2012

Investigation Of Tactile Displays For Robot To Human Communication

Daniel Barber
University of Central Florida

INVESTIGATION OF TACTILE DISPLAYS FOR ROBOT TO HUMAN COMMUNICATION

by

DANIEL JOHNATHAN BARBER
B.S. University of Central Florida, 2004
M.S. University of Central Florida, 2006

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Modeling and Simulation
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Fall Term
2012

Major Professor: Lauren Reinerman-Jones

ABSTRACT

Improvements in autonomous systems technology and a growing demand within military operations are spurring a revolution in Human-Robot Interaction (HRI). These mixed-initiative human-robot teams are enabled by Multi-Modal Communication (MMC), which supports redundancy and levels of communication that are more robust than single mode interaction. (Bischoff & Graefe, 2002; Partan & Marler, 1999). Tactile communication via vibrotactile displays is an emerging technology, potentially beneficial to advancing HRI. Incorporation of tactile displays within MMC requires developing messages equivalent in communication power to speech and visual signals used in the military. Toward that end, two experiments were performed to investigate the feasibility of a tactile language using a lexicon of standardized tactons (tactile icons) within a sentence structure for communication of messages for robot to human communication. Experiment one evaluated tactons from the literature with standardized parameters grouped into categories (directional, dynamic, and static) based on the nature and meaning of the patterns to inform design of a tactile syntax. Findings of this experiment revealed directional tactons showed better performance than non-directional tactons, therefore syntax for experiment two composed of a non-directional and a directional tacton was more likely to show performance better than chance. Experiment two tested the syntax structure of equally performing tactons identified from experiment one, revealing participants' ability to interpret tactile sentences better than chance with or without the presence of an independent work imperative task. This finding advanced the state of the art in tactile displays from one to two word phrases facilitating inclusion of the tactile modality within MMC for HRI.

Dedicated to my family, whose never-ending support and guidance have made everything I have ever accomplished possible.

ACKNOWLEDGMENTS

This research was sponsored by the Army Research Laboratory and was accomplished under Cooperative Agreement Number W911NF-10-2-0016. The views and conclusions contained in this document are those of the author's and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS/ABBREVIATIONS

DoD	Department of Defense
HRC	Human-Robot Communication
HRI	Human-Robot Interaction
ISI	Inter-Stimulus Interval
MIX Testbed	Mixed Initiative Experimental Testbed
MMC	Multi-Modal Communication
ST	Single Tactons
RCTA	Robotics Collaborative Technology Alliance
Tacton	Tactile Icon
TS	Tactile Sentences
US	Unmanned Systems
WI	Work Imperative

CHAPTER ONE: INTRODUCTION

The use of technology and autonomous systems within the military continues to grow as the U.S. Government looks for new ways to support the Warfighter and maintain a competitive edge over current and future enemies. The National Defense Authorization Act for Fiscal Year 2001 (U.S. Congress, 2001) conveys this desire, mandating the Armed Forces to "achieve the fielding of unmanned, remotely controlled technology such that by 2015, one-third of the operational ground combat vehicles of the Armed Forces are unmanned." Released in 2007, the Unmanned Systems Roadmap incorporates master plans for unmanned air, ground, undersea, and surface systems over the next twenty-five years into a comprehensive roadmap for future prioritization of development and U.S. Department of Defense (DoD) needs (Office of the Secretary of Defense, 2007). Seamless integration of Unmanned Systems (US) with manned systems is a key component of the vision illustrated by this roadmap.

As a result of the push for increased use of US's, over 2,000 have been deployed into the battlefield in Afghanistan (Magnuson, 2011), supporting operations including: search and rescue, ordinance disposal, mine clearing, and remote targeting missions. The integration of Soldiers with these highly intricate systems, each equipped with their own human-machine interface, is a complex task. Interfaces must account for different levels of autonomy while providing appropriate user-feedback in an efficient manner to accomplish a variety of tasks. An increasing number of missions require robots to perform in more dynamic and less structured activities including direct interaction with people.

Human-Robot Interaction: From Tools to Teammates

Human-Robot Interaction (HRI) is the interdisciplinary study of interaction dynamics between humans and robots. The fundamental goal for the field of HRI is developing principles and algorithms for robots capable of direct, safe, and effective interaction with humans (Feil-Seifer & Matarić, 2009). Typical HRI in military operations today involves a human operator explicitly controlling or supervising an unmanned asset using a Human Computer Interface (Barnes & Jentsch, 2010). Teleoperation is the contemporary standard and therefore humans do not interact with a robot as a co-located team member when in a real-world dynamic operational environment (e.g., combat), resulting in a lack of team cohesion. In particular, teleoperating a robot requires the operator to withdraw his or her attention from the environment, reducing situation awareness, yet also adding to task requirements, thus increasing workload. Situation awareness is the understanding of one's environment with varying granularities of detail and meaning as well as future state prediction (Endsley, 1995). Situation awareness is influenced by internal (e.g., self-referent cognitions) and external (e.g., changing task complexities) factors. A loss of situation awareness in operational military settings can also result in a loss of assets and failure to complete missions. Workload is a measured difference between cognitive resources available versus those required for completing a given task. Workload is affected by task requirements, meaning the number of responsibilities to complete, or by team demands, specifically team coordination and communication (Bowers, Braun, & Morgan, Jr., 1997). Overloading can result in injury and poor performance. Inclusion of a teleoperated robot further increases the complexities of communication by adding an additional step in the process

(Cosenzo, Capstick, Pomranky, Dungrani, & Johnson, 2009). That is, instead of direct communication to all assets, commanders must first communicate through a robotic operator. Although robots are critical to military operations, functioning as tools does not support human-robot team collaboration and negatively impacts situation awareness and workload for the operator and the entire team (Hancock, 1996; Redden & Elliot, 2010).

In an effort to achieve human-robot teaming, and thus maintain situation awareness and reduce workload, events like the DARPA Grand Challenge (DARPA, 2007) and programs such as the Robotics Collaborative Technology Alliance (RCTA) (U.S. Army Research Laboratory, 2011) have been established to advance sensors and other technologies enabling the creation of highly autonomous robots. These automated systems will collaborate in future mixed-initiative teams with Soldiers, implementing flexible interaction strategies in which each agent (human or robot) contributes what is best-suited at the most appropriate time (Hearst, Allen, Guinn, & Horvitz, 1999). Improved perception and intelligence will support robotic partners that no longer require display-centered interfaces. Instead, robots need to receive commands and acknowledgement of messages just as human teams. This transaction needs to occur naturally and without ambiguity. To achieve that, a human-robot language needs to be developed.

A Historical Overview of the Study of Language

The initial study of language, and thus communication, can be attributed to ancient philosophers such as Gorgias, Socrates, Plato, and Aristotle who examined the prose and context of rhetoric. Campbell and Burkeholder (Campbell & Burkholder, 1996) indicate that rhetoric, in a broad sense, “can refer to any use of symbols to influence others. That includes functions other than persuasion, such as interpersonal identification, confrontation, self-identification, alienation, and negotiation. Rhetoric also includes forms other than written and oral discourse, such as gestural and visual communication, the use of space, and certain dimensions of music, dance, motion pictures, television programs, and painting." The study of rhetoric laid the groundwork for the field of psycholinguistics to form in the 1950s.

Psycholinguistics is a merge between psychology and linguistics that resulted from the logical positivist movement in philosophy (Tanenhaus, 1988). Specifically, that philosophical approach to language encouraged psycholinguists to systematically identify verbal behavior and apply the findings in a stimulus-response manner. The behaviorist approach transformed by Chomsky emphasized innate cognitive components of language acquisition, which were not necessarily observable (Chomsky, 1957; 1965). In fact, his framework is known as transformational grammar and focused on the generative power of grammar for combining an infinite number of sentence constructs. He inductively reasoned that language is innate because there is no way for children to learn every possible combination of words and sounds, and yet they spontaneously generate new sentences. Chomsky's work spawned an era of studying the innateness of language acquisition, but this was broadened to include the relevance of context and semantics (Gleason, 2005; Tanenhaus, 1988). It was at this time that psycholinguistics aligned with mainstream cognitive psychology. This shift was largely due to the information processing approach to explaining the "black box" in the human mind. In particular, a focus on researching semantics, semantic memory, and natural-language processing secured psycholinguistics as a domain of cognitive psychology (Clark, 1973; Collins & Quillian, 1969). In the 1980's and 1990's, the floodgates were opened to all aspects of psycholinguistics, including phonology, morphology, syntax, semantics, and pragmatics. Technology has evolved enabling the use of simulators and neuropsychological sensors to test and expand linguistic models, which brings us to our present day understanding of language.

Components of Language

Regardless of camp, linguists, psychologists, philosophers, and psycholinguists have sought to decompose language into explainable terms. As a result, four core components have emerged. A phoneme is the first component. A phoneme is one unit of sound such as ch, s, or ph (Gleason, 2005, p. 20; Messer, 1994, p. 4). Similar to a phoneme is a morpheme, which is one unit of meaning (Gleason, 2005, p. 21; Messer, 1994, p. 148). For example, the word intended has two morphemes, intend and ed. The ed adds meaning of past tense. Each of these components, phonemes and morphemes, are extended by syntax and semantics. Syntax is the structure of sentences or the manner in which words are combined to form sentences (Gleason, 2005, p. 22; Messer, 1994, p. 148). In other words, this is grammar, like the placement of nouns in relation to adjectives or how language is used. Semantics is the meaning of sentences that results from the order of the words (Gleason, 2005, p. 23; Messer, 1994, p. 93). The same thought can be conveyed in more than one way. “I typed a paper” and “a paper was typed by me” are two structures stating the same idea.

These four concepts seem straight forward, but not considered is the point that the same sentence can send two different messages. “There you have it,” can mean 1. A person is referring to an item and is giving it to another person, or 2. A general statement or popular phrase about a truth established. Without context, the absolute intent of the meaning is non-determined. Pragmatics is the study of language in context (Gleason, 2005, p. 23; Messer, 1994, p. 110). Another area to recognize is lexicology, which is the study of the vocabulary, or lexicon, available in a given language (Jackon & Amvela, 2000, p. 1). Both pragmatics and lexicology address common language usage, and contribute to semantics and overall communication success.

The four core components, along with pragmatics and lexicology, are anticipated to be critical in developing HRC. Currently, a set of commonly used communications is not established across studies for human-robot interaction. Rules have not been investigated for delivery and receipt effectiveness, boundaries have not been established for modes of communication given particular contextual constraints, and lexicons have not been generated for human-robot language. These foundational components are essential for creating successful, effective, and efficient HRC.

Language Development

The components and sub-areas of language are natural and logical. These elements apply to other languages, not just English. Provided their importance, the next step to implementing these factors into HRC is to identify the best methods for attaining these qualities. Continuing with the reasoning that human-human communication rules will extend to HRC, an examination of language development is expected to yield insight.

Age and Milestones

Universal milestones have been identified through research and parental observation. It is likely some variation will occur for each child, but the general ages and events are highlighted in Table 1.

Table 1
Ages with Associated Language Development Milestones, from Kalat (2008)

Age	Typical Language Abilities
3 months	Random vocalization.
6 months	More distinct babbling.
1 year	Babbling that resembles the typical sound of the family's language; probably one or more words including "mama"; language comprehension much better than production.
1.5 years	Can say some words (mean about 50), mostly nouns; few or no phrases.
2 years	Speaks in two-word phrases.
2.5 years	Longer phrases and short sentences with some errors and unusual constructions. Can understand much more.
3 years	Vocabulary near 1,000 words; longer sentences with fewer errors.
4 years	Close to adult speech competence.

The progression of children's attainment of communication is mostly established, but some factors can help or hinder the process. Parentese appears to influence and aid language acquisition. Parentese is the exaggeration on sentences, words, and sounds by caregivers (Fernald & Kuhl, 1987). Multi-Modal parentese and message content are significant contributors to language development. Multi-modal parentese involves verbal emphasis combined with motion or touch (Gogate, Bahrick, & Watson, 2000), while content includes the adult repeating himself or herself with new syntax and expanding what is understood from child utterances to complete sentences (Hoff-Ginsberg, 1990). Given this information, one conclusion is that it is essential for a message to be conveyed with redundancy to ensure it was received and processed completely. Keeping this in mind, it is advised that the creation of a human-robot language capitalize on MMC.

Learning a Second Language

Primary language acquisition is unique and provides recommendations for HRC due to the strength of neuronal connections in the brain for particular syntax, semantics, and modalities. However, learning HRC is likely to resemble, more closely, the process of learning a second language. Learning a second language is easier for children than adults. In fact, attaining fluency in a second language is less likely to occur after the age of 12 (McDonald, 1997). A similar result occurs for deaf individuals learning sign language. Persons who learn sign language during infancy are more fluent than those who learn as adolescents or adults (Newport, 1990; McDonald, 1997). These findings are explained by lateralization of language finalizing between the ages of two and five years old (Kinsbourne & Wallace, 1974; Marcotte & Morere, 1980) and the need for exposure to particular phonemes by the time a child is three years old (Kowalski & Westen). Specifically, two locations in the left hemisphere of the brain have been identified for speech production, *Broca's Area*, and for speech comprehension, *Wernicke's Area*. These areas are the same for signing deaf individuals. It is interesting to note that infants who learn sign language and are not deaf, develop language more readily (Goodwyn, Acredolo, & Brown, 2000) providing additional support for a multi-modal approach to HRC. A further recommendation for developing a human-robot language is to match it as closely as possible to the primary language and modes of communication of the operator.

Models of Communication

At this point, the relevance of psycholinguistic principles and language development to that of creating human-robot language has been established. However, it is important to dig deeper, beyond language production and comprehension, to that of human-human communication. Self-actional models view communication as one-way – a sender delivers a message to a receiver as seen in Figure 1 (Anderson & Ross, 2001, p. 80). This is comparable to the state-of-the-art for HRI, such that the operator is the sender and the robot is the receiver (Figure 1).

Figure 1 Self-actional model of communication, adapted from Anderson & Ross (2001).

A feedback loop extends the self-actional model (Figure 2), making it an interactional model (Anderson & Ross, 2001, p. 80). The argument could be made that this is actually the appropriate model for depicting the current state of display-centered HRI because the operator is able to see the robot or has a video in which he or she receives feedback. A counterargument to that is the robot does not actively respond to the operator, but the visual feedback is a default of teleoperation, or manual control, limitation. Either way, these simplified models barely brush the surface of the complexities involved in communication and certainly does not solve the problem of teleoperation.

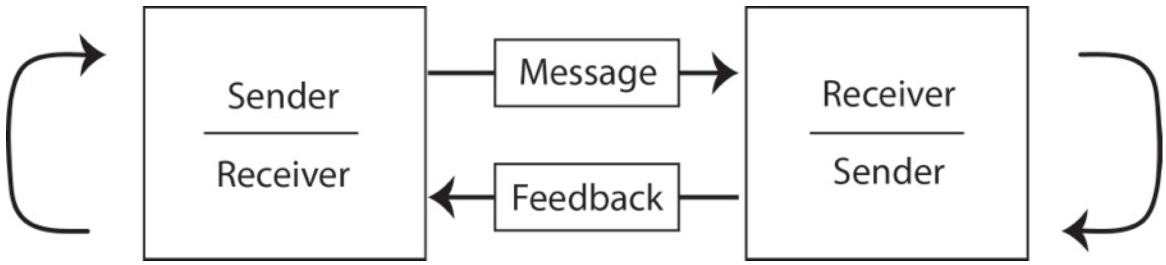


Figure 2. Interactional model of communication, adapted from Anderson & Ross (2001).

As an alternative, instead of attempting to explain the process, Berlo (1960) sought to illustrate significant factors of communication (Figure 3).

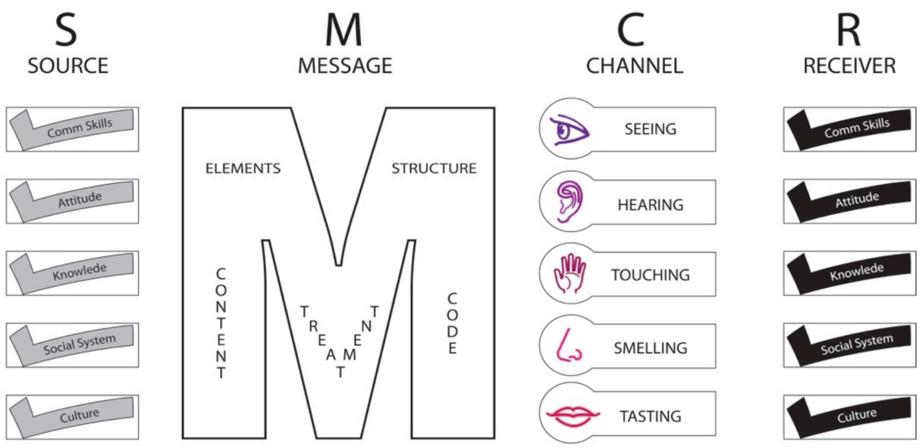


Figure 3. Model of communication factors, adapted from Berlo (1960).

Dance (1967), on the other hand, sought to only illuminate the communication process through a helical model consisting of a starting point with an infinite broadening end (Figure 4).

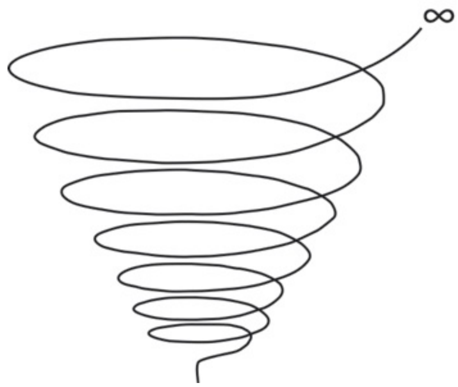


Figure 4. Helical model of communication processes, adapted from Dance (1967).

In an effort to capture both the factors presented by Berlo and the process put forth by Dance, Barnlund (1986) developed a transactional model. This complex model, shown in Figure 5, conveys that each person involved in the communication is changed by the exchange and affected by personal (e.g., feelings, beliefs, and thoughts) and public cues (e.g., environment, culture) as each encodes and decodes messages. Although not every aspect of communication is expressed in the transactional model, it is the best working point for examining and developing HRC. It captures the influence that a human-robot exchange will have on a team member. It illustrates contextual factors and their influence on encoding and decoding messages. It also emphasizes the importance of bi-directional message sending and receiving for all parties involved in the transaction. These notions act as the basis for the need for MMC in HRI.

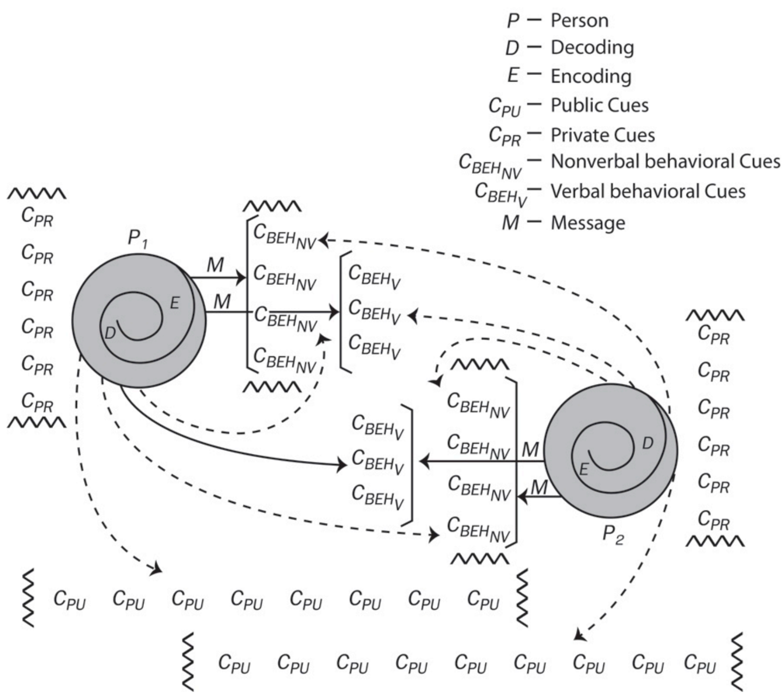


Figure 5. Transactional model of communication, adapted from Barnlund (1986).

Multi-Modal Communication

The relevance of MMC for the development of a human-robot language is established based on models of communication. Throughout literature, six common themes in existing MMC research emerge: meaning, context, natural, efficiency, effectiveness, and flexibility. Numerous authors use meaning and context such that multi-modal systems strive for meaning (Nigay & Coutaz, 1993; Kvale, Wrakagoda, & Knudsen, 2003; Raisamo, 1999), more complex information can be conveyed over multiple modes compared to a single mode (Bischoff & Graefe, 2002), and ideas can be conveyed redundantly (back up signals), non-redundantly (multiple messages) (Partan & Marler, 1999; Parr, 2004). Ultimately, MMC supports multiple levels of complexity (Bischoff & Graefe, 2002).

Similar is the case for the natural theme. MMC results in more robust, natural, and efficient communication (Mariani, 2000). It enables recognition of naturally occurring forms of human language and behavior (Oviatt, 2002) and combines natural inputs to convey meaning (Cohen & McGee, 2004). It also allows users to take advantage of natural communication modes (Kvale, Wrakagoda, & Knudsen, 2003). The most notable trend from literature on the natural theme is modalities. Modalities cited include speech, gestures, mimics, nonlinguistics, touch, gaze, head and body movements, facial expression, and vision (Bunt, 1998; Kvale, Wrakagoda, & Knudsen, 2003; Louwerse, Jeuniaux, Hoque, Wu, & Lewis; Thiran, Marqués, & Bourlard, 2009).

The blending of these modalities for the improvement of HRI is shown to impact effectiveness (how well) and efficiency (how fast) of display-centered interfaces (Parr, 2004; Oviatt, 2002; Oviatt, 2002; Haas, 2007; Haas & Van Erp, 2010). Although there has been extensive research within tactile, visual and audio modalities, there has not been work performed where they are used for MMC within dismounted operations (Haas & Van Erp, 2010). Lackey, Barber, Reinerman-Jones, Badler, and Hudson (2011) began to attack how research can address the gap by operationalizing how each modality can be delivered within mixed-initiative dismounted teams (Table 2).

Table 2
HRI Communication Modalities, Adapted from (Lackey, Barber, Reinerman-Jones, Badler, & Hudson, 2011, p. 2)

Modality	Delivery	Explicit	Implicit
Auditory	Speech	Language	Tone, Rate, Pitch
	Sounds		
Visual	Posture	Intentional Point	Unintentional Body
	Facial Expression,	Hand Signals	Language
	Gesture		Intensity
	Gait		Eye Contact
	Social Distance		Talking with Hands
			Emotions
Tactile	Belt Vest	Intentional Touching	Pressure
		Patterns	Patterns
			Shakiness

Within this domain, and for the purposes of this study, the definition of MMC is taken from Lackey et al. (2011), "the exchange of information through a flexible selection of explicit and implicit modalities that enables interactions and influences behaviors, thoughts, and emotions."

Explicit Communication

As seen in the formal definition, MMC is complex and inherit is the combination of explicit and implicit communications required. Previously shown, Table 2 shows explicit communication composed of auditory, visual, and tactile modalities with respect to medium of delivery and examples of its use. "Explicit Communication is the purposeful conveyance of information through multiple modalities (i.e., audio, visual, tactile) that has a defined meaning" (Lackey, Barber, Reinerman-Jones, Badler, & Hudson, 2011).

The auditory communication modality can be used to convey a range of explicit information from a sound source to a listener including commands and feedback. Its use has been shown to reduce operation time for discrete robotic tasks using explicit voice commands (Redden & Elliot, 2010). Other modalities yield better performance for continuous tasks such as giving directions and navigating. Research has also examined technologies for benefitting performance through the auditory modality. The use of specialized 3-dimensional (3-D) spatial audio displays as localization feedback was hampered by inaccuracies resulting from the front-back confusion phenomenon (Haas, 2007). The front-back phenomenon occurs when a sound is presented directly in front of or in back of the person and he or she cannot identify the direction whence it came. Two additional auditory modality technologies are voice synthesis and voice recognition. In HRI, both can be leveraged to construct a bidirectional communication channel. However, in noisy operational environment, these types of technology lose their effectiveness.

The visual modality for communication, like the auditory modality, yields a variety of tools for enhancing HRI. Hand signals and gestures are already widely used between persons as a natural method of communication (Wexelblat, 1995) and are also prominently used by warfighters in operation who follow the Army Field Manual (U.S. Army, 1987). It should be noted that visual refers to the human team members' perception of a communication even though the robot might receive certain "visual" stimuli through other sensors. One-way communication from humans to robots can take this intuitive form by capturing hand and arm gestures based on computer vision (e.g., Microsoft Kinect) or accelerometer-driven input devices (e.g., data capture glove or Nintendo Wiimote). Accelerometer-based capturing techniques acquire less noisy data and can work outside the line of sight (Varcholik, Barber, & Nicholson, 2008), but require additional testing in multi-tasking environments. A reciprocal communication is possible from robot to human and studies along that line take the form of humanoid robots (and animatronics) mimicking humans. Unfortunately not much research has been found on communication of this kind by non-humanoid robots, which are the dominant type of robots found outside of academia.

