROSPACE MED RSCH LAB ATTN ANGUS RUPERT MD CAPT MC USN PENSACOLA FL 32508-1046
1	WILLIAM ERCOLINE VERIDIAN (AFRL/HEM) 2504 GILLINGHAM DR STE 201 BROOKS AFB TX 78235-5104
1	KRISTEN K LIGGETT CREW SYSTEMS RSCH ENGINEER AFRL/HECI 2210 EIGHTH STREET WRIGHT-PATTERSON AFB OH 45433-7511
1	ENGINEERING ACOUSTICS INC ATTN GARY A ZETS 933 LEWIS DR SUITE C WINTER PARK FL 32789
1	US AIR FORCE ACADEMY DEPT OF BEHAVIORAL SCI & LEADERSHIP DEPUTY DEPT HEAD FOR RESEARCH HQ ATTN USAFA/DFBLLT COL TERENCE ANDRE 2354 FAIRCHILD DRIVE SUITE 6L101 USAF ACADEMY CO 80840

NO. OF COPIES	ORGANIZATION
1	US AIR FORCE ACADEMY DEPT OF BEHAVIORAL SCI & LEADERSHIP PROFESSOR OF PSYCHOLOGY HQ ATTN USAFA/DFBL GEORGE MASTROIANNI 2354 FAIRCHILD DRIVE USAF ACADEMY CO 80840
1	US AIR FORCE ACADEMY DEPT OF BEHAVIORAL SCI & LEADERSHIP CADET USAFA HUMAN FACTORS CONSULTANT TOMMY ARETZ BEH SCI 473 P O BOX 3131 USAF ACADEMY CO 80841
1	UNIV OF SOUTH FLORIDA DEPT OF PSYCHOLOGY ATTN MICHAEL D COOVERT TAMPA FL 33620
1	US AIR FORCE RSCH LAB AFRL BIOBEHAVIORAL PERFORMANCE BR ATTN ANDY MCKINLEY ASSOCIATE BIOMEDICAL ENGINEER 2215 FIRST STREET WRIGHT PATTERSON AFB OH 45433-7947
	ABERDEEN PROVING GROUND
1	DIRECTOR US ARMY RSCH LABORATORY ATTN AMSRD ARL CI OK (TECH LIB) BLDG 4600
1	DIRECTOR US ARMY RSCH LABORATORY ATTN AMSRD ARL CI OK S FOPPIANO BLDG 459
1	DIRECTOR US ARMY RSCH LABORATORY ATTN AMSRD ARL HR MR F PARAGALLO BLDG 459
1	DIRECTOR US ARMY RSCH LABORATORY ATTN AMSRD ARL HR SD B AMREIN BLDG 520

FOREIGN ADDRESSES

JAN B F VAN ERP (2 CYS)
CHIEF SCIENTIST
DEPT HUMAN INTERFACES
TNO HUMAN FACTORS
KAMPWEG 5 PO BOX 23 NL-3769ZG
SOESTERBERG THE NETHERLANDS

LINDA L M BOSSI
LIEUTENANT-COLONEL
HEAD/OPERATIONAL HUMAN ENGINEERING
GROUP DRDC TORONTO TORONTO CANADA
M6C 2R9

TREVOR DOBBINS
SCIENCE ADVISOR EQUIPMENT CAPABILITY
WING HQ SQN ROYAL MARINES POOLE
HAMWORTHY POOLE DORSET
BH15 4NQ
UK

HENDRIK A H C VAN VEEN
TNO HUMAN FACTORS
KAMPWEG 5
3769 DE
SOESTERBERG THE NETHERLANDS

BOB CHEUNG PH D
SENIOR DEFENCE SCIENTIST
AEROSPACE LIFE SUPPORT
DEFENCE RESEARCH AND DEVELOPMENT
CANADA - TORONTO DEPARTMENT OF
NATIONAL DEFENCE
1133 SHEPPARD AVE W
TORONTO ONTARIO
CANADA

LARS ERIKSSON
FOI SWEDISH DEFENCE RESEARCH AGENCY
DIVISION OF COMMAND & CONTROL
SYSTEMS
DEPARTMENT OF MAN-SYSTEM-
INTERACTION MSI
PO BOX 1165
SE-581 11 LINKÖPING SWEDEN

OTTO CARLANDER
RESEARCHER COMMAND AND CONTROL
SYSTEMS
MAN-SYSTEM-INTERACTION MSI
PO BOX 1165
SE-581 11 LINKOPING SWEDEN

MAAIKE DUISTERMAAT
TNO HUMAN FACTORS
PO BOX 23
KAMPWEG 5
3769 ZG SOESTERBERG THE NETHERLANDS