The visual modality seems to be limited at this time for providing communications from the robot to the human in an operational, non-academic setting. However, the limitations from communication in the auditory and visual modalities can be augmented through the tactile modality. Tactile communications can be delivered via electromechanical stimulation of the skin and has been applied in robotics to tasks such as spatial orientation, navigation, and control (Elliot, Coovert, Prewett, Walvord, & Saboe, 2009; White, 2010).

Tactile Communication

Tactile communication replaces or complements some pre-existing modality using vibrotactile stimuli (Cholewiak & Collins, 2003; Gilson, Redden, & Elliott, 2007). Brewster and Brown (2004) described tactons, or tactile icons, which are structured abstract messages that communicate messages non-visually by tactile displays. Tactons are constructed from a range of parameters including: frequency, amplitude and duration of pulse, plus other parameters such as rhythm and location (Brewster & Brown, 2004).

Tactors stimulate and manipulate the parameters of tactons and fall into two categories: inertial shakers and linear actuators (Mortimer, Zets, & Cholewiak, 2007). Inertial shakers employ the motion of an internal eccentric mass to produce vibration, and linear actuators employ a contractor that is driven against the skin (Mortimer, Zets, & Cholewiak, 2007). Linear actuators tend to be the most frequently used type of tactors used in tactile displays and are able to manipulate all tacton parameters (Cholewiak & Collins, 2003; Cholewiak, Brill, & Schwab, 2004). Jones and Sarter (2008) identified the optimal frequencies for perception of tactor vibrations to be between 150 and 300 Hz. In regards to duration, results from Kaaresoja and Linjama (2005) showed that participants prefer vibrotactile alerts between 50 and 200ms. Based on the research performed by Cholewiak et al. (2004) and a feasibility review by White (2010), the torso is identified as the most suitable body location to provide dismounted Soldiers with vibrotactile stimulation using a tactile belt or vest.

Research has typically used tactile belt displays capable of communicating through vibrations in the eight cardinal and inter-cardinal zones (e.g., north, northeast, east) surrounding the abdomen as oriented to wearer. Due to intuitive correspondence to egocentric direction, tactile belts have been particularly effective in navigational tasks. Participants in such tasks exhibit additional agility and speed due to the freeing of the hands and eyes (Elliot, Duistermaat, Redden, & Van Erp, 2007). Gilson et al. (2007) developed tactons matched to visual signals from the Army Field Manual (U.S. Army, 1987). Participants from the study were placed into two groups. Participants from group one classified the signals as they were perceived, and for those in group two, a preparatory signal was provided in advance of the identical signals. The results of this experimentation revealed participants ability to learn the signals with minimal training time of five minutes with no significant difference in performance between groups (Gilson, Redden, & Elliott, 2007). Tactile communications, in general, give the added benefit of being covert (White, 2010), having reduced response times over visual alerts, and high reception during physiological stress (Elliot, Coovert, Prewett, Walvord, & Saboe, 2009; Gilson, Redden, & Elliott, 2007; Merlo, et al., 2006; White, 2010).

Purpose for the Present Studies

Based on the extensive research performed to date, the feasibility of communication using a tactile display for HRI is clear (Brewster & King, 2005; Brown, Brewster, & Purchase, 2006; Gilson, Redden, & Elliott, 2007; Merlo, et al., 2006; Pettitt, Redden, & Carstens, 2006). However, the research to date with tactons is limited to either directional cueing or non-directional signaling using a limited lexicon. Moreover, tacton parameters (e.g., frequency, duration) are not standardized across experiments. Therefore, in order to replace or supplement another communication modality (e.g., visual) in MMC, tactile displays must be able to deliver equivalent messages.

The goal for the current effort is to investigate the feasibility of creating a tactile language for HRC. Specifically, the aim is to standardize tactons previously developed from the literature to create a tactile language that enables HRC. By standardizing the parameters across tactons equally performing patterns will be identified for tactile sentence construction. Based on the tactons discussed in the literature, three categories of tactons can be classified: directional, dynamic, and static. Directional tactons represent specific direction commands within the environment (Elliot, Duistermaat, Redden, & Van Erp, 2007; Mortimer B. , Zets, Mort, & Shovan, 2011). Both dynamic and static tactons are words/commands that do not contain a directional component (Gilson, Redden, & Elliott, 2007). Both directional and dynamic tactons contain motion (alternating tactors) within the sequence and static tactons do not. Comparing tactons by group (e.g., directional, non-directional) will also allow for identification of differences in performance and workload between types of tacton. Specifically, it was expected that for experiment one the following would occur:

1.1. Participants will perform better at classifying directional tactons than dynamic and static tactons.

1.2. Participants will perform better at classifying dynamic tactons than static tactons.

1.3. Participants will have faster reaction times when correctly classifying directional tactons than dynamic and static tactons.

1.4. Participants will have faster reaction times when correctly classifying dynamic tactons than static tactons.

1.5. Participants will experience increased levels of workload interpreting dynamic and static tactons over directional tactons.

1.6. Participants will experience increased levels of workload interpreting static tactons over dynamic and directional tactons.

The purpose for experiment two was to investigate tactile sentences composed of a non-directional tacton followed by a directional tacton based on the findings from experiment one. It is expected that participants will be able to interpret combinations of non-directional and directional tactons within a sentence structure better than chance.

CHAPTER TWO: EXPERIMENT ONE METHODOLOGY

Participants

Thirty-eight University undergraduate students (15 Male, 23 Female) between the ages of 18 and 40 (M = 19.62, SD = 2.35) served as the experimental participants and were recruited using an experiment management website. The participants received credit for their psychology courses for completing the study. Participants were right handed (due to potential differences in brain physiology of left handed participants and linguistic function (Knecht, et al., 2000)), had normal (or corrected to normal) vision, and no prior military service. Participants were asked not to consume alcohol or any sedative medication for 24 hours or caffeine for two hours prior to the study, as these can influence their performance and perceptual sensitivity. Finally, participants were required to have a waistline between 34 and 50 inches to accommodate the size of the Tactor Belt used. The full restrictions checklist is located in APPENDIX A.

Experiment Equipment

The experiment required participants to view and classify tactile icons, known as tactons, associated with visual signals used in standard military operations (U.S. Army, 1987). A tactor is a single vibrating motor that delivers a tactile stimulus and a tacton represents a time-based sequence of one or more tactors being activated. The tactons were presented using the C-2 Tactor Belt with ATC 3.0 Controller from Engineering Acoustics, Inc. (Figure 6) and a custom software application developed for the experiment, called Tacton Presenter (Figure 7).

Figure 6. C-2 Tactor Belt with ATC 3.0 Controller.

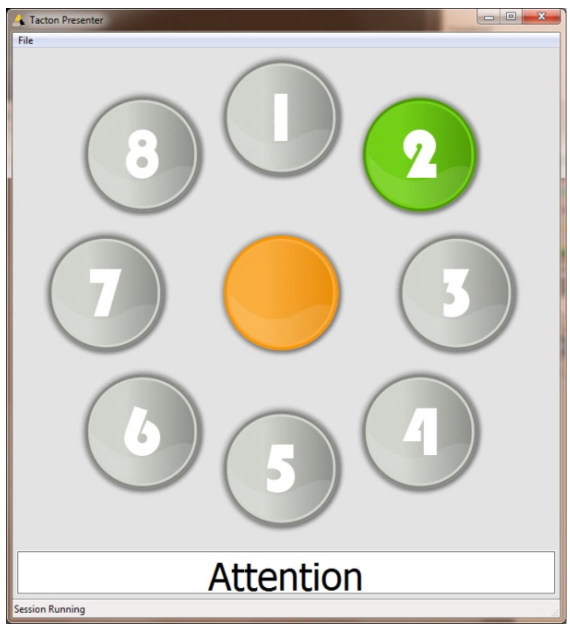


Figure 7. Tacton Presenter software application.

The Tactor Belt contained eight individual tactors that can be activated individually or in combinations to implement tactons. The Tacton Presenter application activates tactons using the

Tactor Belt and has the ability to show a visual equivalent of each individual tactor being activated in addition to the name of the tacton. A video clip of a robot navigating through a geo-typical Middle Eastern environment was also used during the experiment (Figure 8). The task was completed on a standard desktop computer with a 22” (16:10 aspect ratio) monitor with a keyboard and mouse.

Figure 8. Screenshot of robot video animation.

Experimental Design

A repeated measures design was employed with one Independent Variable (IV) and three conditions. This study measured three categories of tactons: directional, dynamic, and static. Directional tactons represent specific direction commands within the environment (e.g., Toward North, Away From North). For all tactons, the duration of vibrotactile stimulation was 250ms at a sinusoid frequency of 230Hz, and inter-tacton interval of 200ms. These parameters were chosen due to the ability for participants to accurately perceive and distinguish individual tactors

(White, Suitable Body Locations and Vibrotactile Cueing Types for Dismounted Soldiers, 2010). Both dynamic and static tactons are words/commands that do not contain a directional component (e.g., Attention, Enemy in Sight, Move Out). Both directional and dynamic tactons contain motion within the sequence and static tactons do not. A motion type tacton has a sequence with different tactors activated at each time increment (Figure 9).

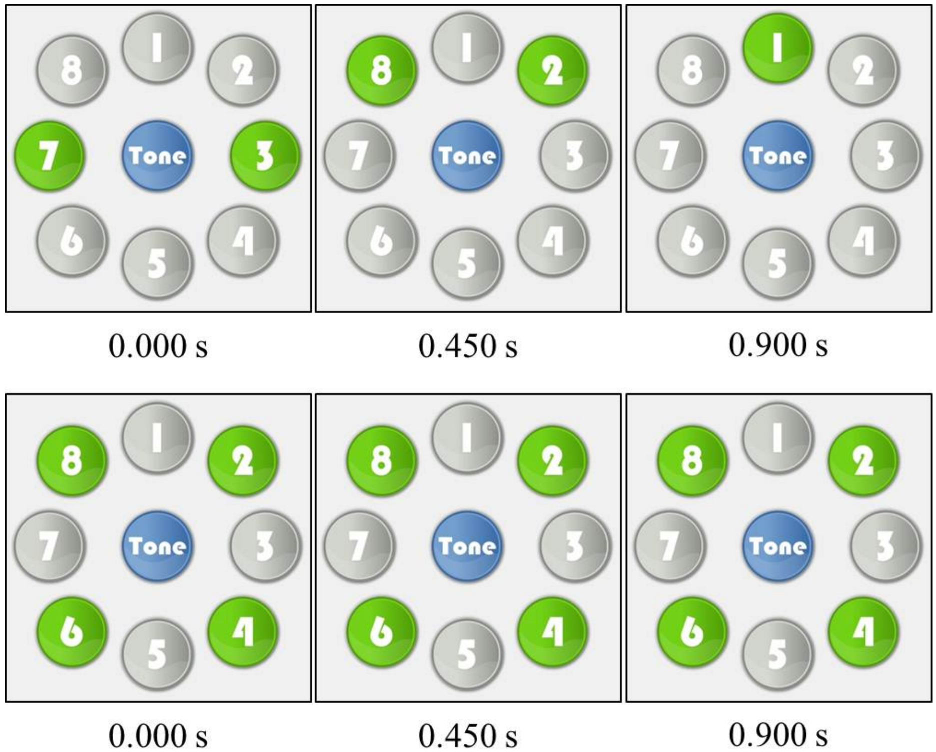


Figure 9. Example of motion tacton (top) and static tacton (bottom).

<u>Independent Variables</u>

Tacton Category

<u>Directional Tactons Category</u>

There were eight directional tactons: Toward North, Toward South, Toward East, Toward West, Away from North, Away from South, Away from East, and Away from West (APPENDIX B).

Dynamic Tactons Category

There were eight dynamic non-directional tactons: Attention, Danger Area, Disperse, Enemy in Sight, Move Out, Rally, Rush, and Take Cover (APPENDIX B).

Static Tactons Category

There were eight static non-directional tactons, named: Acknowledge, Cease Fire, Fire, Halt, I Do Not Understand, Nuclear/Biological/Chemical Attack, Vee Formation, and Wedge Formation (APPENDIX B).

Dependent Variables

Performance Measures

Classification Accuracy

For each tacton presented the classification accuracy was recorded based on the participants' selection from a drop-down menu. If the selection matched the tacton presented, the result was scored as correct, an incorrect match or "I don't know response" was scored as incorrect. The final measure reported for each participant is a percentage of tactons correct out of the total presented.

Reaction Time

For each tacton presented the participant was required to press the spacebar on the keyboard when they recognize the tacton. The reaction time recorded was from end of stimulus presentation to when the participant pressed the spacebar. If the user did not press the spacebar, it was marked as no-response, and the response time recorded was from end of stimulus presentation to when the tacton classification dialog appeared. The final measure reported is the median adjusted reaction time (milliseconds) for all tactons classified correctly.

Questionnaires

Attentional Control Measure

A questionnaire on Attentional Control (Derryberry & Reed, 2002) was used to evaluate participants' Perceived Attentional Control (PAC). The Attentional Control Survey consists of 21 items and measures attention focus and shifting (APPENDIX C). The total score measure reported is the summation of each of the 21 items normalized to a scale of one to five, with one being low attentional control and five high.

Spatial Ability Measure

Participants completed a spatial ability questionnaire to measure participants' Spatial Ability (SpA). The Cube Comparison Test (Ekstrom, French, Harman, & Dermen, 1976) requires participants to compare, in 3-minutes, 21 pairs of 6-sided cubes and determine if the rotated cubes were the same or different (APPENDIX D). This measure produces a total score, which is the number of correct comparisons minus the number incorrect.

Workload Measure

The NASA Task Load Index (TLX) (Hart & Staveland, 1988) was used to measure the participant's subjective workload from each experimental condition. The measure produces six workload subscales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration, as well as a single combined measure of Global Workload based on the mean of the six subscales. Each subscale is scored between 0 and 100; with 0 low workload and 100 high. The NASA-TLX was administered on the computer through a standard computer program (APPENDIX E).

Procedure

Upon arrival, the participant was first confirmed that he or she meet the inclusion criteria. The participant was then provided an Informed Consent that details their rights as a research participant, the purpose for the study, overall procedure, source of funding for the study, and the potential risks associated with participation. After reviewing the Informed Consent, the participant turned off any cell phone or pager they had and gave them to the experimenter along with any watch and personal planners for the duration of the study.

Next, the participant completed a demographics questionnaire to measure standard items such as age and gender, as well as items used to determine their experience with various technologies. This questionnaire was used to document the participant's state of health, color vision, and prior military experience (APPENDIX F). After completing the demographics questionnaire, the participant filled out the Attentional Control Survey and Cube Comparison Test. Once the questionnaires were completed, the participant was fitted with the Tactor Belt, such that it is seated around the abdomen, and not the hips, with the belt buckle on the belly button.

With the belt fitted, the participant was tested on their tactile sensitivity by activating each tactor on the Tactor Belt individually. This was completed to ensure that the participants were equated in not just their waist size, but for perception of the tactors. Before testing for sensitivity, the participant was introduced and trained for the sensations generated by each tactor on the Tactor Belt. Each tactor was activated individually in a clockwise order starting at tactor one and ending at tactor eight, then counter clockwise starting at eight and ending at one. During this presentation, a visual equivalent was also shown to the participant with the name of the tactor. Each tactor activation implemented a vibration with a duration of 250 milliseconds consisting of a sinusoid frequency of 230 Hz and a two second Inter-Stimulus Interval (ISI) between each tactor presentation.

After introduction to the sensations generated by the Tactor Belt, the participant's sensitivity was tested by classifying each individual tactor presented in a random sequence ten times each for a total of 80 presentations. After each individual tactor vibration, the participant pressed the spacebar key as soon as the tactor presented was identified. A dialog-box appeared two seconds after completion of tactor presentation, where the user classified the tactor perceived using a drop-down menu. The response time for pressing the spacebar along with the accuracy of the choice of the participant was recorded. There was no time limit for the participant to make a selection using the classification dialog. After selection of the tacton and closing the dialog-box using the "OK" button, the next tactor was activated one second later. Upon completion of sensitivity training and testing the participant was given a two-minute break with the Tactor Belt removed. The purpose of this break was to enable the participant's tactile system to reset to a resting baseline, avoiding loss in tactile sensitivity (Vitello, Ernst, & Fritschi, 2006).

After the break, the Tactor Belt was put back on according to previously stated protocol and the participant began completion of the three tacton category conditions: directional, dynamic, and static. Each condition comprised two training tasks and an experimental task, and the conditions were presented in random order. The purpose for the two training tasks was to familiarize participants with the proper expected responses and to learn the tactons. In the first training task of a condition, each tacton and its name was presented to the participant two times in random order. The presentation of each tacton lasted approximately three seconds with a one second ISI. During the presentation, the participant was shown an animated sequence of the pattern, which was the visual equivalent to the given tacton on the computer screen in addition to the tactons' name.

In the second training task, the participant was provided the visual animation of the tacton, but did not see the tacton name during presentation using the Tactor Belt. Additionally, the participant was asked to classify the tactons presented using the same method as the tactile sensitivity test. The participant pressed the spacebar on a keyboard when they identified the tacton. After a pre-defined time of two seconds from the end of tacton presentation, the participant was asked to select the correct name (or "I don't know") of the tacton he or she experienced from a drop-down list box on the computer. The participant was given feedback, which included the correct answer, immediately following classification. The next tacton was presented one second after clicking "Continue" on the feedback window and this is called the ISI for the purposes of the present experiment. Each of the eight tactons within the condition were presented four times. The reaction time and accuracy of the selection made by the participant was recorded. There was no time limit for classification of the tacton and presentation of feedback.

The participant next completed the experimental condition associated with the given training. The participant experienced each of the eight tactons ten times with an ISI of one second in random order and only the Tactor Belt was used to present the tacton; no visual animation or name was given. The visual animation of the tacton presented during the training was substituted with the video of the robot driving through a geo-typical Middle Eastern environment. The video looped continuously during the entire experimental condition. The participant classified each tacton using the same dialog-box as the second training task. After the participant classified a tacton, the next tacton was presented one second later with no feedback. There was no time limit for the participant to make a classification using the dialog-box.

Upon completion of the experimental task for a condition, the Tactor Belt was removed and the participant completed the NASA-TLX. The belt was put back on the participant for the completion of the next tacton category condition, following the same procedure of two training and one experimental task. After all three tacton category conditions were completed, the Tactor Belt was removed and the participant collected their cell phone, pager, timepiece, and planners to exit.

CHAPTER THREE: EXPERIMENT ONE RESULTS

A summary of all ANOVAs from Experiment One is located in APPENDIX K. A summary of all tables describing means and standard deviations from Experiment One is located in APPENDIX L.

Manipulation Checks

Sensitivity Test

Analyses of the sensitivity test were conducted to eliminate participants that did not achieve a minimum classification accuracy score of 90% and determine the number of individual tactor presentations needed to evaluate participant sensitivity for use in experiment two. Based upon overall classification accuracy for the entire sensitivity test, one participant (Female) was eliminated from further analysis by not achieving a score of greater than or equal to 90%. Results for the sensitivity test were split into five time periods: four representing 20 tactor presentations each and one containing the entire sequence of 80 presentations. Mean classification accuracy scores for each time period indicate participant's ability to demonstrate better than 90% tactile sensitivity in all time periods. A repeated measures Analyses of Variance (ANOVAs) with the Greenhouse-Geisser correction revealed that mean classification accuracy did not differ significantly between time periods, $F(2.32, 81.35) = 1.86$, $p = .156$, $\eta^2 = .05$. These results indicate that the number of tactor presentations used within the sensitivity test can be reduced in future experiments.

Training

A repeated measures ANOVA with Greenhouse-Geisser correction to adjust for violation of sphericity was performed between tacton categories and determined that the mean classification accuracy differed significantly between tacton categories during the second training task, $F(1.51, 53.00) = 35.62$, $p < .05$, $\eta^2 = .50$. Post hoc tests using the Bonferroni correction revealed that participants classified directional tactons ($M = 95.57$, $SD = 5.59$) with significantly higher accuracy than dynamic ($M = 75.78$, $SD = 17.28$), with $p < .05$. Participants classified static tactons ($M = 93.93$, $SD = 11.00$) with significantly higher accuracy than dynamic tactons ($M = 75.78$, $SD = 17.28$) also, with $p < 0.05$. These differences are illustrated in Figure 11.

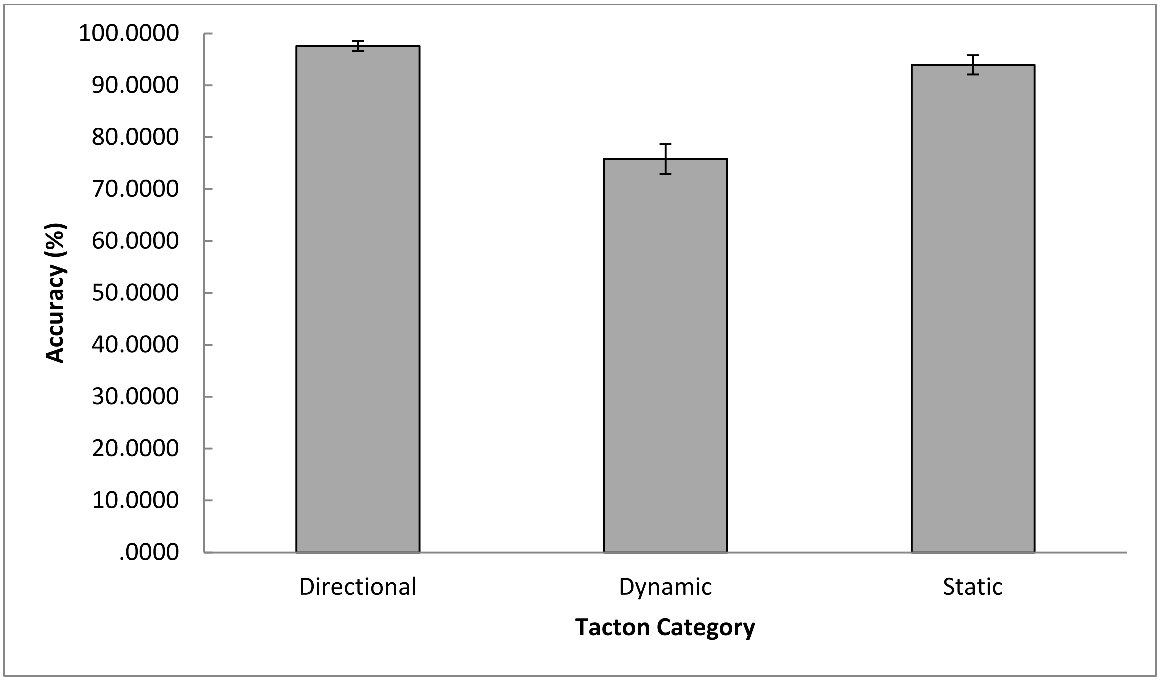


Figure 10. Mean classification accuracy for tacton categories during training. Error bars in this figure represent the standard error.

A repeated measures ANOVA with Greenhouse-Geisser correction was performed between tacton categories and revealed no significant difference for participant reaction time, $F(1.16, 40.49) = 2.768$, $p = .099$, $\eta^2 = .073$. Median reaction times were chosen for this analysis based upon literature indicating high variability in response time data, and therefore the median is the best representation of this data and is used for all further reaction time analyses.

Tacton Category Analyses

Classification Accuracy

A repeated measures ANOVA with Greenhouse-Geisser correction was performed between tacton categories and determined that the mean classification accuracy differed significantly between tacton categories, *F*(1.69, 59.38) = 55.83, $p < .001$, $\eta^2 = .615$. Post hoc tests using the Bonferroni correction revealed that participants classified directional (*M* = 95.42, *SD* = 7.99) tactons with significantly higher accuracy than both dynamic (*M* = 72.50, *SD* = 24.36) and static tactons (*M* = 62.81, SD = 17.41), and dynamic tactons (*M* = 72.50, *SD* = 24.36) showed significantly better performance than static (*M* = 62.81, SD = 17.41), with $p < .001$, illustrated in Figure 11.

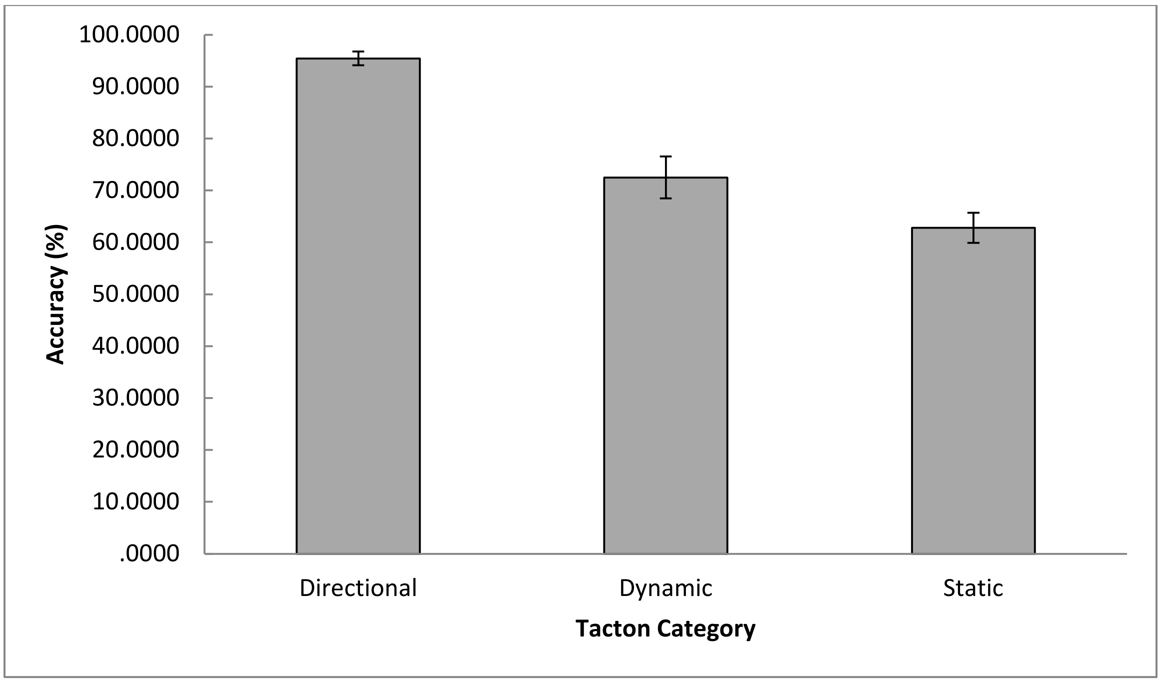


Figure 11. Mean classification accuracy for tacton categories. Error bars in this figure represent the standard error.

Reaction Time

A repeated measures ANOVA was performed between tacton categories and determined median reaction time differed significantly between tacton categories, *F*(2, 70) = 6.12, *p* = .006,

η^2 = .149. Post hoc tests revealed that participants reacted significantly more quickly to directional tactons (*M* = 739, *SD* = 906) and dynamic tactons (*M* = 760, *SD* = 1247) than static tactons (*M* = 1124, *SD* = 967), *p* = *.001* and *p* = .043. This is illustrated in Figure 12.

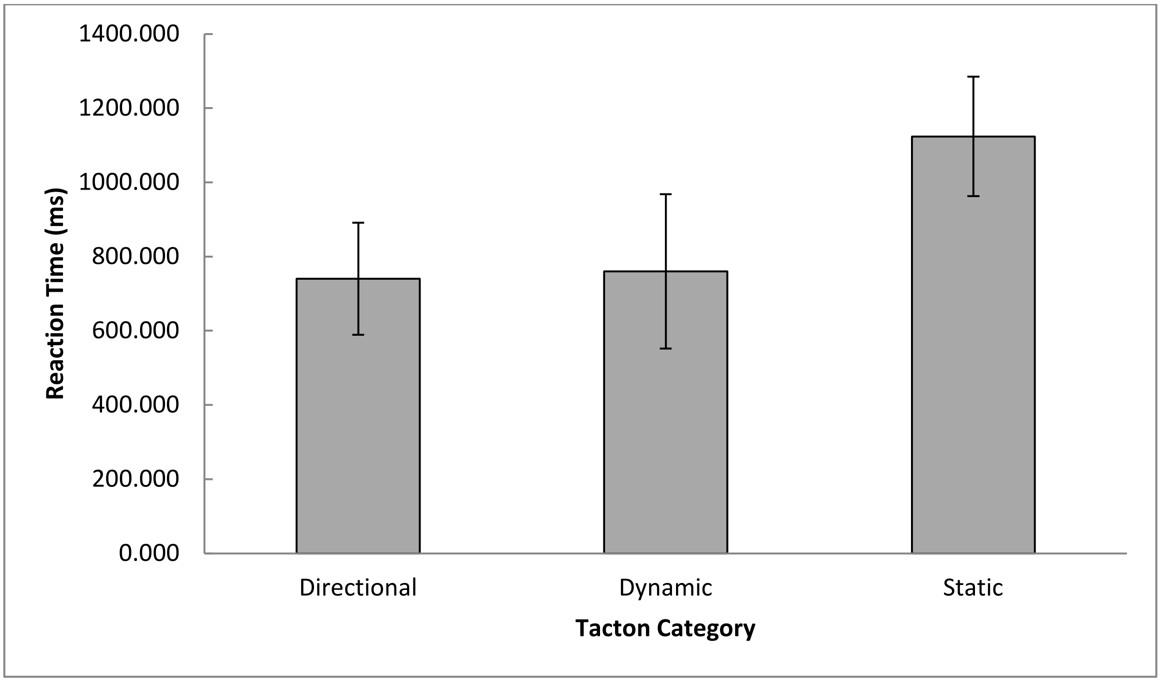


Figure 12. Median reaction time for tacton categories. Error bars in this figure represent the standard error.

Training Transfer

A 2 (Session: Training and Experimental) x 3 (Tacton Category: Directional, Dynamic, and Static) repeated measures ANOVA showed a significant main effect for training transfer using Hotelling's T to correct for violations of normality ($F(1, 35) = 83.09$, $p < .001$, $\eta^2 = .704$), such that training (*M* = 89.10, *SD* = 1.28) showed better performance than experimental (*M* = 79.91, *SD* = 2.35) sessions (Figure 13).

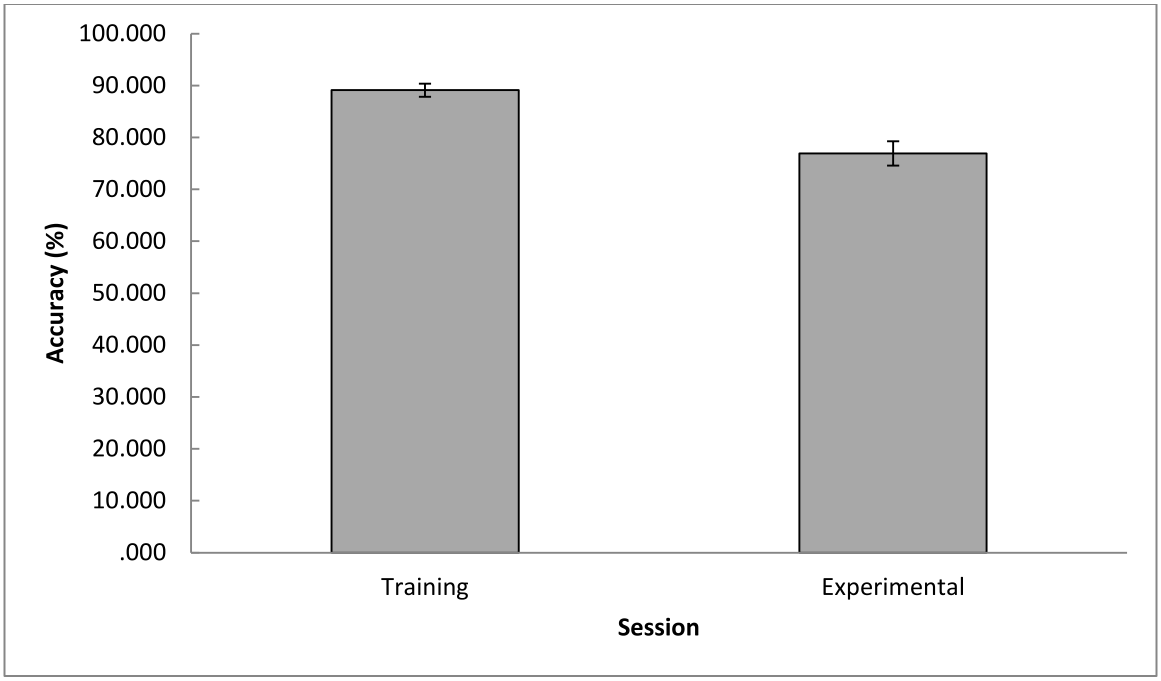


Figure 13. Classification accuracy for training and experimental sessions. Error bars in this figure represent the standard error.

A significant main effect was also found for tacton category using Hotelling's T ($F(2, 34) = 50.24$, $p < .001$, $\eta^2 = .747$), such that directional ($M = 96.49$, $SD = 1.03$) showed better performance than dynamic ($M = 74.14$, $SD = 3.34$) and static ($M = 78.37$, $SD = 2.11$) tacton categories, and static ($M = 78.37$, $SD = 2.11$) showed better performance than dynamic ($M = 74.14$, $SD = 3.34$; Figure 14).

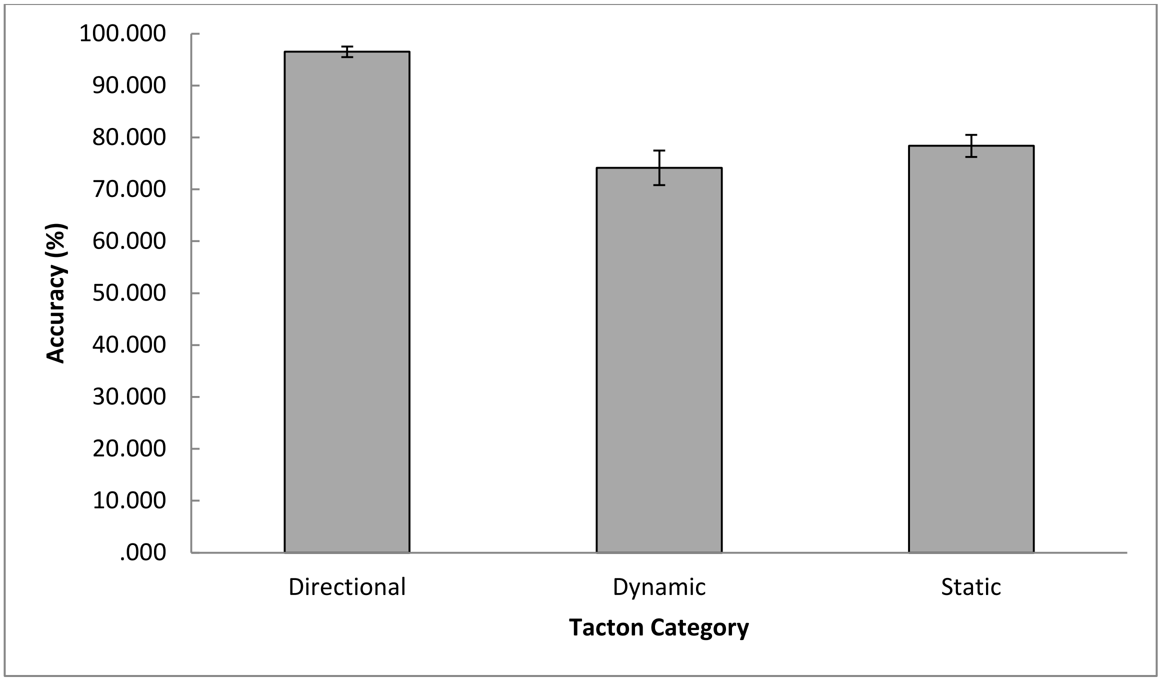


Figure 14. Combined classification accuracy for training and experimental sessions by tacton category. Error bars in this figure represent the standard error.

A significant interaction was found between training transfer and tacton category using Hotelling's T ($F(2, 34) = 82.11$, $p < .001$, $\eta^2 = .828$), such that performance was shown to be better for directional ($M = 97.57$, $SD = 5.59$) and static ($M = 93.93$, $SD = 7.99$) tacton training than experimental directional ($M = 95.42$, $SD = 7.99$) and static ($M = 62.81$, $SD = 17.41$) sessions (Figure 15).

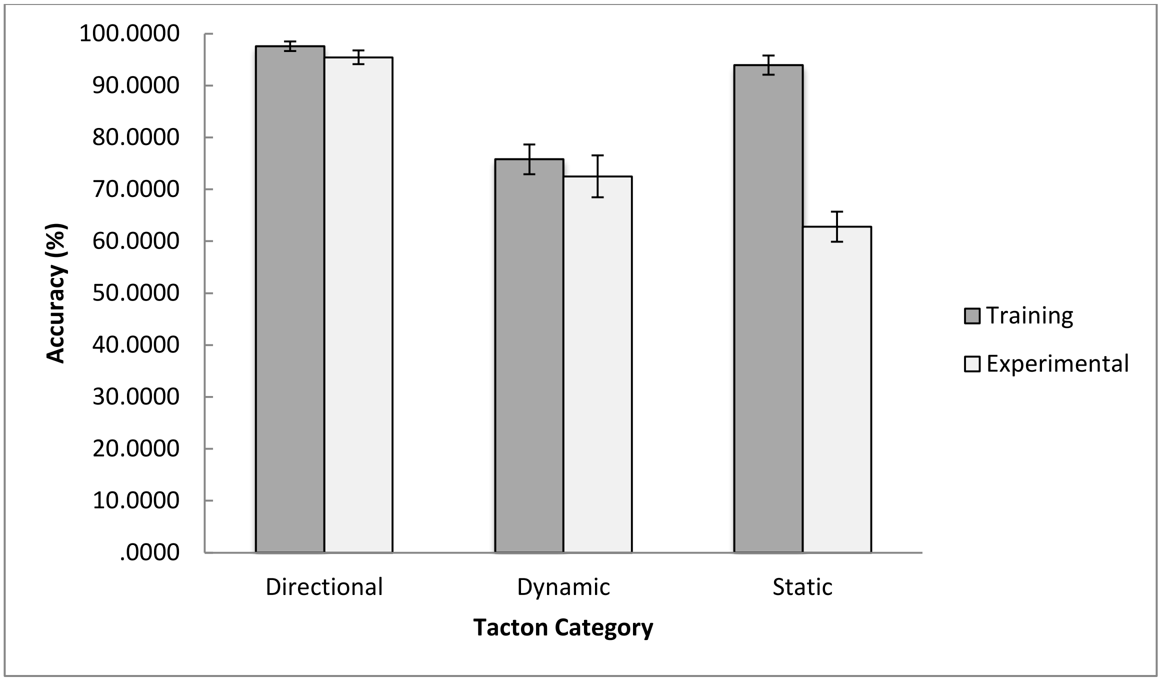


Figure 15. Classification accuracy for both training and experimental sessions by tacton category. Error bars in this figure represent the standard error.

Workload

A repeated measures ANOVA determined a significant difference in participants perceived workload for each subscale with Global Workload ($F(2, 70) = 38.17$, $p < .001$, $\eta^2 = .522$), Mental Demand ($F(2, 70) = 43.97$, $p < .001$, $\eta^2 = .557$), Physical Demand ($F(2, 70) = 5.96$, $p = .004$, $\eta^2 = .145$), Effort ($F(2, 70) = 13.76$, $p < .001$, $\eta^2 = .282$), Frustration ($F(2, 70) = 23.35$, $p < .001$, $\eta^2 = .400$), and Performance ($F(2, 70) = 18.94$, $p < .001$, $\eta^2 = .351$) between tacton categories. A repeated measures ANOVA with Greenhouse-Geisser correction also determined a significant difference in participants perceived Temporal Demand, $F(1.65, 57.66) = 6.37$, $p = .005$, $\eta^2 = .154$. Post hoc tests revealed participants rated their Global Workload significantly lower during directional tactons ($M = 32.01$, $SD = 11.96$) than dynamic ($M = 49.33$, $SD = 15.04$) and static ($M = 51.81$, $SD = 12.07$) tactons, with $p < .001$. Participants rated Mental Demand significantly lower during directional tactons ($M = 49.44$, $SD = 23.48$) than dynamic ($M = 74.86$, $SD = 19.55$) and static ($M = 70.14$, $SD = 20.48$) tactons, with $p < .001$. Participants rated Physical Demand significantly lower during directional tactons ($M = 16.39$, $SD = 12.51$) than static tactons ($M = 25.28$, $SD = 18.82$), with $p = .001$. Participants rated Effort significantly lower during directional tactons ($M = 47.50$, $SD = 24.33$) than dynamic ($M = 64.44$, $SD = 19.85$) and static ($M = 66.94$, $SD = 17.82$) tactons, with $p = .002$ and $p < .001$ respectively. Participants rated Frustration significantly lower during directional tactons ($M = 22.64$, $SD = 19.29$) than dynamic ($M = 47.78$, $SD = 27.37$) and static ($M = 52.22$, $SD = 26.29$) tactons, with $p < .001$. Participants rated Performance significantly better during directional tactons ($M = 19.17$, $SD = 16.97$) than dynamic ($M = 40.14.17$, $SD = 25.14$) and static ($M = 45.69$, $SD = 22.81$) tactons, with $p < .001$. A post hoc test with Bonferroni correction revealed participants rated Temporal Demand significantly lower during directional tactons ($M = 36.94$, $SD = 20.33$) than static tactons ($M = 50.56$, $SD = 20.59$), with $p < .001$. These findings are illustrated in Figure 16.

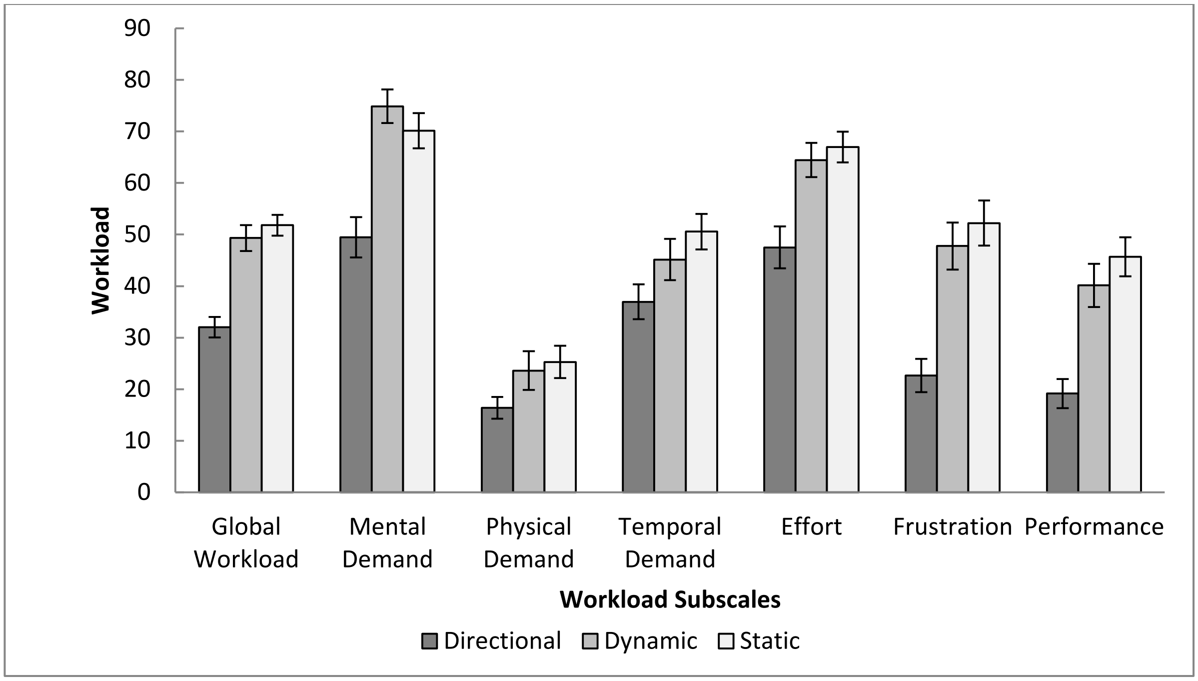


Figure 16. Workload measures reported from the NASA-TLX for each tacton category. Error bars in this figure represent the standard error.

Correlates of Attentional Control

A Spearman's Rank Order correlation was run to determine the relationship between Attentional Control and classification accuracy for tacton categories. There was no significant correlation between Attentional Control and classification accuracy for directional tactons, dynamic tactons, or static tactons.

A Spearman's Rank Order correlation was run to determine the relationship between Attentional Control and reaction time for tacton categories. There was no significant correlation between Attentional Control and reaction time for directional tactons, dynamic tactons, or static tactons.

Correlates of Spatial Ability

A Spearman's Rank Order correlation was run to determine the relationship between Spatial Ability and classification accuracy for tacton categories. There was no significant correlation between Spatial Ability and classification accuracy for directional tactons. A significantly moderate positive correlation was revealed for dynamic tactons ($rs(34) = .36$, $p = .033$) and static tactons ($rs(34) = .39$, $p = .019$) and Spatial Ability.

A Spearman's Rank Order correlation was run to determine the relationship between Spatial Ability and reaction time for tacton categories. There was no significant correlation between Spatial Ability and reaction time for directional tactons, dynamic tactons, or static tactons.

Within Tacton Category Analyses

Directional Tactons

Repeated measures ANOVAs determined there was no significant difference for classification accuracy or reaction time between directional tactons.

Dynamic Tactons

A repeated measures ANOVA with Greenhouse-Geisser correction determined a significant difference in classification accuracy within the dynamic tactons category, $F(5.28, 184.67) = 4.10$, $p = .001$, $\eta^2 = 0.105$. Post hoc tests with a Bonferroni correction revealed participants ability to classify the Rally tacton (*M* = 93.61, *SD* = 15.33) more accurately than Danger Area (*M* = 66.39, *SD* = 2.64), Enemy In Sight (*M* = 69.17, *SD* = 35.81), Move Out (*M* =

65.83, *SD* = 39.16), Rush (*M* = 65.00, *SD* = 39.68), and Take Cover (*M* = 68.33, *SD* = 38.43), with *p* = .015, *p* = .003, *p* = .006, *p* = .001, and *p* = .027 respectively. These findings are illustrated in Figure 17.

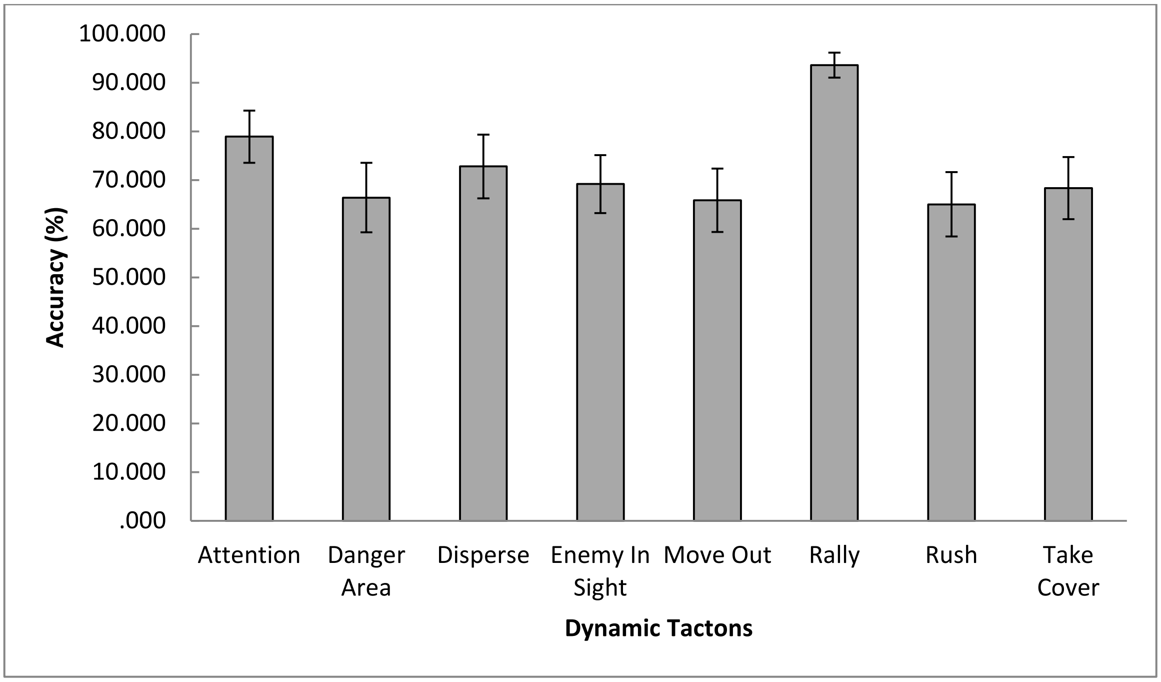


Figure 17. Mean classification accuracy for dynamic tactons. Error bars in this figure represent the standard error.

A repeated measures ANOVA with Greenhouse-Geisser correction revealed a significant difference in reaction time for dynamic tactons, $F(4.85, 97.06) = 3.34$, $p = .009$, $\eta^2 = .143$. Post hoc tests with a Bonferroni correction revealed participants reacted to the Danger Area tacton (*M* = 627.29, *SD* = 1012.73) more slowly than Attention (*M* = 279.00, *SD* = 1191.29) and Enemy In Sight (*M* = 216.52, *SD* = 1309.63), with *p* = .023 and *p* = .007 respectively. These findings are illustrated in Figure 18.

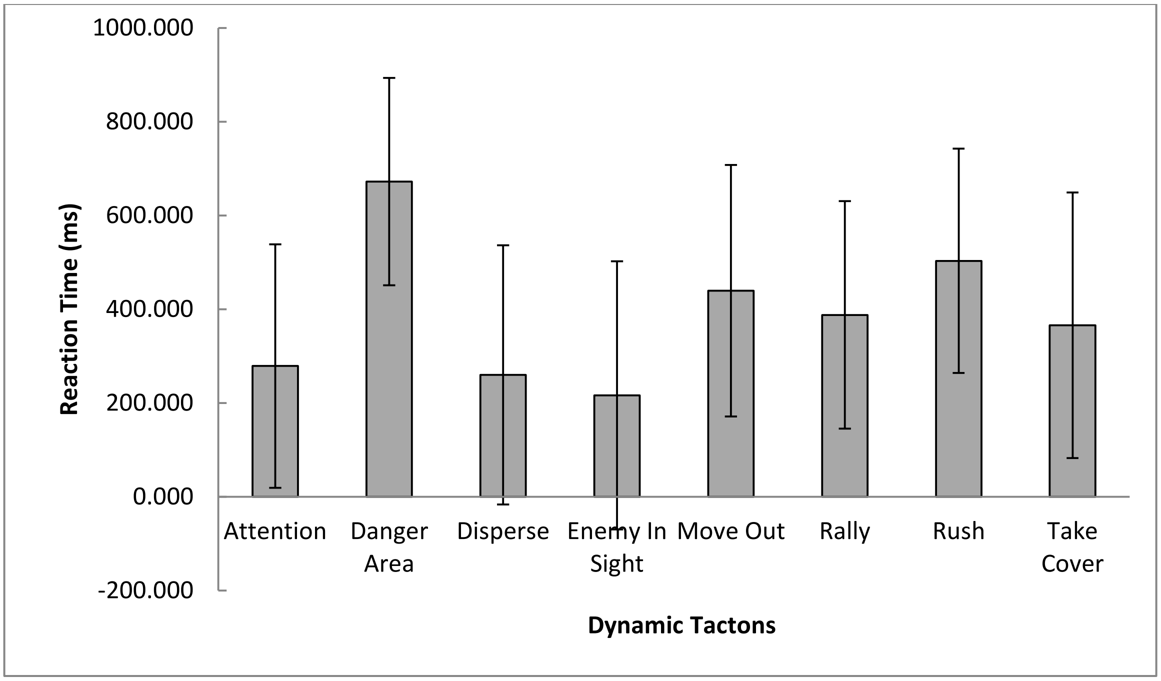


Figure 18. Reaction times for dynamic tactons. Error bars in this figure represent the standard error.

Static Tactons

A repeated measures ANOVA with Greenhouse-Geisser correction determined a significant difference in classification accuracy within the static tactons category, $F(5.00, 175.06) = 15.70$, $p < .001$, $\eta^2 = .310$. Post hoc tests with a Bonferroni correction revealed participants classified the Acknowledged tacton ($M = 85.56$, $SD = 25.60$) significantly more accurately than Cease Fire ($M = 49.72$, $SD = 27.52$), Fire ($M = 56.39$, $SD = 29.29$), Halt ($M = 61.11$, $SD = 27.23$), Nuclear/Biological/Chemical Attack ($M = 47.22$, $SD = 24.68$), Vee Formation ($M = 56.67$, $SD = 32.60$), and Wedge Formation ($M = 58.89$, $SD = 30.22$), with $p < .001$, $p < .001$, $p = .004$, $p < .001$, $p = .001$, $p < .001$ respectively. Participants classified the Halt tacton (M = 61.11, SD = 27.23) significantly more accurately than the Nuclear/Biological/Chemical Attack tacton (M = 47.22, SD = 24.68), with p = .033. Participants classified the I Do Not Understand tacton (M = 85.56, SD = 25.60) significantly more accurately than Cease Fire (M = 49.72, SD = 27.52), Fire (M = 56.39, SD = 29.29), Halt (M = 61.11, SD = 27.23), Nuclear/Biological/Chemical Attack (M = 47.22, SD = 24.68), Vee Formation (M = 56.67, SD = 32.60), and Wedge Formation (M = 58.89, SD = 30.22), with $p < .001$, $p < .001$, $p = .001$, $p < .001$, $p = .001$, $p < .001$ respectively. These findings are illustrated in Figure 19.

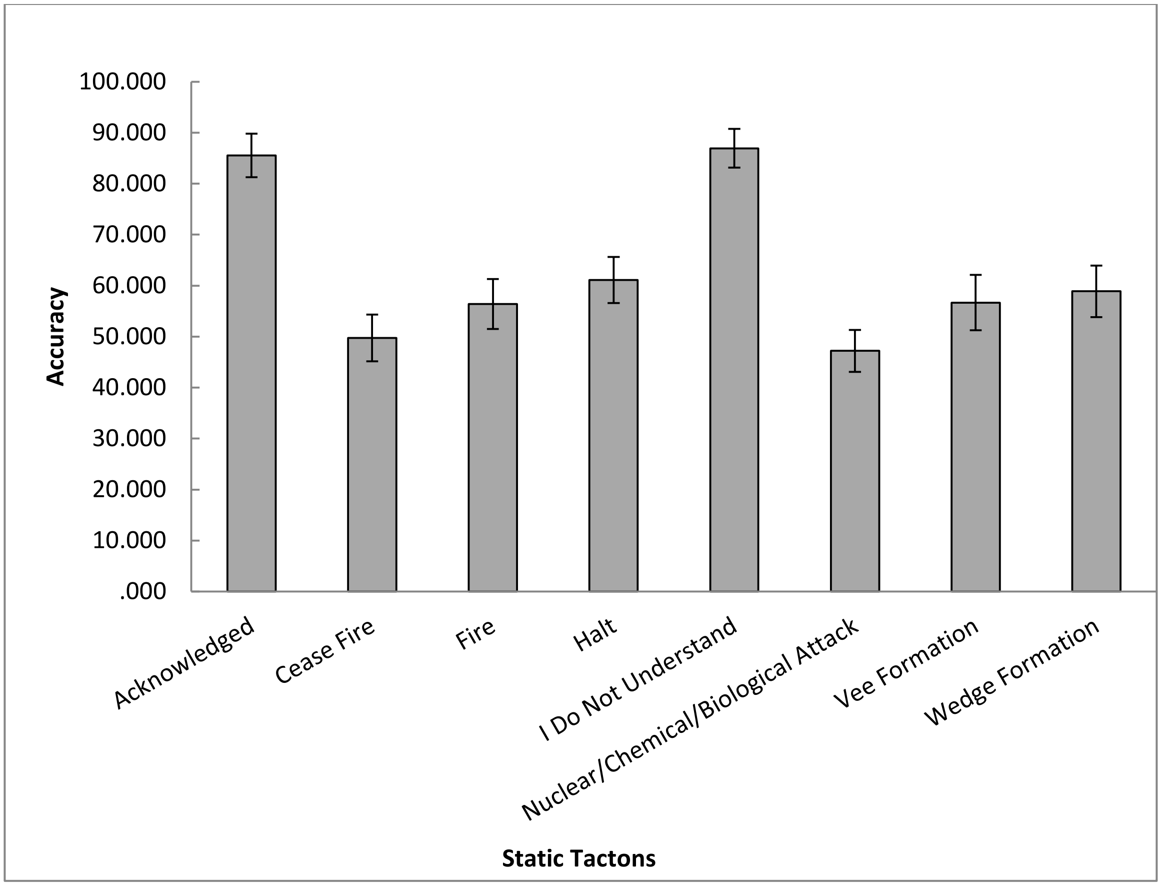


Figure 19. Classification accuracy for static tactons. Error bars in this figure represent the standard error.

A repeated measures ANOVA with Greenhouse-Geisser correction a significant differences in reaction time for static tactons, $F(4.32, 103.68) = 3.59$, $p = .007$, $\eta^2 = .130$. Post hoc tests with Bonferroni correction revealed participants reacted to the Acknowledged tacton ($M = 692.48$, $SD = 742.42$) significantly more quickly than the Fire tacton ($M = 995.44$, $SD = 815.02$), with $p = .025$. This is illustrated in Figure 20.

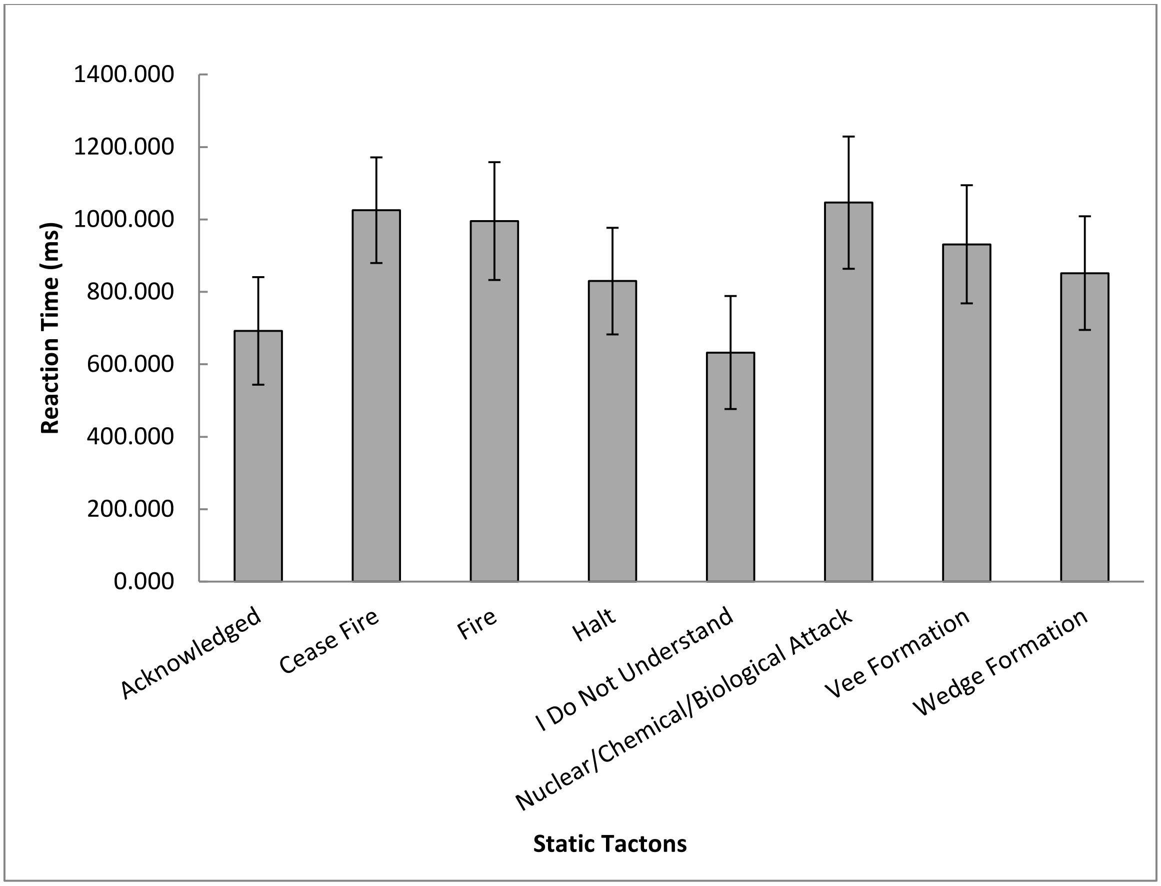


Figure 20. Reaction times for static tactons. Error bars in this figure represent the standard error.

CHAPTER FOUR: EXPERIMENT ONE DISCUSSION

Experiment one was designed to standardize and evaluate tactons previously developed from the literature for future use in creating a tactile language enabling HRC. Tactons selected for use in this study from the literature did not include standardized parameters (e.g., frequency, duration) and used different methods of training. Tactons were classified into three categories (directional, dynamic, and static) with equated tactor parameters and compared by group for identification of differences in performance and workload. Classification into tacton categories was done to support selection of tactons and design of a tactile sentence structure.

Manipulation checks for sensitivity showed no significant difference in classification accuracy between time periods of 20 tactor presentations and the entire task, therefore it is recommended that the sensitivity test be reduced from 80 to 40 presentations in future experiments. Tactor presentations were reduced to 40 rather than 20 to account for individual differences in sensitivity.

Manipulation checks for the training sessions revealed directional tactons showed better performance than dynamic and static tactons, and static tactons showed better performance than dynamic. Additional analyses of training transfer revealed a significant main effect in that training showed better performance than the experimental sessions. In other words, participants' performance dropped significantly from training to experimental sessions. It is apparent that the training method employed may not have adequately prepared participants for the experimental sessions. The training for each experimental session was composed of two parts, both including a visual animation representing the pattern of the tacton. It is possible participants were influenced more by visual than tactile patterns during training. This corresponds with findings from

Behrman and Ewell (2003) that showed visual training has a significant influence on tactile pattern recognition. Static tactons are also likely to show better classification as a visual pattern than dynamic tactons due to the nature of the patterns themselves, which tended to be less complex in terms of presentation duration and sequence of tactors. Removal of the visual component of training is not advised because visual training is shown to improve learning of tactile patterns (Behrmann & Ewell, 2003). However the utility of the tactile display can only be realized in a situation that allows for use independent of visual presentations. Therefore, it is recommended that future experiments include a third training task only presenting tactons using the Tactor Belt.

Outcomes for the experimental sessions supported hypotheses one and two that stated directional tactons would show better performance than both dynamic and static, and dynamic better than static, which corresponds with participant performance found in the literature (Elliot, Duistermaat, Redden, & Van Erp, 2007; Gilson, Redden, & Elliott, 2007). Analyses of reaction time for tacton categories revealed participants responded more quickly to directional and dynamic tactons than static, which supports hypotheses four and five for experiment one. These findings taken together imply that directional and dynamic tactons are recommended for inclusion within a tactile language for HRC. Specifically, an important consideration when selecting tactons for a lexicon is using “words” comparable to other communication modalities in terms rate of message receipt. However, since performance during the experimental session differed significantly for training using static tactons, they should still be included in the next study to investigate this relationship in more depth. This difference in performance might be due to insufficient training strategies as described above.

Experiment one provides a foundation of understanding tacton category performance and reaction time, however, the question still remains regarding the syntax of a tactile language. In other words, investigating the feasibility of a tactile language for HRC requires leveraging concepts from language development described in chapter one. Specifically, the state-of-the art in tactile communication from the literature and experiment one demonstrate a persons' ability to interpret tactile sequences equivalent to babbling at the developmental milestone for language of a one year old as described by Kalat (2008). The next milestone in language development is speaking in two-word phrases at the age of two. Therefore, the next step in the advancement of tactile communication is evaluating a person's ability to interpret two-tacton sentences. Results from experiment one clearly show participants performed better at interpreting directional tactons than non-directional dynamic and static tactons, indicating a paired non-directional and directional sentence structure is likely to show better performance than a syntax composed of two non-directional tactons. Following this reasoning, the next step in tactile sentence development is selection of tactons from each category tested in experiment one.

This decision is further supported by workload measures that revealed significant differences between tacton categories for all subscales, with participants perceiving significantly better Performance and lower Frustration, Mental Demand, Effort, and Global Workload during directional tactons than both dynamic and static, and lower Temporal Demand and Physical Demand between directional tactons and static. These findings supports hypothesis five that stated participants would perceive increased workload interpreting dynamic and static tactons compared to directional. No significant differences in workload were discovered between dynamic and static tacton categories, conflicting with hypothesis six that stated participants would experience increased workload during static tactons over dynamic tactons. This is another reason supporting continued inclusion of static tactons in sentence construction.

Directional tactons showed no significant differences in classification accuracy between tactons indicating equal performance for all eight. Therefore, the following four tactons were chosen for the directional component of the two-part sentence structure tested in experiment two: Toward North, Toward East, Toward South, and Toward West. It was determined for the dynamic category that the Rally tacton showed significantly better performance than the remaining seven tactons that showed equal performance for classification accuracy. Due to this finding of equal performance with the Rally tacton excluded, the four dynamic tactons selected for experiment two were: Attention, Enemy In Sight, Move Out, and Rush. This selection was based on the meaning of the labels associated with the tactons and how they pair with direction information. For example, the Attention and Enemy In Sight labels are different variations on looking in a specific direction, and Move Out and Rush are associated with motion/movement in a direction. Two tactons from the static category (Wedge Formation and Vee Formation) were selected for testing during experiment two. These tactons were selected due to equality of classification accuracy between participants and the labels associated with them that both correspond to military formations. An additional aspect of these two tactons is their tactor sequences are equated in that they are mirrored patterns when presented on the torso.

Additional support for continued investigation into tactile displays as a method for HRC is that no significant correlation between Attentional Control and classification accuracy and Attentional Control and reaction time for tacton categories, indicating Attentional Control has no relationship with performance. This expands the utility of tactile displays to the general population. Further a significant moderate positive correlation was revealed between Spatial

Ability and classification accuracy for both dynamic and static tactons. This finding indicates a relationship between spatial ability and classification accuracy and re-enforces the need to control for left handed participants during experimentation with and development of tactile sequences due to potential differences in brain physiology (Knecht, et al., 2000).

In conclusion, the goal for experiment one was to evaluate tactons from the literature using standardized parameters (e.g., frequency, duration) and training for development of a lexicon and syntax for testing the feasibility of tactile sentences for HRC. Analyses of the training data and experimental task results indicated the need for an additional training task when training participants on tactons and the need for continued investigation of static tactons. A tacton syntax composed of a non-directional and directional tactons is more likely to show better performance than two non-directional tactons and was selected as the basis for experiment two. The purposes of experiment two is to investigate this tactile sentence structure and was expected that the following would occur:

2.1. Participants will be able to interpret tactile sentences better than chance.

2.2. Participants will be able to interpret tactile sentences with equal performance to tactons presented individually.

2.3. Participants will be able to interpret tactile sentences with equal performance with or without a work imperative.

2.4. Participants will be able to interpret individual tactons with equal performance with or without a work imperative.

2.5. Participants will experience equal levels of workload interpreting tactile sentences and individual tactons.

2.6. Participants will experience higher levels of workload interpreting tactile sentences and individual tactons with work imperative than without.

CHAPTER FIVE: EXPERIMENT TWO METHODOLOGY

Participants

University undergraduate students between the ages of 18 and 40 (*M* = 19.73, *SD* = 5.25) served as the experimental participants and were recruited using an experiment management website. The participants received credit for their psychology courses for completing the study. Participants were right handed (due to potential differences in brain physiology of left handed participants and linguistic function (Knecht, et al., 2000)), normal (or corrected to normal) vision, and no prior military service. Participants were asked not to consume alcohol or any sedative medication for 24 hours or caffeine for two hours prior to the study, as these can influence their performance and perceptual sensitivity. Finally, participants were required to have a waistline between 34 and 50 inches to accommodate the size of the Tactor Belt used. The full restrictions checklist is located in APPENDIX A. The total number of participants included in this study was 76, 39 Male, 32 Female, 5 without gender specified.

Experiment Equipment

The experiment required participants to view and classify tactons using the same Tactor Belt (Figure 6) and Tacton Presenter application (Figure 7) used in Experiment One. In addition to these items, the Mixed Initiative Experimental (MIX) testbed (Barber, Leontyev, Sun, Davis, Nicholson, & Chen, 2008) was used to simulate a robot navigating through a geo-typical Middle Eastern urban environment. The MIX testbed was used for the present experiment to simulate a robot operated using a joystick, or navigating autonomously following pre-defined waypoints, using a video feed and route map (Figure 21). The task was completed on a standard desktop computer with a 22" (16:10 aspect ratio) monitor using a keyboard, joystick, and mouse.

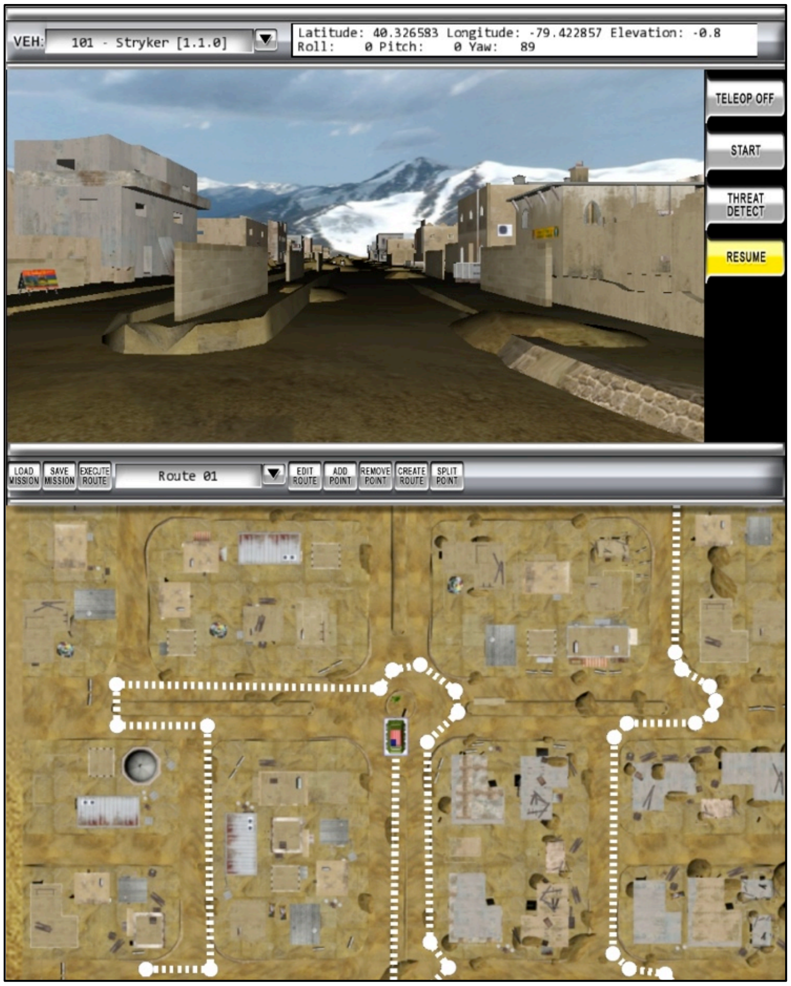


Figure 21. The MIX Testbed, video feed (top), route map (bottom).

Experimental Design

A 2 (Syntax: Tactile Sentences and Single Tactons) x 2 (Work Imperative: Present and Absent) mixed design with repeated measures on Syntax was employed. The order for assignment of participants to the Work Imperative (WI) group was random. All participants experienced both conditions of Syntax, which included Tactile Sentences (TS) and Single Tactons (ST), with the order randomized and balanced within WI groups (Table 3).

Table 3
Experiment Two Design

	Work Imperative	
Syntax	Present (Teleoperation)	Absent (Autonomous)
Tactile Sentences (TS)	Present – TS	Absent – TS
Single Tactons (ST)	Present – ST	Absent – ST

Independent Variables

Syntax

Tactile Sentences

Tactile sentences were composed of two tactons in the order of a Non-Directional (Dynamic or Static) tacton followed by a Directional tacton. Six Non-Directional and four Directional tactons were used for a total of 24 tactile sentences. The tactons were chosen based on the results of Experiment One, using the best equal performing tactons. The Non-Directional tactons selected were: Attention, Enemy In Sight, Move Out, Rush, Vee Formation, Wedge Formation. The Directional tactons selected were: Toward North, Toward East, Toward South, and Toward West. An example of one of the possible 24 sentences is: Attention – Toward North. The time between tactons (inter-tacton time) was 350ms. This value was selected due to recommended speech rates for audiobooks and to be within the limits of average human perception which ranges from 150-200 words per minute (Williams, 1998; Griffiths, 1992).

Single Tactons

Single tactons are those presented standalone in a randomized order. The same 10 individual tactons selected for TS were used for ST.

Work Imperative

Present

In the Present WI condition, participants were required to drive a robot using a joystick through a geo-typical Middle Eastern urban environment following a pre-defined route. The MIX testbed simulated the robot.

Absent

In the Absent WI condition, participants were required to watch a robot navigating autonomously along a pre-defined route. The MIX testbed simulated the robot.

Dependent Variables

Performance Measures

The same classification accuracy and reaction time performance measures as in Experiment One were collected for this experiment, in addition to a confidence rating.

Confidence Measure

Participants were required to rate how confident they were with their classification. For the ST condition they entered their confidence for one tacton, in the TS condition they entered a confidence value for both tactons composing the sentence. The confidence score was a seven-point Likert-type scale with a value of one representing low, four neutral, and seven high confidence.

Questionnaires

Participants were required to complete the same questionnaires as in Experiment One.

Procedure

Upon arrival, the participant first confirmed that he or she met the inclusion criteria. The participant was then provided an Informed Consent that detailed their rights as a research participant, the purpose for the study, overall procedure, source of funding for the study, and the potential risks associated with participation. After reviewing the Informed Consent, the participant turned off any cell phone or pager they had and gave them to the experimenter along with any watch and personal planners for the duration of the study. The participant was then assigned to a specific WI group.

Next, the participant completed a demographics questionnaire to measure standard items such as age and gender, as well as items used to determine their experience with various technologies. This questionnaire was used to document the participant's state of health, color vision, and prior military experience (APPENDIX F). After completing the demographics questionnaire, the participant filled out the Attentional Control Survey and Cube Comparison

Test. Once the questionnaires were completed, the participant was fitted with the Tactor Belt, such that it is seated around the abdomen, and not the hips, with the belt buckle on the belly button.

With the belt fitted, the participant was tested on their tactile sensitivity by activating each tactor on the Tactor Belt individually. This was completed to ensure that the participants were equated in not just their waist size, but for perception of the tactors. White noise with an amplified sinusoid frequency equal to the vibrating frequency of the tactors (230 Hz) was played during every task using the Tactor Belt for the present study. The White Noise eliminated any chance of the participant's ability to hear tactor activation and controls for additional audio cueing by the Tactor Belt, which may influence the performance in the TS condition. Before testing for sensitivity, the participant was introduced and trained for the sensations generated by each tactor on the Tactor Belt. Each tactor was activated individually in a clockwise order starting at tactor one and ending at tactor eight, then counter clockwise starting at eight and ending at one. During this presentation, a visual equivalent was also shown to the participant with the name of the tactor. Each tactor activation implemented a vibration with duration of 250 milliseconds consisting of a sinusoid frequency of 230 Hz and a two second ISI between each tactor presentation.

After introduction to the sensations generated by the Tactor Belt, the participant's sensitivity was tested by classifying each individual tactor presented in a random sequence five times each, for a total of 40 presentations. After each individual tactor vibration, the participant pressed the spacebar key as soon as the tactor presented was identified. A dialog-box was presented two seconds after completion of tactor presentation, where the user classified the tactor perceived using a drop-down menu. The response time for pressing the spacebar along with the classification accuracy was recorded. There was no time limit for the participant to make a selection. After selection of the tacton and closing the dialog-box using the "OK" button, the next tactor was activated one second later.

After testing participant sensitivity, the participant was trained on the individual tactons used within both Tactile Conditions. Training for each tacton category (Directional and Non-Directional) comprised three training tasks. The purpose for the three training tasks was to familiarize participants with the proper expected responses and to learn the tactons. The first tacton category trained was the Directional Condition, followed by the Non-Directional tacton category. In the first training task of a tacton category, each tacton and its name was presented two times in random order. The presentation of each tacton lasted approximately three seconds with a one second ISI. During the presentation, the participant was shown an animated sequence of the pattern, which was the visual equivalent to the given tacton on the computer screen in addition to the tactons' name.

In the second training task, the participant was still provided the visual animation of the tacton, but did not see the tacton name during presentation using the Tactor Belt. Additionally, the participant was asked to classify the tactons presented using the same method as the tactile sensitivity test with the addition of a scale to measure participant confidence. The participant pressed the spacebar on the keyboard when they identified the tacton. After a pre-defined time of two seconds from the end of tacton presentation, the participant was asked to select the correct name (or "I don't know") of the tacton he or she experienced from a drop-down box and rate their confidence using a sliding scale. The participant was given feedback, which included the correct answer, immediately following classification. The next tacton was presented one second after clicking "Continue" on the feedback window and this is called the ISI for the purposes of the present experiment. Each of the tactons within the category was presented one time in random order. The reaction time, accuracy of the selection, and confidence selected by the participant was recorded. There was no time limit for classification of the tacton or presentation feedback.

The third training task for the tacton category was performed in the same manner as the second training task, except the visual animation was not shown. Each of the tactons within the tacton category were presented one time in random order. The participant was given feedback, which included the correct answer, immediately following classification. The next tacton was presented one second after clicking “Continue” on the feedback window. After completion of the three Directional Tacton training tasks, the participant completed the Non-Directional tacton category training following the same three-part protocol.

After training for individual tactons was completed, the participant experienced two tasks to familiarize them with the Syntax conditions. In the first task the participant was presented with training for ST followed by TS in the second task. The stimulus presentation for both tasks comprised delivery using the Tactor Belt only. After a pre-defined time of two seconds from the end of sequence presentation, the participant was asked to select the correct name(s) (or “I don’t know”) of the tacton(s) he or she experienced from a drop-down box and rate their confidence using a sliding scale. The participant was given feedback, which included the correct answer, immediately following classification. There was no time limit given for classification, confidence rating, or presentation feedback. The accuracy, reaction time, and confidence selection made by the participant was recorded. The next tacton sequence was presented one second after clicking “Continue” on the feedback window in random order. For both the ST and TS training tasks, each sequence was presented one time.

Participants within the Present WI group were next trained on how to drive the robot using a joystick with the MIX testbed simulation. The participant navigated the robot following a pre-defined route using a joystick for one minute. A practice task was then performed to allow operators to drive (Present WI group) or monitor (Absent WI group) the robot while responding to tactile sequences as required in the ST and TS experimental conditions. The participants in both WI groups were required to complete practice ST and TS classifications in the order of ST practice followed by TS practice. The tactile sequences were presented using only the Tactor Belt with no visual animation, tacton name(s), or feedback provided. The participant was required to press the spacebar on the keyboard when they identified the completed sequence (one tacton for ST, two tactons for TS). After a pre-defined time of two seconds from the end of sequence presentation, the same dialog box used for classification and confidence selection from the previous training tasks was presented. There was no time limit for classifying and rating confidence. The accuracy, reaction time, and confidence selection made by the participant was recorded. The next tactile sequence was presented one second after the participant clicked the "OK" button on the classification dialog-box. The participant experienced each tacton in the ST practice task once, and a subset of six sentences from the 24 potential tacton combinations one time for the TS practice task. Tactile sequences were presented in random order for both conditions. The six tacton combinations selected were: Attention – North, Enemy In Sight – East, Move Out – West, Rush – South, Vee Formation – North, and Wedge Formation – South. Due to the unequal number of Non-Directional and Directional tactons, a subset of six was selected to include one presentation of each Non-directional Tacton.

After robot operation and classification practice, the participant completed a ST and TS condition in random order with both with Present WI or Absent WI based on assigned group number. Participants were presented tacton sequences using the Tactor Belt with no visual animation, tacton name(s), or feedback provided. Participants were required to press the spacebar on the keyboard when they identify each tacton sequence (one tacton for ST, two tactons for TS). After a pre-defined time of two seconds from the end of tacton presentation, the same dialog box used for classification and confidence selection from the previous tasks was presented. There was no time limit given for classification and confidence rating. The reaction time, accuracy, and confidence selection made by the participant was recorded. The next tactile sequence was presented one second after the participant clicked the "OK" button on the dialog-box. Within the ST condition, tactons were presented eight times each for a total of 80 presentations, and lasted approximately 20 min. For the TS condition, each tacton sequence was presented three times for a total of 72 presentations and lasting roughly 20 min. This approximate duration was due to participant variation in time to classify and rate confidence using the available dialog. Participants within the Present WI group were required to manually teleoperate a robot using the MIX testbed along a pre-defined route during tacton sequence presentation. Participants were not required to continue manual control of the robot using the joystick during classification with the dialog-box. Participants within the Absent WI group only monitored the robot navigating a pre-defined route through the environment. The NASA-TLX was administered to participants upon completion of each experimental condition.

After completing both experimental conditions, the Tactor Belt was removed and the participant collected their cell phone, pager, timepiece, and planners to exit.

CHAPTER SIX: EXPERIMENT TWO RESULTS

A summary of all ANOVAs from Experiment Two is located in APPENDIX M. A summary of all tables describing means and standard deviations from Experiment Two is located in APPENDIX N.

Manipulation Checks

Sensitivity Test

Analyses of the sensitivity test were conducted to eliminate participants that did not achieve a minimum classification accuracy score of 90%. Based upon overall classification accuracy for the entire sensitivity test, 14 participants (7 Male, 6 Female, 1 no gender specified) were eliminated from further analysis by not achieving a score of greater than or equal to 90%. Two additional participants (1 Male, 1 Female) were eliminated from further analysis for not completing the experiment. After all eliminations a total of 60 participants (31 Male, 25 Female, 4 no gender specified) were included in remaining analyses.

Training

A repeated measures ANOVA was performed between syntax conditions (TS and ST) to evaluate training tasks revealing no significant difference for participant classification accuracy ($F(1, 58) = .43$, $p = .516$, $\eta^2 = .007$) or reaction time ($F(1, 58) = 1.16$, $p = .285$, $\eta^2 = .020$) for the final training task. A 2 (Session: Training and Experimental) x 2 (Syntax: TS and ST) mixed ANOVA, performed to evaluate the addition of a third training task on training transfer, showed no significant main effect for classification accuracy between training and experimental sessions, $F(1, 59) = 1.58$, $p = .214$, $\eta^2 = .026$.

Tacton Category Analyses

Single Tactons Sessions

A repeated measures ANOVA was performed between tacton categories (directional, dynamic, and static) for comparison with results from experiment one, which showed a significant difference for classification accuracy during ST sessions, $F(2, 116) = 4.28$, $p = .016$, $\eta^2 = .069$. Post hoc tests with Bonferroni correction determined participants classified directional tactons ($M = 96.83$, $SD = 5.03$) with better accuracy than dynamic tactons ($M = 89.69$, $SD = 19.20$), with $p = .018$. This is illustrated in Figure 22.

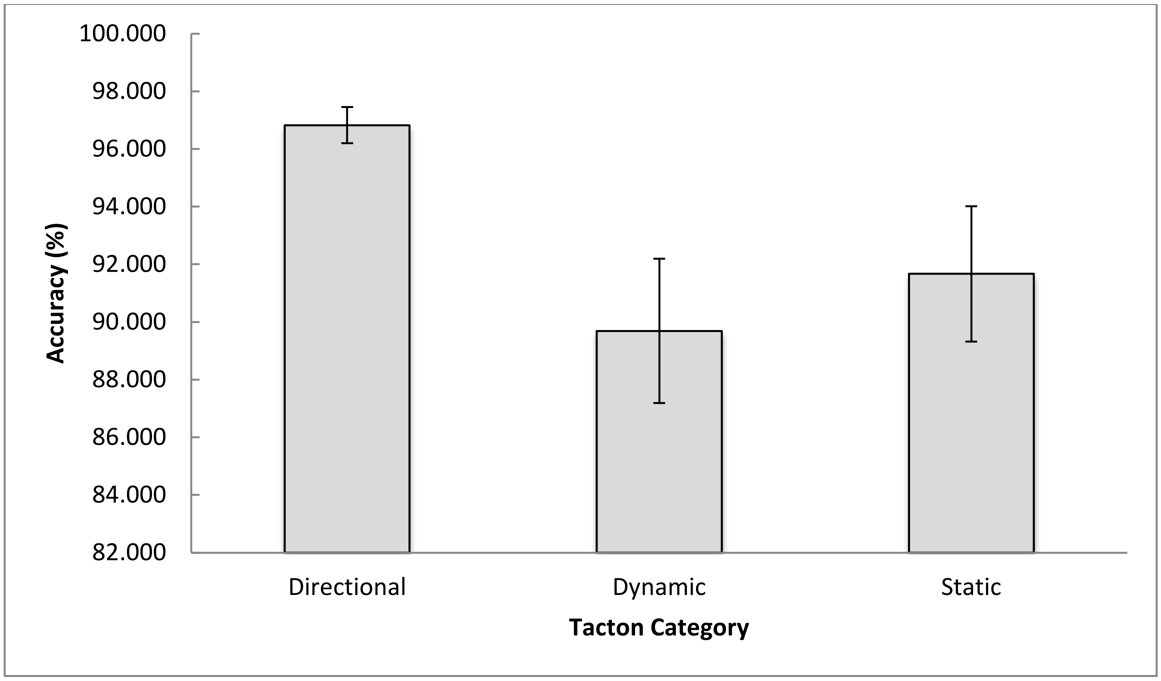


Figure 22. Classification accuracy for tacton categories during ST sessions. Error bars in this figure represent the standard error.

Tactile Sentences Sessions

A repeated measures ANOVA with Greenhouse-Geisser correction was performed between tacton categories (directional, dynamic, and static) for comparisons with results from experiment one, which revealed a significant difference for classification accuracy during TS sessions, $F(1.56, 90.29) = 7.98$, $p = .002$, $\eta^2 = .121$. Post hoc tests with Bonferroni correction determined participants classified directional tactons ($M = 96.69$, $SD = 5.41$) with better accuracy than dynamic ($M = 88.72$, $SD = 19.11$) and static tactons ($M = 91.60$, $SD = 11.60$), with $p = .003$ and $p = .001$ respectively. This is illustrated in Figure 23.

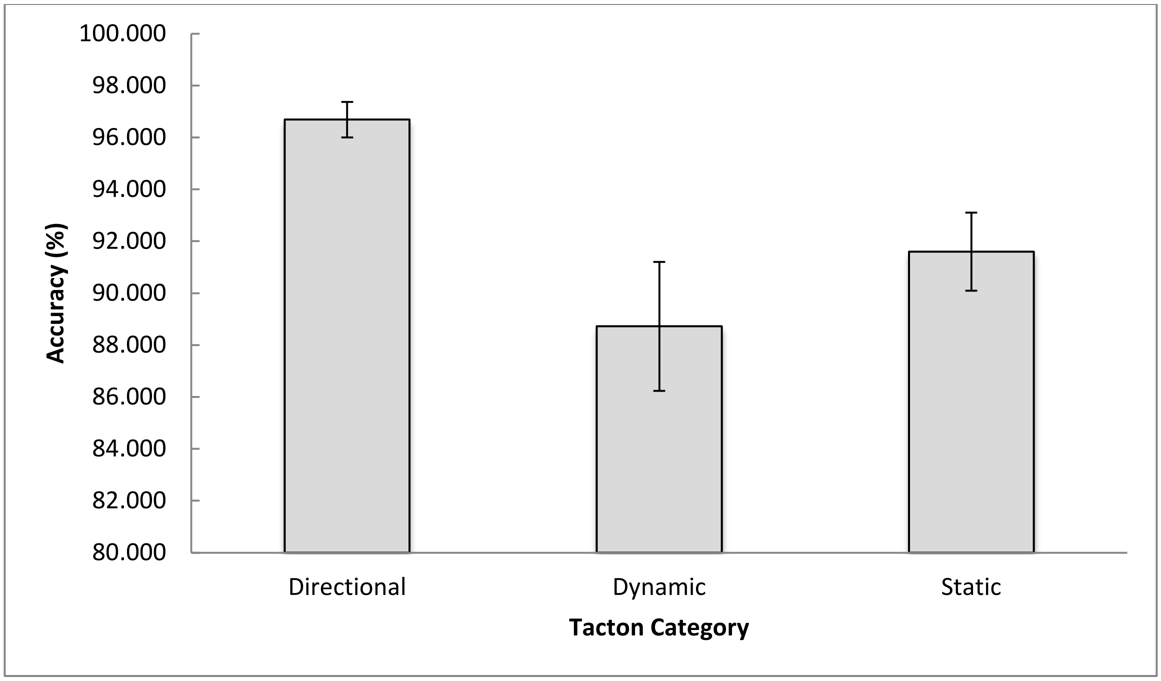


Figure 23. Classification accuracy for tacton categories during TS sessions. Error bars in this figure represent the standard error.

Analyses of Tactons

Classification Accuracy

A 2 (Syntax: TS and ST) x 10 (Tacton: Attention, East, Enemy In Sight, Move Out, North, Rush, South, Vee Formation, Wedge Formation, and West) mixed ANOVA with Greenhouse-Geisser correction was performed to compare individual tactons between TS and ST sessions. No significant main effect for syntax was shown for classification accuracy during experimental sessions, $F(1, 59) = .43$, $p = .513$, $\eta^2 = .007$. A significant main effect was revealed for individual tactons and classification accuracy, $F(9, 187.06) = 6.17$, $p = .001$, $\eta^2 = .086$. Post hoc tests with Bonferroni correction determined participants classified the East tacton (M =

97.65, *SD* = 24.73) with higher accuracy than Move Out (*M* = 87.99, *SD* = 22.07), Rush (*M* = 84.62, *SD* = 28.96), and Wedge Formation (*M* = 90.21, *SD* = 14.31) tactons, with p = .047, p = .042, p = .007, and p = .497 respectively. Post hoc tests with Bonferroni correction determined participants classified the North tacton (*M* = 97.41, *SD* = 6.00) with higher accuracy than Rush (*M* = 84.62, *SD* = 28.96) and Wedge Formation (*M* = 90.21, *SD* = 14.31) tactons, with p = .038 and p = .005 respectively. This is illustrated in Figure 24.

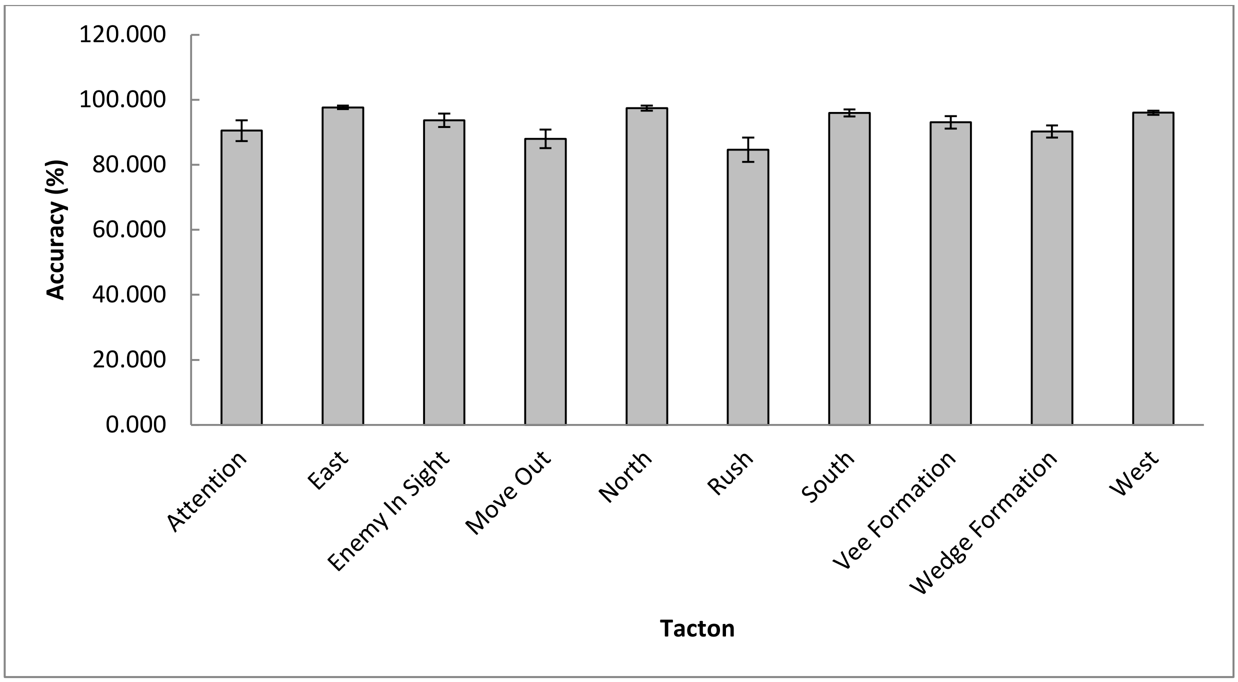


Figure 24. Mean classification accuracy for tactons across syntax conditions. Error bars in this figure represent the standard error.

Confidence

A 2 (Syntax: TS and ST) x 10 (Tacton: Attention, East, Enemy In Sight, Move Out, North, Rush, South, Vee Formation, Wedge Formation, and West) mixed ANOVA with

Greenhouse-Geisser correction was performed to compare reported confidence between TS and ST sessions and showed no significant main effect for syntax during experimental sessions, $F(1, 59) = 1.25$, $p = .267$, $\eta^2 = .021$. A significant main effect was revealed for tactons and confidence, $F(9, 176.39) = 6.17$, $p = .001$, $\eta^2 = .095$. Post hoc tests with Bonferroni correction determined participants rated higher confidence in their classification for the East tacton (*M* = 96.65, *SD* = 0.62) than Rush (*M* = 6.16, *SD* = 1.32) and Wedge Formation (*M* = 6.32, *SD* = 1.03) tactons, with *p* = .040 and *p* = .048 respectively. Post hoc tests with Bonferroni correction determined participants rated higher confidence in their classification for the North tacton (*M* = 6.66, *SD* = 0.62) than Move Out (*M* = 6.22, *SD* = 1.27), Rush (*M* = 6.16, *SD* = 1.32), and Wedge Formation (*M* = 6.32, *SD* = 1.03) tactons, with *p* = .039, *p* = .025, and *p* = .046 respectively. Post hoc tests with Bonferroni correction determined participants rated higher confidence in their classification for the West tacton (*M* = 6.65, *SD* = 0.59) than Rush (*M* = 6.16, *SD* = 1.32) tacton, *p* = .043. This is illustrated in Figure 25.

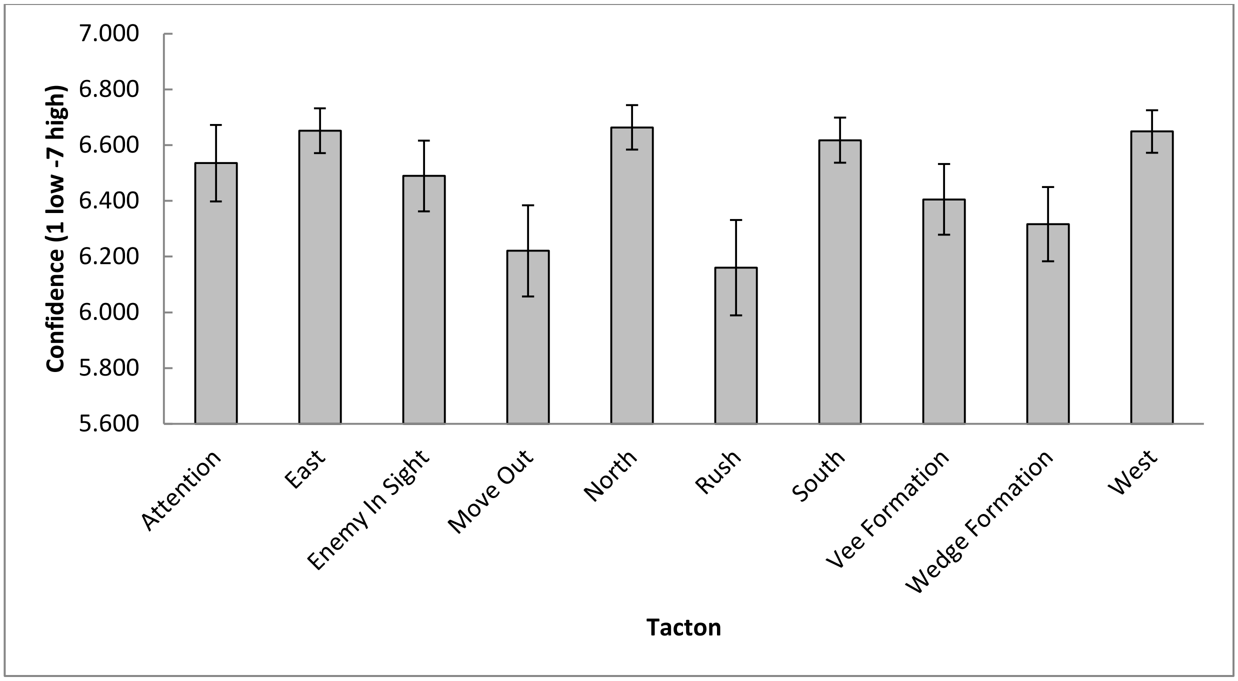


Figure 25. Mean confidence ratings for tactons across syntax conditions. Error bars in this figure represent the standard error.

Syntax Analyses

Classification Accuracy

A 2 (Syntax: TS and ST) x 2 (WI: Present and Absent) mixed ANOVA was performed to investigate the impact syntax and WI had on classification accuracy. A significant main effect for syntax was revealed between TS and ST, ($F(1, 58) = 20.75$, $p < .001$, $\eta^2 = .263$), such that ST ($M = 92.94$, $SD = 10.11$) showed better performance than TS ($M = 87.96$, $SD = 15.52$) for classification accuracy (Figure 26). No significant main effect was found for syntax between WI groups for classification accuracy, $F(1, 58) = .32$, $p = .571$, $\eta^2 = .006$.

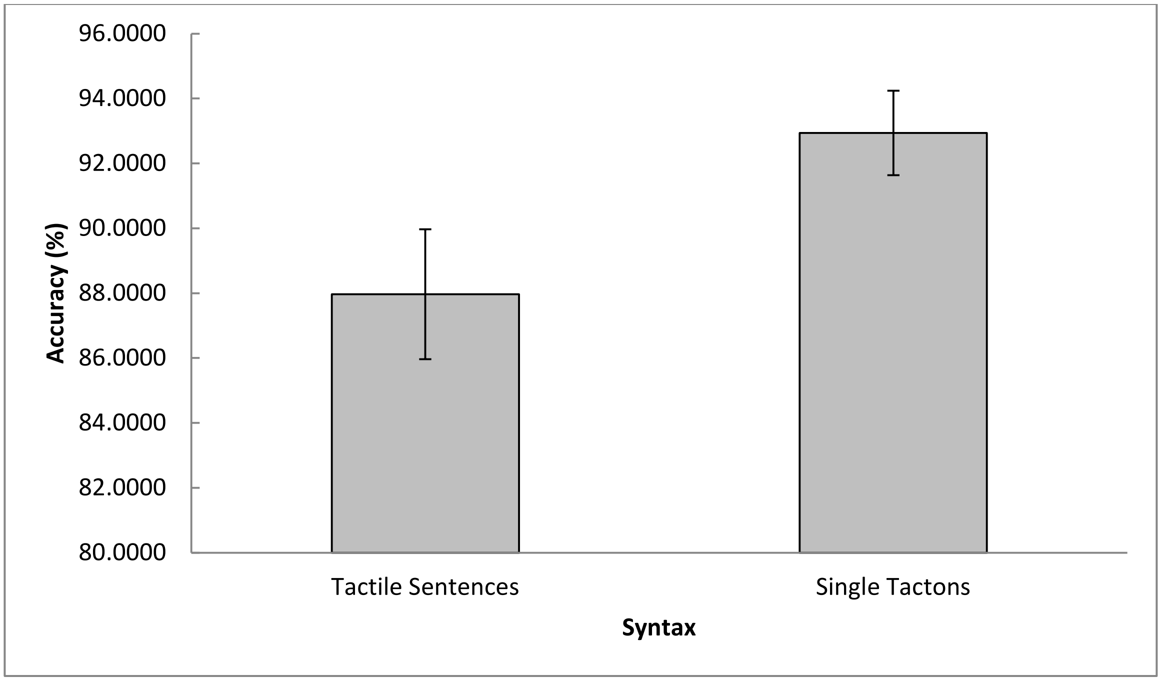


Figure 26. Mean classification accuracy of syntax conditions. Error bars in this figure represent the standard error.

Reaction Time

A 2 (Syntax: TS and ST) x 2 (WI: Present and Absent) mixed ANOVA was performed to investigate the impact syntax and WI had on reaction time. No significant main effect was found for median reaction time between syntax, $F(1, 58) = .33$, $p = .568$, $\eta^2 = .006$. A significant main effect was found for median reaction time for syntax between WI groups, ($F(1, 58) = 4.85$, $p = .032$, $\eta^2 = .077$), such that participants responded more quickly without WI ($M = 427.03$, $SD = 487.70$) than with ($M = 704.35$, $SD = 487.70$). This is illustrated in Figure 27.

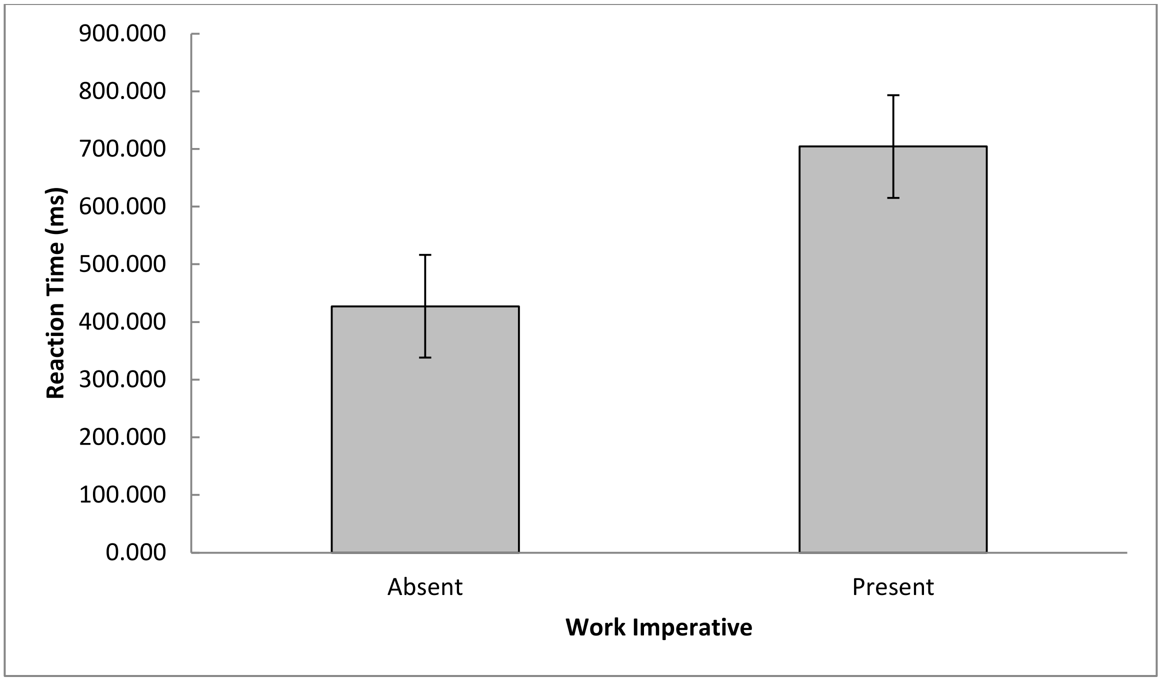


Figure 27. Median reaction time between WI groups. Error bars in this figure represent the standard error.

Confidence Measure

A 2 (Syntax: TS and ST) x 2 (WI: Present and Absent) mixed ANOVA was performed to investigate the impact syntax and WI had on confidence values reported. No significant main effect for participant confidence was found for syntax, $F(1, 58) = .09$, $p = .780$, $\eta^2 = .001$. No significant effect was found for participant confidence between WI groups, $F(1, 58) = .03$, $p = .864$, $\eta^2 = .001$.

Workload

A 2 (Syntax: TS and ST) x 2 (WI: Present and Absent) x 7 (Workload: Global Workload, Mental Demand, Physical Demand, Temporal Demand, Effort, Frustration, and Performance) mixed ANOVA with Greenhouse-Geisser correction was performed to provide additional insight into the impact syntax and WI had on performance. A significant main effect for syntax was revealed for participants perceived Global Workload ($F(1, 58) = 11.73$, $p = .001$, $\eta^2 = .168$), Mental Demand ($F(1, 58) = 10.89$, $p = .002$, $\eta^2 = .158$), Effort ($F(1, 58) = 9.97$, $p = .003$, $\eta^2 = .147$), and Performance ($F(1, 58) = 17.15$, $p < .001$, $\eta^2 = .228$). Participants rated their perceived Global Workload higher during TS ($M = 45.07$, $SD = 19.22$) than ST ($M = 41.40$, $SD = 18.75$) sessions. Participants rated their perceived Mental Demand higher during TS ($M = 65.83$, $SD = 27.73$) than ST ($M = 59.58$, $SD = 29.92$) sessions. Participants rated their perceived Effort higher during TS ($M = 61.17$, $SD = 29.01$) than ST ($M = 54.08$, $SD = 25.93$) sessions. Participants rated their perceived Performance worse during TS ($M = 27.58$, $SD = 24.71$) than ST ($M = 22.67$, $SD = 22.76$) sessions. This is illustrated in Figure 28.

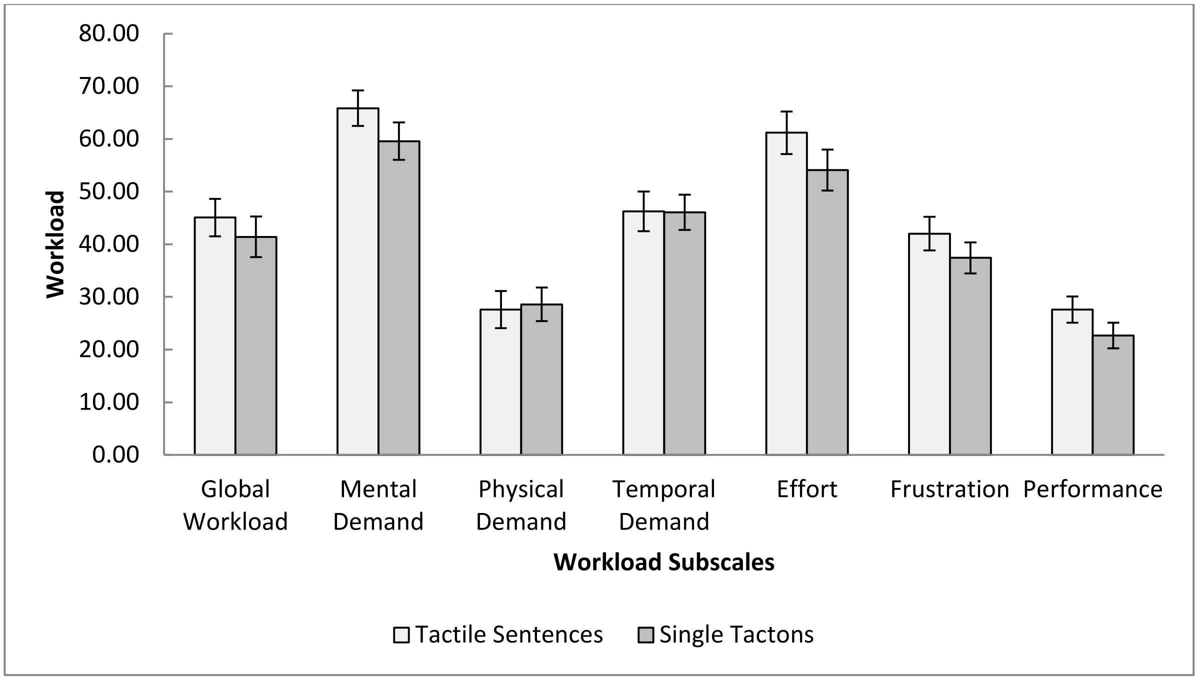


Figure 28. Workload measures reported from the NASA-TLX by syntax. Error bars in this figure represent the standard error.

A significant interaction between syntax and WI was revealed for Performance, (F(1, 58) = 9.11, p = .004, η^2 = .136), such that participants rated performance worse during TS (M = 27.58, SD = 24.71) than ST (M = 22.67, SD = 22.76) sessions within both WI groups. A significant main effect was revealed between work imperative groups for perceived Global Workload (F(1, 58) = 17.59, p < .001, η^2 = .233), Mental Demand (F(1, 58) = 17.97, p < .001, η^2 = .236), Physical Demand (F(1, 58) = 23.53, p < .001, η^2 = .289), Temporal Demand (F(1, 58) = 8.26, p = .006, η^2 = .125), and Effort (F(1, 58) = 16.30, p < .001, η^2 = .219). Participants rated Global Workload higher with WI (M = 52.10, SD = 16.36) than without (M = 34.38, SD = 16.36). Participants rated Mental Demand higher with WI (M = 76.17, SD = 24.60) than without (M = 49.25, SD = 24.60). Participants rated Physical Demand higher with WI (M = 41.67, SD = 21.69) than without (M = 14.50, SD = 21.69). Participants rated Temporal Demand higher with WI (M = 54.92, SD = 23.58) than without (M = 37.42, SD = 23.58). Participants rated Effort higher with WI (M = 69.75, SD = 23.26) than without (M = 45.5, SD = 23.26). This is illustrated in Figure 29.

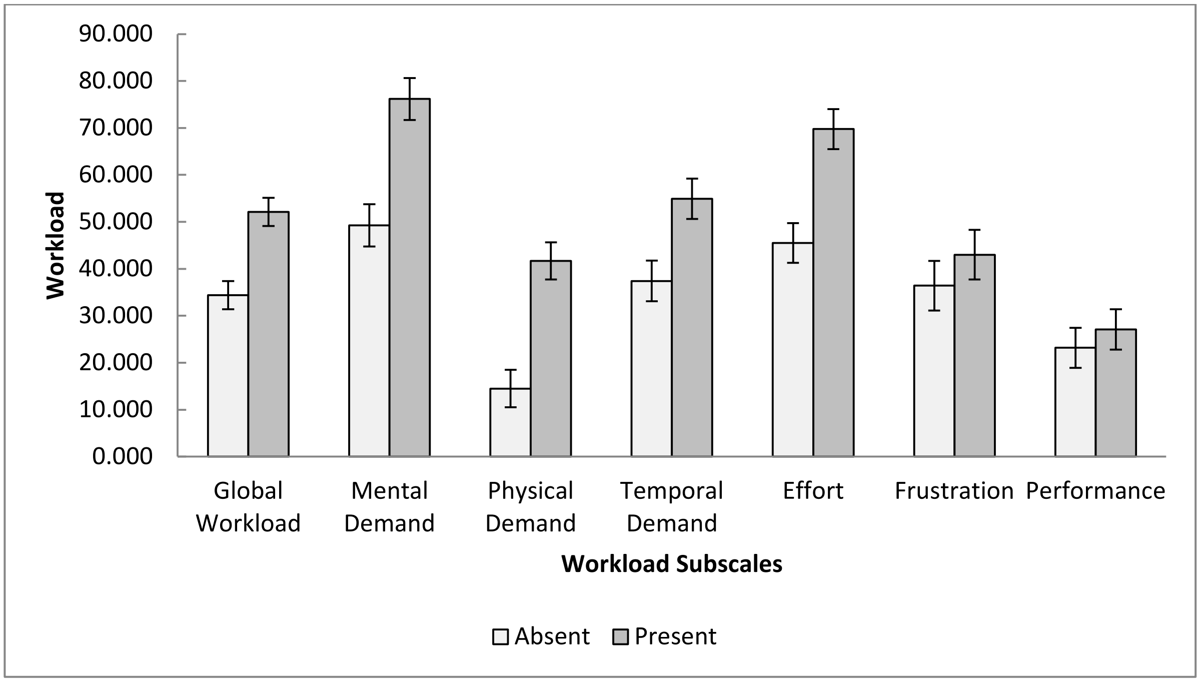


Figure 29. Workload measures reported from the NASA-TLX by WI group. Error bars in this figure represent the standard error.

Correlates of Confidence

A Spearman's Rank Order correlation was run to determine the relationship between answer confidence and classification accuracy for Syntax. A significant strong positive correlation was revealed between confidence classification accuracy for both TS ($r_s(58) = .841$, $p < .001$) and ST ($r_s(58) = .643$, $p < .001$) sessions.

Correlates of Attentional Control

A Spearman's Rank Order correlation was run to determine the relationship between Attentional Control and classification accuracy for Syntax. There was no significant correlation between Attentional Control and classification accuracy for TS or ST sessions.

A Spearman's Rank Order correlation was run to determine the relationship between Attentional Control and reaction time for tacton classifications. There was no significant correlation between Attentional Control and reaction time for TS or ST sessions.

Correlates of Spatial Ability

A Spearman's Rank Order correlation was run to determine the relationship between Spatial Ability and classification accuracy for syntax. There was no significant correlation between Spatial Ability and classification accuracy for TS or ST sessions.

A Spearman's Rank Order correlation was run to determine the relationship between Spatial Ability and reaction time for syntax. A significant negative correlation was revealed between Spatial Ability and reaction time for both TS ($r_s(58) = -.283$, $p = .028$) and ST ($r_s(58) = -.343$, $p = .007$) syntax.

Analyses of Sentences

A 6 (Non-Directional Tacton: Attention, Enemy In Sight, Move Out, Rush, Vee Formation, Wedge Formation) x 4 (Directional Tacton: East, North, South, West) mixed ANOVA with Greenhouse-Geisser correction was performed for tactile sentences across WI groups to gain additional insight into differences in classification accuracy between syntax conditions, with emphasis on the pairing of non-directional and directional tactons. No significant main effect was found for the non-directional component of the sentences, $F(3.18, 187.33) = 2.43$, $p = .063$, $\eta^2 = .040$. A significant main effect was revealed for the directional component, $F(2.76, 162.89) = 3.46$, $p = .021$, $\eta^2 = .055$. Post-hoc tests with Bonferroni correction determined that participants classified sentences with the North tacton ($M = 89.26$, $SD = 16.83$) more accurately than those with the West tacton ($M = 88.33$, $SD = 16.23$), with $p = .042$.

CHAPTER SEVEN: EXPERIMENT TWO DISCUSSION

Experiment two was designed to investigate the feasibility of tactile sentences for HRC using a two-word syntax composed of non-directional and directional tactons. Recommendations based on the results of experiment one were incorporated into the methodology to improve training transfer and test performance of tacton categories when combined into single or two word sequences. Participants were divided into two groups to measure the impact of WI on classification performance for further evaluation of the utility of tactile sentences in multi-tasking environments expected in military operations.

Manipulation checks for the training sessions revealed no significant difference in classification accuracy or reaction time between TS and ST training indicating participants were equally prepared for both syntax conditions before experimental sessions. Additional analyses of classification accuracy between training and experimental TS and ST conditions determined no significant change in performance like that found in experiment one. This finding supports the addition of a third training task with no visual representation as recommended in the discussion of experiment one.

Analyses of tacton categories within each syntax session revealed that directional tactons showed better performance than dynamic tactons in both TS and ST sessions. This result confirms findings from experiment one. However, in both syntax conditions, dynamic tactons did not significantly outperform static tactons, and directional tactons only showed better performance than static tactons during the TS condition. This outcome suggests participant performance during static tactons in experiment one may have been considerably impacted by improper training as previously described. It is also possible that participants show better performance with static tactons mixed with directional and dynamic tactons. Therefore, further study of static tactons for inclusion in tactile lexicons is needed.

Analyses of individual tactons were performed between TS and ST conditions to understand the impact of syntax on participant performance. The results showed no significant difference in classification accuracy or confidence between syntax conditions, indicating that the participants were able to classify single and paired tacton sequences equally. Moreover, results for mean classification accuracy across WI groups during the TS condition (M = 87.96, SD = 15.52) revealed participants were able to interpret paired non-directional and directional tacton sentences better than chance supporting the overall goal for this effort. However, analyses of syntax (single or sentence) determined a significant difference in classification accuracy between TS and ST conditions with ST showing better performance showing hypothesis two, classification accuracy equality between syntax conditions, as false.

Analyses of reaction time, confidence, and workload were performed to further understand what factor(s) effected classification accuracy between TS and ST conditions resulting in unequal performance disproving hypothesis two. Results determined no effect for syntax on reaction time or user confidence, however perceived Global Workload was significantly higher during TS than ST conditions. The decrease in classification accuracy and increase in perceived workload while interpreting tactile sentences is therefore most likely a direct result of paring non-directional tactons with directional tactons. As described previously for TS conditions and shown in experiment one results, directional tactons exhibited better performance than both dynamic and static tactons. Moreover, experiment one findings showed perceived global workload was lower during directional than both dynamic and static. Further study of individual sentences grouped by non-directional and directional components revealed a significant main effect between sentences with North sentences showing better performance than West sentences. These findings combined indicate that participants are not able to classify each word of a paired non-directional and directional tacton syntax equally. Therefore, an unequal probability of correct classification for each piece of the sentence and scoring requiring both parts to be correct explains the reason for overall classification accuracy being lower and perceived workload higher for TS than ST conditions. Following this reasoning, a next step in tactile sentence syntax development is comparison of a paired non-directional tacton structure with single tacton sequences for comparison with the syntax pairing of the present study.

Investigation of a WI task was performed to provide understanding of its' impact on classification accuracy, reaction time, and workload. Results showed no significant main effect for classification accuracy or user confidence between groups supporting hypothesis three and four, which stated classification accuracy would be equal for both syntax conditions between WI groups. However, reaction time was significantly increased for both TS and ST conditions when a WI was present. This finding is not unexpected and is consistent with the literature such that the addition of a secondary task increases response time of the primary task (Mohebbi, Gray, & Tan, 2009; Wickens & Hollands, 2000). Therefore, system developers and researchers using tactile communication should consider this effect when determining appropriate situational use of tactile communication. Understanding the impact of various secondary tasks is critical in the development of tactile displays to maximize utility in HRC due to requirements of users to perform tasks independent of messages being received.

Perceived workload was also shown to be significantly higher with WI than without, supporting hypothesis six, which stated participants would experience increased workload with a WI than without. During experiment two the WI task was teleoperation of a robot, which is primarily a physical task and may explain why no change in classification accuracy was exhibited. Specifically, although tactile displays employ physical contact, the signals generated are for communication and is a language interpretation task. Understanding language requires cognitive resources and plays a role in models of human cognition (Carruthers, 2002). Therefore, it appears that interpretation of tactile communications more closely resembles cognitive rather than physical tasks, and different or multiple WI tasks that are more cognitively demanding might show an impact on classification accuracy and should be investigated in future efforts.

Similar to experiment one, additional support for continued investigation into tactile displays as a method for HRC is an absence of correlations with Attentional Control. Specifically, no correlation was found between Attentional Control and classification accuracy or Attentional Control and reaction time for syntax, indicating Attentional Control has no relationship with performance. This further expands the utility of tactile displays to the general population. In contrast to experiment one, no correlation was revealed between Spatial Ability and classification accuracy for syntax conditions, but a significant negative correlation was shown for reaction time. The differences in correlation between syntax and Spatial Ability compared to experiment one may be related to the way in which the tactile messages were categorized and presented. Specifically, performance (classification accuracy and reaction time) for tactons was correlated with Spatial Ability when compared with dynamic, and static categories in experiment one, but experiment two evaluated performance of conditions including all tacton categories combined or tactile sentences. Future experiments should continue to measure the relation of Spatial Ability and new tactons to determine if tactons leveraging spatial information perform better overall. Furthermore, if Spatial Ability is shown to correlate with classification accuracy, inclusion of mental transformation training (Rehfeld, 2006; Write, Thompson, Ganis, Newcombe, & Kosslyn, 2008) for Spatial Ability may improve overall performance.

Results from experiment two clearly demonstrate the ability of participants to accurately interpret a tactile syntax of two words better than chance. This finding moves the state-of-the-art in tactile communication from the developmental milestone of a one year old to a two year old speaking in two-word phrases (Kalat, 2008). This is a significant outcome in that using sentences reduces the need for an exponentially large tactile lexicon to share complex statements and thoughts. Future directions into tactile displays for HRC is the expansion of the tactile lexicon and investigating different syntax structures supporting longer phrases at the associated age of 2.5 years of language development. A larger lexicon is needed to enable transmission of more information about the environment or task from a robot to a human such as named objects, multi-step directions, and mission status. A longer or more complex syntax enables a robot to send phrases that may or may not include a directional component (e.g. door is open vs. door on the left). Enabling human-robot teaming requires reliable communication supported by MMC due to its redundancy and levels of communication that are more robust than single mode interactions (Bischoff & Graefe, 2002; Partan & Marler, 1999). Previous efforts including the tactile modality within MMC were restricted to discrete tactile alerts and cues (Haas, 2007) due to lack of a tactile language capable of transmitting multi-part messages equivalent to complex speech and visual signals used in the military. The two-word tactile syntax resulting from this effort facilitates investigation of MMC systems capable of delivering complex messages using combinations of auditory, visual and tactile modalities. These and future advanced MMC systems incorporating combinations of all modalities will support the seamless integration of robots with manned systems envisioned by the U.S. DoD Unmanned Systems Roadmap (Office of the Secretary of Defense, 2007).

APPENDIX A: RESTRICTIONS CHECKLIST

Participant #: Date:

Start time:

Restrictions Checklist

Answering "Yes" to questions below may prohibits participation in the study

	Yes	No
Are you less than 18 years old?		
Are you greater than 40 years old?		
Have you had any caffeine in the last 2 hours?		
Have you had any nicotine in the last 2 hours?		
Have you had any Alcohol in the last 24 hours?		
Have you had any sedatives or tranquilizers in the last 24 hours?		
Have you had any aspirin, Tylenol, or similar medications in the last 24 hours?		
Have you had any antihistamines or decongestants in the last 24 hours?		
Have you had any anti-psychotics or anti-depressants in the last 24 hours?		
Is your hair wet?		
Do you have woven or artificial hair?		
Are you pregnant?		
Do you have any metal plates in your head?		
Do you lack normal or corrected to normal vision?		
Do you have a history of epilepsy or seizures?		
Is your waistline less than 34 inches?		
Is your waistline greater than 50 inches?		
Do you have any impairment of your dominant arm or hand?		

Answering "Left" or "Either" to questions below may prohibit participation in the study

	Left	Right	Either
Are you right handed?			
Which hand do you use to write with?			
Which hand do you use to throw a ball?			
Which hand do you hold a toothbrush with?			
Which hand holds a knife when you cut things?			
Which hand holds a hammer when you nail things?			

APPENDIX B: TACTONS SEQUENCES

Tacton Parameters:
Sinusoid Frequency: 230 Hz
Inter-Tactor Interval: 100 milliseconds
Tactor Vibration Duration: 250 milliseconds
Tactor Sequence Example: (1), (4, 2), (5, 1) = Tactor 1 on for 250ms, 100ms all off, Tactors 4 and 2 on for 250ms, 100ms all off, Tactors 5 and 1 on for 250ms, 100ms all off.

Category	Tacton Name	Tactor Sequence	Source
Directional	Away from East	(1), (4,2), (5,1)	(Mortimer B. , Zets, Mort, & Shovan, 2011)
	Away from North	(1), (8,2), (7,3)	(Mortimer B. , Zets, Mort, & Shovan, 2011)
	Away from South	(5), (6,4), (7,3)	(Mortimer B. , Zets, Mort, & Shovan, 2011)
	Away from West	(7), (8,6), (5,1)	(Mortimer B. , Zets, Mort, & Shovan, 2011)
	Toward East	(5,1), (4,2), (3)	(White, ARL-TR-5557, 2011)
	Toward North	(7,3), (8,2), (1)	(White, ARL-TR-5557, 2011)
	Toward South	(7,3), (6,4), (5)	(White, ARL-TR-5557, 2011)
	Toward West	(5,1), (8,6), (7)	(White, ARL-TR-5557, 2011)
Static	Acknowledge	(5,4,2,1), (5,4,2,1), (5,4,2,1)	(U.S. Army, 1987)
	Cease Fire	(6,5,4,1), (6,5,4,1), (6,5,4,1)	(U.S. Army, 1987)
	Fire	(8,5,2,1), (8,5,2,1), (8,5,2,1)	(U.S. Army, 1987)
	Halt	(8,6,4,2), (8,6,4,2), (8,6,4,2)	(Gilson, Redden, & Elliott, 2007)
	I Do not Understand	(8,6,5,1), (8,6,5,1), (8,6,5,1)	(U.S. Army, 1987)
	Nuclear/ Biological / Chemical Attack	(7,5,3,1), (7,5,3,1), (7,5,3,1)	(Gilson, Redden, & Elliott, 2007)
	Vee Formation	(8,7,3,2), (8,7,3,2), (8,7,3,2)	(U.S. Army, 1987)
	Wedge Formation	(7,6,4,3), (7,6,4,3), (7,6,4,3)	(U.S. Army, 1987)
Dynamic	Attention	(8), (1), (2), (1), (8), (1), (2), (1), (8)	(Gilson, Redden, & Elliott, 2007)
	Danger Area	(7), (8,7), (8,7,2), (8,7,3,2), (8,7,2), (8,7), (7)	(Gilson, Redden, & Elliott, 2007)
	Disperse	(8,2,1), (6,5,4), (8,2,1), (6,5,4), (8,2,1), (6,5,4), (8,2,1), (6,5,4), (8,2,1)	(U.S. Army, 1987)
	Enemy In Sight	(7,3), (5,1), (7,3), (5,1), (7,3), (5,1), (7,3), (5,1), (7,3)	(Gilson, Redden, & Elliott, 2007)
	Move Out	(5), (6,4), (7,3), (8,2), (1), (5), (6,4), (7,3), (8,2), (1)	(Gilson, Redden, & Elliott, 2007)
	Rally	(1), (2), (3), (4), (5), (6), (7), (8), (1)	(Gilson, Redden, & Elliott, 2007)
	Rush	(5), (6,4), (7,3), (6,4), (5), (6,4), (7,3), (8,2), (1)	(Gilson, Redden, & Elliott, 2007)
	Take Cover	(1), (4), (6), (2), (5), (7), (3), (6), (8), (4),	(Gilson, Redden, & Elliott, 2007)

APPENDIX C: ATTENTIONAL CONTROL SURVEY

For each of the following questions, circle the response that best describes you.

It is very hard for me to concentrate on a difficult task when there are noises around.
Almost never Sometimes Often Always

When I need to concentrate and solve a problem, I have trouble focusing my attention.
Almost never Sometimes Often Always

When I am working hard on something, I still get distracted by events around me.
Almost never Sometimes Often Always

My concentration is good even if there is music in the room around me.
Almost never Sometimes Often Always

When concentrating, I can focus my attention so that I become unaware of what's going on in the room around me.
Almost never Sometimes Often Always

When I am reading or studying, I am easily distracted if there are people talking in the same room.
Almost never Sometimes Often Always

When trying to focus my attention on something, I have difficulty blocking out distracting thoughts.
Almost never Sometimes Often Always

I have a hard time concentrating when I'm excited about something.
Almost never Sometimes Often Always

When concentrating, I ignore feelings of hunger or thirst.
Almost never Sometimes Often Always

I can quickly switch from one task to another.
Almost never Sometimes Often Always

It takes me a while to get really involved in a new task.
Almost never Sometimes Often Always

It is difficult for me to coordinate my attention between the listening and writing required when taking notes during lectures. Almost never Sometimes Often Always

I can become interested in a new topic very quickly when I need to.
Almost never Sometimes Often Always

It is easy for me to read or write while I'm also talking on the phone.
Almost never Sometimes Often Always

I have trouble carrying on two conversations at once.
Almost never Sometimes Often Always

I have a hard time coming up with new ideas quickly.
Almost never Sometimes Often Always

After being interrupted or distracted, I can easily shift my attention back to what I was doing before.
Almost never Sometimes Often Always

When a distracting thought comes to mind, it is easy for me to shift my attention away from it.
Almost never Sometimes Often Always

It is easy for me to alternate between two different tasks.

Almost never Sometimes Often Always

It is hard for me to break from one way of thinking about something and look at it from another point of view.

Almost never Sometimes Often Always

APPENDIX D: CUBE COMPARISON TEST

Name ____

CUBE COMPARISONS TEST -- S-2 (Rev.)

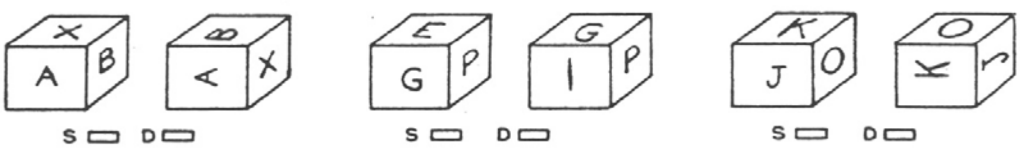
Wooden blocks such as children play with are often cubical with a different letter, number, or symbol on each of the six faces (top, bottom, four sides). Each problem in this test consists of drawings of pairs of cubes or blocks of this kind. Remember, there is a different design, number, or letter on each face of a given cube or block. Compare the two cubes in each pair below.

The first pair is marked D because they must be drawings of <u>different</u> cubes. If the left cube is turned so that the A is upright and facing you, the N would be to the left of the A and hidden, not to the right of the A as is shown on the right hand member of the pair. Thus, the drawings must be of different cubes.

The second pair is marked S because they could be drawings of the same cube. That is, if the A is turned on its side the X becomes hidden, the B is now on top, and the C (which was hidden) now appears. Thus the two drawings could be of the same cube.

<u>Note</u>: No letters, numbers, or symbols appear on more than one face of a given cube. Except for that, <u>any</u> letter, number or symbol can be on the hidden faces of a cube.

Work the three examples below.



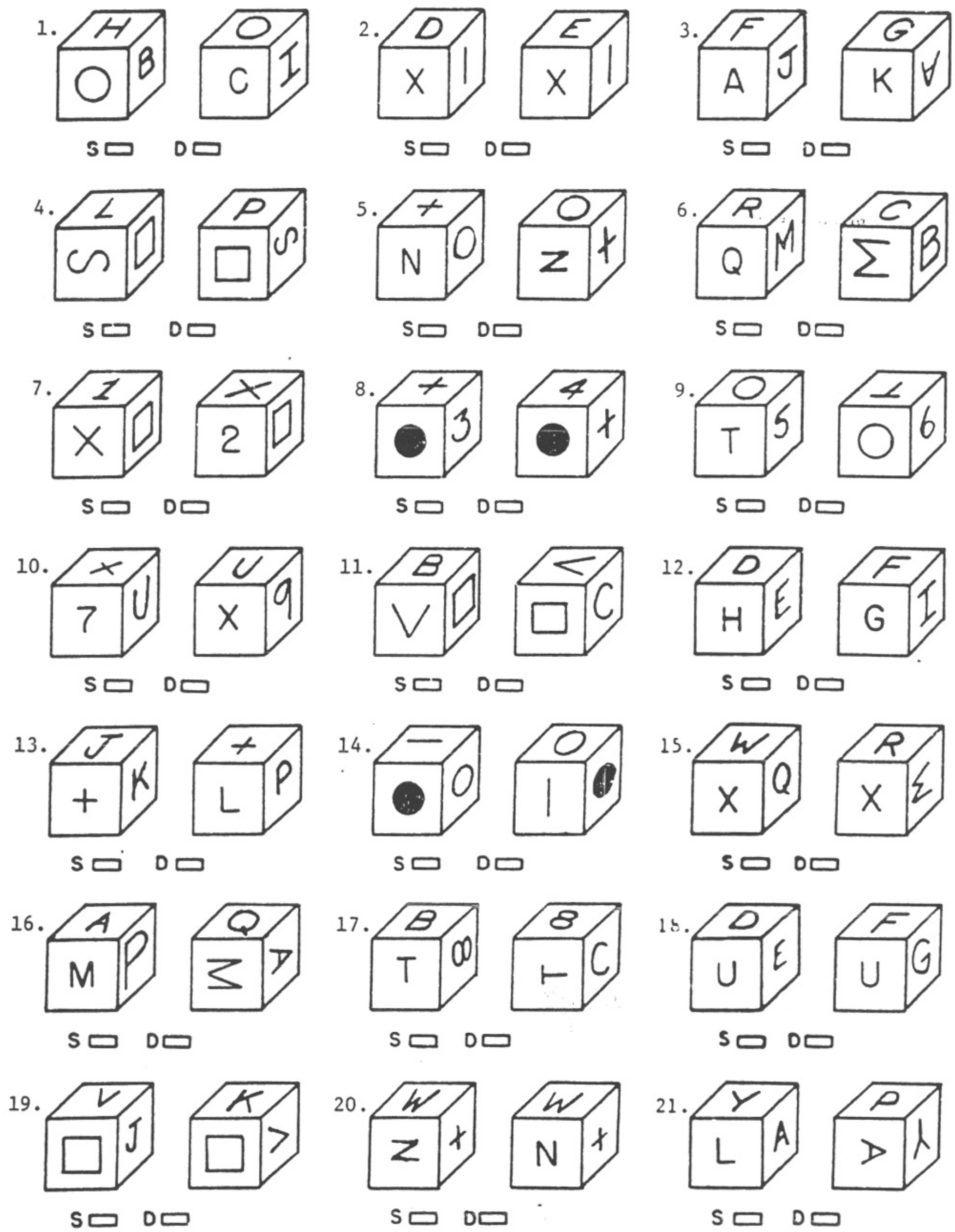
The first pair immediately above should be marked D because the X cannot be at the peak of the A on the left hand drawing and at the base of the A on the right hand drawing. The second pair is "different" because P has its side next to G on the left hand cube but its top next to G on the right hand cube. The blocks in the third pair are the same, the J and K are just turned on their side, moving the O to the top.

Your score on this test will be the number marked correctly minus the number marked incorrectly. Therefore, it will <u>not</u> be to your advantage to guess unless you have some idea which choice is correct. Work as quickly as you can without sacrificing accuracy.

You will have <u>3 minutes</u> for each of the two parts of this test. Each part has one page. When you have finished Part 1, STOP.

DO NOT TURN THE PAGE UNTIL YOU ARE ASKED TO DO SO.

Part 1 (3 minutes)



DO NOT GO ON TO THE NEXT PAGE UNTIL ASKED TO DO SO. STOP.

APPENDIX E: NASA-TLX

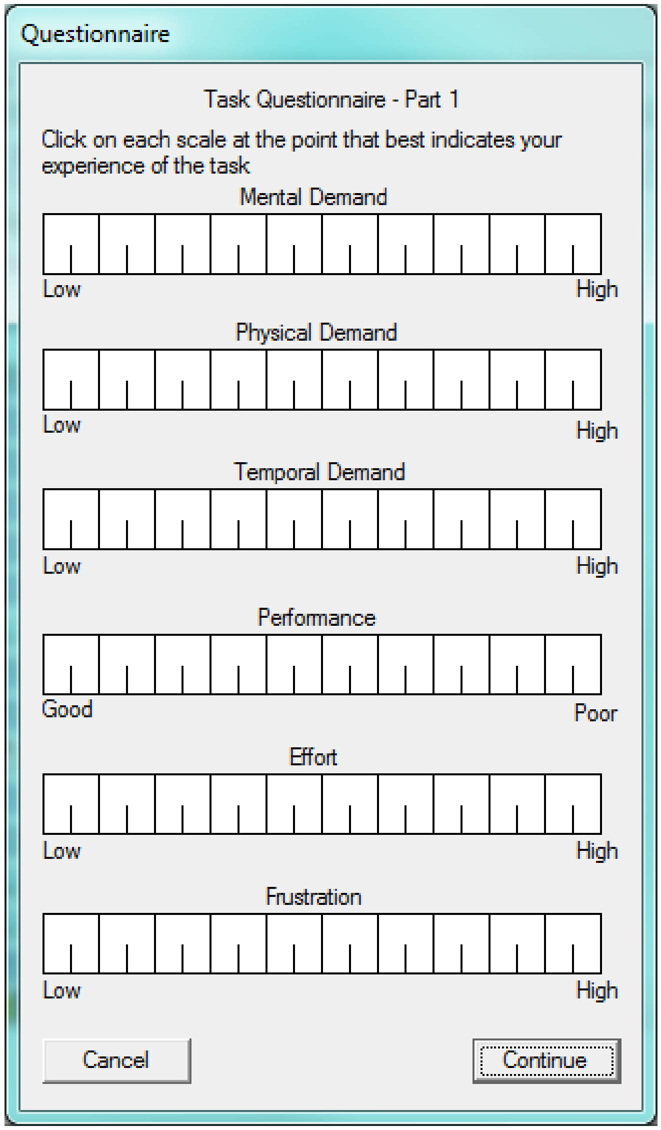


Figure 30. The NASA-TLX computer program. The participant uses a mouse to indicate their rating of each scale.

APPENDIX F: DEMOGRAPHICS QUESTIONNAIRE

Participant # _______ Age ______ Major ________________ Date ___________ Gender ___

1. What is the <u>highest</u> level of education you have had?
Less than 4 yrs of college ____ Completed 4 yrs of college ____ Other ____

2. When did you use computers in your education? (*<u>Circle all that apply</u>*)

Grade School	Jr. High	High School
Technical School	College	Did Not Use

3. Where do you currently use a computer? (*<u>Circle all that apply</u>*)
Home Work Library Other________ Do Not Use

4. How many hours per day do you use a computer? ___________

5. For each of the following questions, <u>circle</u> the response that best describes you.

How often do you:	
Use a mouse?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use a joystick?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use a touch screen?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use icon-based programs/software?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use programs/software with pull-down menus?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use graphics/drawing features in software packages?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use E-mail?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Operate a radio controlled vehicle (car, boat, or plane)?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Play computer/video games?	Daily, Weekly, Monthly, Once every few months, Rarely, Never

6. Which type(s) of computer/video games do you most often play if you play at least once every few months?

7. Which of the following best describes your expertise with computers? (check √ one)
_____ Novice
_____ Good with one type of software package (such as word processing or slides)
_____ Good with several software packages
_____ Can program in one language and use several software packages
_____ Can program in several languages and use several software packages

8. How many hours per day do you watch television? ________

9. How many hours per day do you spend reading? __________

10. Are you in your usual state of health physically? YES NO
If NO, please briefly explain:

11. How many hours of sleep did you get last night? ______ hours

12. How much experience do you have with virtual environments?

0	1	2	3	4	5
Not at all	Mildly		Average		Highly

13. What is your occupation? _______________

14. How often do you feel eye strain?

0	1	2	3	4	5
Not at all	Mildly		Average		Highly

15. During an average work day, do you feel that you focus on near objects (about 2 meters away) more than objects that are far away (6 meters or more)?

1	2	3	4	5
Strongly disagree		Agree		Strongly agree

APPENDIX G: INFORMED CONSENT EXPERIMENT ONE

RCTA Tactile Encoding Schemes

Informed Consent

Principal Investigator(s): *Daniel Barber*
Stephanie Lackey, PhD.

Sponsor: *ARL – U.S. Army Research Laboratory*

Investigational Site(s): *Institute for Simulation and Training*
University of Central Florida
3100 Research Parkway
Orlando, FL 32826

Introduction: Researchers at the University of Central Florida (UCF) study many topics. To do this we need the help of people who agree to take part in a research study. You are being invited to take part in a research study which will include people at UCF. You have been asked to take part in this research study because you are a student at UCF.

The investigators conducting this research are Dr. Stephanie Lackey and Mr. Daniel Barber of the University of Central Florida's Institute for Simulation and Training.

What you should know about a research study:

- Someone will explain this research study to you.
- A research study is something you volunteer for.
- Whether or not you take part is up to you.
- You should take part in this study only because you want to.
- You can choose not to take part in the research study.
- You can agree to take part now and later change your mind.
- Whatever you decide it will not be held against you.
- Feel free to ask all the questions you want before you decide.

Purpose of the research study: The purpose for this study is to determine how well tactile communication (i.e., communication via the sense of touch) can be learned and applied.

What you will be asked to do in the study:

First, the experimenter will complete a pre-screen checklist to make sure you qualify for the study. Next an Electroencephalogram (EEG) cap will be fitted to your head for collection of brain activity information throughout the study. Next you will be asked to complete additional questionnaires and surveys including: demographics, current health status, attentional control, and spatial ability using a cube comparison test. You will then be presented with a tactile "belt" device which fits on the abdomen. Motors on the belt will vibrate to create a variety of sensations around the abdomen. An example of a sensation would be a vibration starting from the navel moving in a clockwise direction towards your back and then towards again the front of your body. A computer will present different sensations through the belt and you will be asked to learn the meanings of each sensation. You will be presented with three training sessions to learn the tactile patterns for the study. After a learning period, you will be administered a computerized task for classifying the sensations of the tactile patterns while watching a video of a truck driving through a virtual environment from the perspective of the driver. This study is a within group design including 60 participants.

Tactile Belt: The tactile belt is noninvasive and can be fastened or removed easily using a Velcro buckle. The belt is composed of a flat cloth tube with eight motors sewn between the cloth tube. The motors will oscillate perpendicular to the skin at up to 250Hz which creates a "buzzing" sensation similar to a cell phone motor but is generally considered to be more intense and localized. You will be told when to expect the first sensations from the tactile belt.

Once you are briefed on the experimental procedures a research assistant will first fit you with the physiological sensing devices used in the study. Then you will fill out some pre-questionnaires. Sensor and performance data will be gathered as you complete the research tasks where you will classify tactile patterns you feel from the tactile belt.

All of the equipment being used is noninvasive. Additional devices used in this experiment will be a 10 channel Electroencephalogram (EEG) cap, which means that 9 sensors will measure activity in the brain and one is an Electrocardiogram (ECG) sensor that will measure heart rate activity. Each sensor will be custom set for each individual using its respective setup procedure. The following sections provide a description of the EEG and ECG procedures.

EEG: The EEG sensors are contained in a neoprene cap that will be placed over your head and adjusted by the lab technician. The conductive gel is placed on the sensor sponge, which allows the sensor to touch the scalp without being abrasive.

For cap placement, you will be seated in front of the computer. The researcher will take an alcohol swab (or equivalent if allergic) and wipe the mastoid bone (behind your ears just above your neck) where the sensors will touch. The research assistant will set the cap so that the front is aligned with the nasium (brow ridge between the eyes) and inion (occipital bone at the back of the head). Once the EEG cap is in place, the research assistant will test the impedance of the sensors to assure that proper conductance is occurring.

ECG: There are two sensors that need to be placed on the right collar bone and the lower left rib bone. These sensors will be placed by you, the participant. You will take an alcohol swab and clean the areas where the sensors will be placed. The research assistant will attach the sensor to the lead and put some conductive gel on the sensor. You will then place the sensor in their respective place on the right collar bone or the lower left rib bone. The research assistant will turn on the device and check to see that the EEG and ECG sensors are receiving signal. The signal strength will be evaluated via software on the experimenter's computer station.

When the study is over, the research assistant will help you remove all the sensors and give you debriefing information about the study. It is most helpful to the research being conducted that you answer all questions and complete all tasks to the best of your abilities, but you are not required to answer every question or complete every task. You will not lose any benefits if you choose not to complete questions or tasks.

Location: Human Performance and Neuroergonomics Lab located in room 220 of the ACTIVE Lab, Institute for Simulation and Training's Partnership III building.

Time required: We expect that you will be in this research study for 2.5 hours.

Funding for this study: This research study is being paid for by the U.S. Army Research Laboratory (ARL).

Risks: There are no foreseeable risks or discomforts other than those normally encountered in the daily lives of healthy persons. All the neurosensing equipment and the tactile-belt are unobtrusive, non-invasive, and have been fully tested and inspected to maintain safety. All electronic devices attached to the body are battery-operated and low-power. The researchers performing this study have completed training on the use and safety of each of the sensors used in the experiment. Because of the conductance gel used in the EEG cap and the ECG sensors, there is a minimal possibility of skin irritation, although the gel is water-based. If this happens, participants are urged to notify the research assistant immediately.

Compensation or payment: Participants may expect to spend 3 hours performing experimental tasks, for which they may elect to receive course credit for the amount of time they participate. Maximum course credit will be 150 minutes (2.5 Sona credits) and is awarded at the discretion of the individual course professor.

Confidentiality: We will limit your personal data collected in this study to people who have a need to review this information. Data will be secured in locked cabinets at the Institute for

Simulation and Training (IST) and disposed of following IRB protocol, which includes the shredding of all documents and proper deletion of electronic information.

Study contact for questions about the study or to report a problem: If you have questions, concerns, or complaints, or think the research has hurt you, talk to Daniel Barber at 407-882-1128, or by email at dbarber@ist.ucf.edu.

IRB contact about your rights in the study or to report a complaint: Research at the University of Central Florida involving human participants is carried out under the oversight of the Institutional Review Board (UCF IRB). This research has been reviewed and approved by the IRB. For information about the rights of people who take part in research, please contact: Institutional Review Board, University of Central Florida, Office of Research & Commercialization, 12201 Research Parkway, Suite 501, Orlando, FL 32826-3246 or by telephone at (407) 823-2901. You may also talk to them for any of the following:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.
- You want to talk to someone besides the research team.
- You want to get information or provide input about this research.

APPENDIX H: INFORMED CONSENT EXPERIMENT TWO

RCTA Tactile Sentences

Informed Consent

Principal Investigator(s):	*Stephanie Lackey, PhD.*
Co-Investigator(s):	*Daniel Barber* *Florian Jentsch, Ph.D.*
Sponsor:	*ARL – U.S. Army Research Laboratory*
Investigational Site(s):	*Institute for Simulation and Training* *University of Central Florida* *3100 Research Parkway* *Orlando, FL 32826*

Introduction: Researchers at the University of Central Florida (UCF) study many topics. To do this we need the help of people who agree to take part in a research study. You are being invited to take part in a research study which will include 100 people at UCF.

The investigators conducting this research are Dr. Stephanie Lackey and Mr. Daniel Barber of the University of Central Florida's Institute for Simulation and Training.

What you should know about a research study:

- Someone will explain this research study to you.
- A research study is something you volunteer for.
- Whether or not you take part is up to you.
- You should take part in this study only because you want to.
- You can choose not to take part in the research study.
- You can agree to take part now and later change your mind.
- Whatever you decide it will not be held against you.
- Feel free to ask all the questions you want before you decide.

Purpose of the research study: The purpose for this study is to determine how well tactile communication (i.e., communication via the sense of touch) can be learned and applied.

What you will be asked to do in the study:

First, the experimenter will complete a pre-screen checklist to make sure you qualify for the study. The researcher will then setup the Electroencephalogram (EEG) cap which will be fitted to your head for collection of brain activity. Next you will be asked to complete some questionnaires and surveys including: the demographics, current health status, attentional control questionnaire, NASA-TLX, and a cube comparison test that measures spatial ability. You will then be presented with a tactile "belt" device which fits on the abdomen. Motors on the belt will vibrate to the same degree as a cell phone to create a variety of sensations around the abdomen. An example of a sensation would be a vibration starting from the navel moving in a clockwise direction towards your back and then towards the front of your body. A computer will present different sensations through the belt and you will be asked to learn the meanings of each sensation. You will complete training sessions in order to familiarize yourself with the tactile sensations. After a learning period, you will be administered a computerized task for classifying the tactile sensations. While completing the computerized classification task you will also either drive a truck through a virtual environment or watch a video of a truck driving through a virtual environment; depending on the scenario you are completing at the time.

All of the equipment being used is noninvasive. Devices used in this experiment will include a 10 channel Electroencephalogram (EEG) cap and a tactile belt. The 10 channel EEG cap has 9 sensors that will measure activity in the brain and one sensor for Electrocardiogram (ECG) data that will measure heart rate activity. Each sensor will be custom set for each individual using its respective setup procedure. The following sections provide a description of the EEG and ECG procedures as well as the tactile belt procedures.

EEG: The EEG sensors are contained in a neoprene cap that will be placed over your head and adjusted by the lab technician. The conductive gel is placed on the sensor sponge, which allows the sensor to touch the scalp without being abrasive. The conductive gel is hypoallergenic and water soluble.

For cap placement, you will be seated in front of the computer. The researcher will take an alcohol swab (or equivalent if allergic) and wipe the mastoid bone (behind your ears just above your neck) where the sensors will touch. The research assistant will set the cap so that the front is aligned with the nasium (brow ridge between the eyes) and inion (occipital bone at the back of the head). Once the EEG cap is in place, the research assistant will test the impedance of the sensors to assure that proper conductance is occurring.

*ECG***:** There are two sensors that need to be placed on the right collar bone and the lower left rib bone. These sensors will be placed by you, the participant. You will take an alcohol swab and clean the areas where the sensors will be placed. The research assistant will attach the sensor to the lead and put some conductive gel on the sensor. You will then place the sensor in their respective place on the right collar bone or the lower left rib bone. The research assistant will turn on the device and check to see that the EEG and ECG sensors are receiving signal. The signal strength will be evaluated via software on the experimenter's computer station.

Tactile Belt: The tactile belt is noninvasive and can be fastened or removed easily using a Velcro buckle. The belt is composed of a flat cloth tube with eight motors sewn between the cloth tube. The motors will oscillate perpendicular to the skin at up to 250Hz which creates a "buzzing" sensation similar to a cell phone motor but is generally considered to be more intense and localized. You will be told when to expect the first sensations from the tactile belt.

When the study is over, the research assistant will help you remove all the sensors and give you debriefing information about the study. It is most helpful to the research being conducted that you answer all questions and complete all tasks to the best of your abilities, but you are not required to answer every question or complete every task. You will not lose any benefits if you choose not to complete questions or tasks.

Location: Human Performance and Neuroergonomics Lab located in room 220 of the ACTIVE Lab, Institute for Simulation and Training's Partnership III building.

Time required: We expect that you will be in this research study for 3 hours.

Funding for this study: This research study is being paid for by the U.S. Army Research Laboratory (ARL).

Risks: There are no foreseeable risks or discomforts other than those normally encountered in the daily lives of healthy persons. All the neurosensing equipment and the tactile-belt are unobtrusive, non-invasive, and have been fully tested and inspected to maintain safety. All electronic devices attached to the body are battery-operated and low-power. The researchers performing this study have completed training on the use and safety of each of the sensors used in the experiment. Because of the conductance gel used in the EEG cap and the ECG sensors, there is a minimal possibility of skin irritation, although the gel is water-based. If this happens, participants are urged to notify the research assistant immediately.

Compensation or payment: Participants may expect to spend 3 hours participating in the study, for which they will receive 1 SONA credit for every hour of participation.. If the experiment takes longer and the participant is able to stay and complete the experiment they will receive extra credit in increments of 15 minutes / .25 SONA credits. Additionally if a participant is unable to complete the study for any reason they will receive .25 SONA credits for every 15 minutes of study participation but will not receive less than 1 SONA credit.

Confidentiality: We will limit your personal data collected in this study to people who have a need to review this information. The principal investigators, co-investigators, and research assistants working on this project will have access to your data. Additionally, there is a possibility that the U.S. Army Human Research Protections Office (AHRPO) will also review the records related to this study. Data will be secured in locked cabinets at the Institute for Simulation and Training (IST) and disposed of following UCF IRB protocol, which includes the shredding of all documents and proper deletion of electronic information. Please note that your name will not be associated with any of the data collected during this study. Once you sign the informed consent it will be kept in a locked cabinet separate from your data.

Study contact for questions about the study or to report a problem: If you have questions, concerns, or complaints, or think the research has hurt you, talk to Daniel Barber at 407-882-1128, or by email at dbarber@ist.ucf.edu.

IRB contact about your rights in the study or to report a complaint: Research at the University of Central Florida involving human participants is carried out under the oversight of the Institutional Review Board (UCF IRB). This research has been reviewed and approved by the IRB. For information about the rights of people who take part in research, please contact: Institutional Review Board, University of Central Florida, Office of Research & Commercialization, 12201 Research Parkway, Suite 501, Orlando, FL 32826-3246 or by telephone at (407) 823-2901. You may also talk to them for any of the following:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.
- You want to talk to someone besides the research team.
- You want to get information or provide input about this research.

Once all of your questions about the study have been answered and if you want to continue your participation in this study please sign below.

The researcher will then take this entire informed consent and place it in a locked cabinet separate from your data. You will be given another copy of the exact same informed consent for you to keep.

____
Participant printed name

____________________________________ __________
Participant signature Date

____________________________________ __________
Signature of person obtaining consent Date

____
Printed name of person obtaining consent

APPENDIX I: IRB APPROVAL LETTER EXPERIMENT ONE

University of Central Florida

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Approval of Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Stephanie Jane Lackey and Daniel J Barber**

Date: **September 13, 2011**

Dear Researcher:

On September 13, 2011, the IRB approved the following human participant research until 9/12/2012 inclusive:

Type of Review:	UCF Initial Review Submission Form Expedited Review Category # 4 & 7 This approval includes a Waiver of Written Documentation of Consent
Project Title:	RCTA Tactile Encoding Schemes
Investigator:	Stephanie Jane Lackey
IRB Number:	SBE-11-07836
Funding Agency:	US Army Research Laboratory
Grant Title:	Robotics Collaborative Technology Alliance (RCTA) H5 Explicit Communications
Research ID:	1052758

The Continuing Review Application must be submitted 30days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu .

If continuing review approval is not granted before the expiration date of 9/12/2012, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., CF IRB Chair, this letter is signed by:

Signature applied by Janice Turchin on 09/13/2011 11:52:29 AM EDT

Janice m Turchin

IRB Coordinator

APPENDIX J: IRB APPROVAL LETTER EXPERIMENT TWO

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Approval of Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Stephanie Jane Lackey** and Co-PIs: **Daniel J. Barber, Florian G. Jentsch**

Date: **February 08, 2012**

Dear Researcher:

On 2/8/2012, the IRB approved the following human participant research until 2/7/2013 inclusive:

Type of Review:	UCF Initial Review Submission Form Expedited Review Category #4 and #7
Project Title:	RCTA Tactile Sentences
Investigator:	Stephanie Jane Lackey
IRB Number:	SBE-12-08189
Funding Agency:	DOD/Army/ARL
Grant Title:	Robotics Collaborative Technology Alliance (RCTA) H5 Explicit Communications
Research ID:	1052758

The Continuing Review Application must be submitted 30days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu .

If continuing review approval is not granted before the expiration date of 2/7/2013, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a signed and dated copy of the consent form(s).

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., CF IRB Chair, this letter is signed by:

Signature applied by Joanne Muratori on 02/08/2012 10:30:54 AM EST

IRB Coordinator

APPENDIX K: ANOVA TABLES FOR EXPERIMENT ONE

Table 4
ANOVA of Classification Accuracy for Sensitivity Test

Source		*df*	*MS*	*F*	*p*
Sensitivity	Sphericity Assumed	4.000	20.321	1.856	.121
	Greenhouse-Geisser	2.324	34.972	1.856	.156
	Huynh-Feldt	2.500	32.520	1.856	.153
	Lower-bound	1.000	81.285	1.856	.182
Error (Sensitivity)	Sphericity Assumed	140.000	10.946		
	Greenhouse-Geisser	81.349	18.838		
	Huynh-Feldt	87.483	17.517		
	Lower-bound	35.000	43.785		

Table 5
ANOVA of Training Classification by Tacton Category

Source		*df*	*MS*	*F*	*p*
Type	Sphericity Assumed	2.000	4902.341	35.622	.000
	Greenhouse-Geisser	1.514	6474.694	35.622	.000
	Huynh-Feldt	1.568	6251.852	35.622	.000
	Lower-bound	1.000	9804.683	35.622	.000
Error (Type)	Sphericity Assumed	70.000	137.622		
	Greenhouse-Geisser	53.001	181.762		
	Huynh-Feldt	54.890	175.506		
	Lower-bound	35.000	275.243		

Table 6
ANOVA of Training Reaction Time

Source		*df*	*MS*	*F*	*p*
Category	Sphericity Assumed	2.000	1970896.148	2.768	.070
	Greenhouse-Geisser	1.157	3407718.946	2.768	.099
	Huynh-Feldt	1.171	3365190.343	2.768	.098
	Lower-bound	1.000	3941792.296	2.768	.105
Error (Category)	Sphericity Assumed	70.000	712091.586		
	Greenhouse-Geisser	40.485	1231220.626		
	Huynh-Feldt	40.997	1215854.895		
	Lower-bound	35.000	1424183.172		

Table 7
ANOVA of Classification Accuracy for Tacton Categories

Source		*df*	*MS*	*F*	*p*
Type	Sphericity Assumed	2.000	10092.318	55.834	.000
	Greenhouse-Geisser	1.697	11896.638	55.834	.000
	Huynh-Feldt	1.774	11378.054	55.834	.000
	Lower-bound	1.000	20184.635	55.834	.000
Error (Type)	Sphericity Assumed	70.000	180.755		
	Greenhouse-Geisser	59.383	213.070		
	Huynh-Feldt	62.090	203.782		
	Lower-bound	35.000	361.510		

Table 8
ANOVA for Reaction Time by Tacton Category

Source		*df*	*MS*	*F*	*p*
Category	Sphericity Assumed	2.000	1679067.120	6.119	.004
	Greenhouse-Geisser	1.646	2039972.678	6.119	.006
	Huynh-Feldt	1.717	1956038.526	6.119	.006
	Lower-bound	1.000	3358134.241	6.119	.018
Error (Category)	Sphericity Assumed	70.000	274392.863		
	Greenhouse-Geisser	57.616	333371.988		
	Huynh-Feldt	60.088	319655.483		
	Lower-bound	35.000	548785.726		

Table 9
ANOVA for Training Transfer

Effect		*F*	*df*	*Error df*	*p*	η^2
Training Transfer	Pillai's Trace	83.089[a]	1.000	35.000	.000	.704
	Wilks' Lambda	83.089[a]	1.000	35.000	.000	.704
	Hotelling's Trace	83.089[a]	1.000	35.000	.000	.704
	Roy's Largest Root	83.089[a]	1.000	35.000	.000	.704
Category	Pillai's Trace	50.238[a]	2.000	34.000	.000	.747
	Wilks' Lambda	50.238[a]	2.000	34.000	.000	.747
	Hotelling's Trace	50.238[a]	2.000	34.000	.000	.747
	Roy's Largest Root	50.238[a]	2.000	34.000	.000	.747
Training Transfer * Category	Pillai's Trace	82.106[a]	2.000	34.000	.000	.828
	Wilks' Lambda	82.106[a]	2.000	34.000	.000	.828
	Hotelling's Trace	82.106[a]	2.000	34.000	.000	.828
	Roy's Largest Root	82.106[a]	2.000	34.000	.000	.828

a. Exact statistic, b. Computed using alpha = .05, c. Design: Intercept Within Subjects Design: Training Transfer + Category + Training Transfer * Category

Table 10
ANOVA of Classification Accuracy for Directional Tactons

Source		*df*	*MS*	*F*	*p*
Tacton	Sphericity Assumed	7.000	105.556	1.969	.06
	Greenhouse-Geisser	3.703	199.518	1.969	.108
	Huynh-Feldt	4.196	176.092	1.969	.099
	Lower-bound	1.000	738.889	1.969	.169
Error (Tacton)	Sphericity Assumed	245.000	53.617		
	Greenhouse-Geisser	129.618	101.345		
	Huynh-Feldt	146.861	89.446		
	Lower-bound	35.000	375.317		

Table 11
ANOVA of Reaction Time for Directional Tactons

Source		*df*	*MS*	*F*	*p*
Tacton	Sphericity Assumed	7.000	69874.071	2.076	.047
	Greenhouse-Geisser	3.301	148174.109	2.076	.101
	Huynh-Feldt	3.686	132704.969	2.076	.093
	Lower-bound	1.000	489118.497	2.076	.159
Error (Tacton)	Sphericity Assumed	245.000	33658.677		
	Greenhouse-Geisser	115.534	71376.183		
	Huynh-Feldt	129.002	63924.624		
	Lower-bound	35.000	235610.739		

Table 12
ANOVA of Classification Accuracy for Dynamic Tactons

Source		*df*	*MS*	*F*	*p*
Tacton	Sphericity Assumed	7.000	3358.730	4.086	.000
	Greenhouse-Geisser	5.276	4456.033	4.086	.001
	Huynh-Feldt	6.323	3718.320	4.086	.001
	Lower-bound	1.000	23511.111	4.086	.051
Error (Tacton)	Sphericity Assumed	245.000	821.995		
	Greenhouse-Geisser	184.668	1090.543		
	Huynh-Feldt	221.307	909.999		
	Lower-bound	35.000	5753.968		

Table 13
ANOVA of Reaction Time for Dynamic Tactons

Source		*df*	*MS*	*F*	*p*
Tacton	Sphericity Assumed	7.000	464649.660	3.337	.003
	Greenhouse-Geisser	4.853	670244.379	3.337	.009
	Huynh-Feldt	6.596	493122.524	3.337	.003
	Lower-bound	1.000	3252547.619	3.337	.083
Error(Tacton)	Sphericity Assumed	140.000	139247.647		
	Greenhouse-Geisser	97.056	200860.909		
	Huynh-Feldt	131.916	147780.483		
	Lower-bound	20.000	974733.532		

Table 14
ANOVA of Classification Accuracy for Static Tactons

Source		*df*	*MS*	*F*	*p*
Tacton	Sphericity Assumed	7.00	8286.855	15.695	.000
	Greenhouse-Geisser	5.00	11597.459	15.695	.000
	Huynh-Feldt	5.94	9772.519	15.695	.000
	Lower-bound	1.00	58007.986	15.695	.000
Error (Tacton)	Sphericity Assumed	245.00	527.978		
	Greenhouse-Geisser	175.06	738.905		
	Huynh-Feldt	207.75	622.633		
	Lower-bound	35.00	3695.843		

Table 15
ANOVA of Reaction Time for Static Tactons

Source		*df*	*MS*	*F*	*p*
Tacton	Sphericity Assumed	7.000	587628.742	3.594	.001
	Greenhouse-Geisser	4.320	952149.430	3.594	.007
	Huynh-Feldt	5.386	763669.027	3.594	.004
	Lower-bound	1.000	4113401.195	3.594	.070
Error (Tacton)	Sphericity Assumed	168.000	163506.218		
	Greenhouse-Geisser	103.683	264933.182		
	Huynh-Feldt	129.273	212488.984		
	Lower-bound	24.000	1144543.528		

Table 16
ANOVA for Workload Measures by Tacton Category

Source	Measure		*df*	*MS*	*F*	*p*
Category	Performance	Sphericity Assumed	2.0	7046.528	18.942	.000
		Greenhouse-Geisser	1.949	7231.851	18.942	.000
		Huynh-Feldt	2.000	7046.528	18.942	.000
		Lower-bound	1.000	14093.056	18.942	.000
	Frustration	Sphericity Assumed	2.0	9161.343	23.353	.000
		Greenhouse-Geisser	1.957	9362.661	23.353	.000
		Huynh-Feldt	2.000	9161.343	23.353	.000
		Lower-bound	1.000	18322.685	23.353	.000
	Mental Demand	Sphericity Assumed	2.0	6579.398	43.969	.000
		Greenhouse-Geisser	1.931	6813.022	43.969	.000
		Huynh-Feldt	2.000	6579.398	43.969	.000
		Lower-bound	1.000	13158.796	43.969	.000
	Physical Demand	Sphericity Assumed	2.0	803.704	5.958	.004
		Greenhouse-Geisser	1.801	892.641	5.958	.006
		Huynh-Feldt	1.892	849.401	5.958	.005
		Lower-bound	1.000	1607.407	5.958	.020
	Temporal Demand	Sphericity Assumed	2.0	1690.509	6.373	.003
		Greenhouse-Geisser	1.647	2052.285	6.373	.005
		Huynh-Feldt	1.718	1967.716	6.373	.005
		Lower-bound	1.000	3381.019	6.373	.016
	Effort	Sphericity Assumed	2.0	4028.704	13.762	.000
		Greenhouse-Geisser	1.871	4306.400	13.762	.000
		Huynh-Feldt	1.973	4084.232	13.762	.000
		Lower-bound	1.000	8057.407	13.762	.001
	Mean	Sphericity Assumed	2.0	4185.886	38.173	.000
		Greenhouse-Geisser	1.845	4538.687	38.173	.000
		Huynh-Feldt	1.942	4309.872	38.173	.000
		Lower-bound	1.000	8371.772	38.173	.000
Error (Category)	Performance	Sphericity Assumed	70.0	372.004		
		Greenhouse-Geisser	68.206	381.788		
		Huynh-Feldt	70.000	372.004		
		Lower-bound	35.000	744.008		
	Frustration	Sphericity Assumed	70.0	392.295		
		Greenhouse-Geisser	68.495	400.916		

	Huynh-Feldt	70.000	392.295
	Lower-bound	35.000	784.590
Mental Demand	Sphericity Assumed	70.0	149.636
	Greenhouse-Geisser	67.600	154.950
	Huynh-Feldt	70.000	149.636
	Lower-bound	35.000	299.272
Physical Demand	Sphericity Assumed	70.0	134.894
	Greenhouse-Geisser	63.026	149.822
	Huynh-Feldt	66.234	142.564
	Lower-bound	35.000	269.788
Temporal Demand	Sphericity Assumed	70.0	265.271
	Greenhouse-Geisser	57.660	322.040
	Huynh-Feldt	60.139	308.770
	Lower-bound	35.000	530.542
Effort	Sphericity Assumed	70.0	292.751
	Greenhouse-Geisser	65.486	312.930
	Huynh-Feldt	69.048	296.786
	Lower-bound	35.000	585.503
Mean	Sphericity Assumed	70.0	109.656
	Greenhouse-Geisser	64.559	118.898
	Huynh-Feldt	67.986	112.904
	Lower-bound	35.000	219.312

APPENDIX L: SUMMARY OF ALL TABLES FOR EXPERIMENT ONE

Table 17
Classification Accuracy Scores for Sensitivity Test

Time Period	*M*	*SD*
Sensitivity Part One	96.11	5.36
Sensitivity Part Two	96.53	5.05
Sensitivity Part Three	97.36	4.05
Sensitivity Part Four	98.06	3.64
Sensitivity Overall	97.05	3.12

Table 18
Classification Accuracy for Training

Tacton Category	*M*	*SD*
Directional	95.57	5.59
Dynamic	75.78	17.28
Static	93.93	11.00

Table 19
Classification Accuracy for Tacton Categories

Tacton Category	*M*	*SD*
Directional	95.42	7.99
Dynamic	72.50	24.36
Static	62.81	17.41

Table 20
Median Reaction Time for Tacton Categories

Tacton Category	*MS*	*SD*
Directional	739	906
Dynamic	760	1247
Static	1124	967

Table 21
NASA-TLX Workload Scales by Tacton Category

Workload Scale	Tacton Category	*M*	*SD*
Performance	Directional	19.17	16.97
	Dynamic	40.14	25.14
	Static	45.69	22.81
Frustration	Directional	22.64	19.29
	Dynamic	47.78	27.37
	Static	52.22	26.29
Mental Demand	Directional	49.44	23.48
	Dynamic	74.86	19.55
	Static	70.14	20.48
Physical Demand	Directional	16.39	12.51
	Dynamic	23.61	22.51
	Static	25.28	18.82
Temporal Demand	Directional	36.94	20.33
	Dynamic	45.14	23.95
	Static	50.56	20.59
Effort	Directional	47.50	24.33
	Dynamic	64.44	19.85
	Static	66.94	17.82
Global	Directional	32.01	11.96
	Dynamic	49.33	15.04
	Static	51.81	12.07

Table 22
Classification Accuracy for Dynamic Tactons

Tacton	*M*	*SD*
Attention	78.89	32.32
Danger Area	66.39	42.63
Disperse	72.78	39.18
Enemy In Sight	69.17	35.82
Move Out	65.83	39.16
Rally	93.61	15.34
Rush	65.00	39.68
Take Cover	68.33	38.43

Table 23
Reaction Times for Dynamic Tactons

Tacton	*M*	*SD*
Attention	279.00	1191.29
Danger Area	672.29	1012.73
Disperse	260.14	1267.79
Enemy In Sight	216.52	1309.63
Move Out	439.67	1227.89
Rally	388.05	1111.80
Rush	503.48	1097.34
Take Cover	366.00	1297.64

Table 24
Classification Accuracy for Static Tactons

Tacton	*M*	*SD*
Acknowledged	85.56	25.60
Cease Fire	49.72	27.52
Fire	56.39	29.29
Halt	61.11	27.23
I Do Not Understand	86.94	22.91
Nuclear/Biological/Chemical Attack	47.22	24.68
Vee Formation	56.67	32.60
Wedge Formation	58.89	30.22

Table 25
Reaction Time for Static Tactons

Tacton	*M*	*SD*
Acknowledged	692.48	742.42
Cease Fire	1025.56	730.60
Fire	995.44	815.02
Halt	829.76	735.12
I Do Not Understand	632.32	780.54
Nuclear/Biological/Chemical Attack	1046.44	911.15
Vee Formation	931.32	816.47
Wedge Formation	851.60	784.74

APPENDIX M: ANOVA TABLES FOR EXPERIMENT TWO

Table 26
ANOVA of Classification Accuracy and Reaction Time for Training

Source			*df*	*MS*	*F*	*p*
Syntax	Accuracy	Sphericity Assumed	1.00	37.019	.428	.516
		Greenhouse-Geisser	1.00	37.019	.428	.516
		Huynh-Feldt	1.00	37.019	.428	.516
		Lower-bound	1.00	37.019	.428	.516
	RT	Sphericity Assumed	1.00	54570.675	1.162	.285
		Greenhouse-Geisser	1.00	54570.675	1.162	.285
		Huynh-Feldt	1.00	54570.675	1.162	.285
		Lower-bound	1.00	54570.675	1.162	.285
Syntax * Group	Accuracy	Sphericity Assumed	1.00	1.481	.017	.896
		Greenhouse-Geisser	1.00	1.481	.017	.896
		Huynh-Feldt	1.00	1.481	.017	.896
		Lower-bound	1.00	1.481	.017	.896
	RT	Sphericity Assumed	1.00	79361.633	1.691	.199
		Greenhouse-Geisser	1.00	79361.633	1.691	.199
		Huynh-Feldt	1.00	79361.633	1.691	.199
		Lower-bound	1.00	79361.633	1.691	.199
Error(Syntax)	Accuracy	Sphericity Assumed	58.00	86.501		
		Greenhouse-Geisser	58.00	86.501		
		Huynh-Feldt	58.00	86.501		
		Lower-bound	58.00	86.501		
	RT	Sphericity Assumed	58.00	46944.469		
		Greenhouse-Geisser	58.00	46944.469		
		Huynh-Feldt	58.00	46944.469		
		Lower-bound	58.00	46944.469		

Table 27
ANOVA for Tacton Categories for Single Tacton Sessions

Source		*df*	*MS*	*F*	*p*
Category	Sphericity Assumed	2.000	814.207	4.283	.016
	Greenhouse-Geisser	1.908	853.450	4.283	.018
	Huynh-Feldt	2.000	814.207	4.283	.016
	Lower-bound	1.000	1628.413	4.283	.043
Category * Group	Sphericity Assumed	2.000	145.549	.766	.467
	Greenhouse-Geisser	1.908	152.564	.766	.462
	Huynh-Feldt	2.000	145.549	.766	.467
	Lower-bound	1.000	291.098	.766	.385
Error(Category)	Sphericity Assumed	116.000	190.105		
	Greenhouse-Geisser	110.666	199.267		
	Huynh-Feldt	116.000	190.105		
	Lower-bound	58.000	380.210		

Table 28
ANOVA for Tacton Categories for Tactile Sentences

Source		df	MS	F	p
Category	Sphericity Assumed	2.000	977.081	7.981	.001
	Greenhouse-Geisser	1.557	1255.380	7.981	.002
	Huynh-Feldt	1.619	1206.807	7.981	.001
	Lower-bound	1.000	1954.163	7.981	.006
Category * Group	Sphericity Assumed	2.000	3.761	.031	.970
	Greenhouse-Geisser	1.557	4.832	.031	.942
	Huynh-Feldt	1.619	4.645	.031	.947
	Lower-bound	1.000	7.521	.031	.861
Error(Category)	Sphericity Assumed	116.000	122.424		
	Greenhouse-Geisser	90.285	157.293		
	Huynh-Feldt	93.918	151.207		
	Lower-bound	58.000	244.847		

Table 29
ANOVA for Training Transfer

Source			*df*	*MS*	*F*	*p*
TrainingTransfer	AccuracySingle	Sphericity Assumed	1.000	426.576	6.355	.014
		Greenhouse-Geisser	1.000	426.576	6.355	.014
		Huynh-Feldt	1.000	426.576	6.355	.014
		Lower-bound	1.000	426.576	6.355	.014
	AccuracySentences	Sphericity Assumed	1.000	.250	.002	.964
		Greenhouse-Geisser	1.000	.250	.002	.964
		Huynh-Feldt	1.000	.250	.002	.964
		Lower-bound	1.000	.250	.002	.964
Error(TrainingTransfer)	AccuracySingle	Sphericity Assumed	59.000	67.121		
		Greenhouse-Geisser	59.000	67.121		
		Huynh-Feldt	59.000	67.121		
		Lower-bound	59.000	67.121		
	AccuracySentences	Sphericity Assumed	59.000	119.083		
		Greenhouse-Geisser	59.000	119.083		
		Huynh-Feldt	59.000	119.083		
		Lower-bound	59.000	119.083		

Table 30
ANOVA for Classification Accuracy and Confidence of Individual Tactons by Syntax

Source			*df*	*MS*	*F*	*p*
Syntax	Accuracy	Sphericity Assumed	1.000	62.139	.432	.513
		Greenhouse-Geisser	1.000	62.139	.432	.513
		Huynh-Feldt	1.000	62.139	.432	.513
		Lower-bound	1.000	62.139	.432	.513
	Confidence	Sphericity Assumed	1.000	.443	1.253	.267
		Greenhouse-Geisser	1.000	.443	1.253	.267
		Huynh-Feldt	1.000	.443	1.253	.267
		Lower-bound	1.000	.443	1.253	.267
Error(Syntax)	Accuracy	Sphericity Assumed	59.000	143.692		
		Greenhouse-Geisser	59.000	143.692		
		Huynh-Feldt	59.000	143.692		
		Lower-bound	59.000	143.692		
	Confidence	Sphericity Assumed	59.000	.354		
		Greenhouse-Geisser	59.000	.354		
		Huynh-Feldt	59.000	.354		
		Lower-bound	59.000	.354		
Tacton	Accuracy	Sphericity Assumed	9.000	2236.150	5.533	.000
		Greenhouse-Geisser	3.171	6347.540	5.533	.001
		Huynh-Feldt	3.372	5969.080	5.533	.001
		Lower-bound	1.000	20125.354	5.533	.022
	Confidence	Sphericity Assumed	9.000	4.197	6.169	.000
		Greenhouse-Geisser	2.990	12.635	6.169	.001
		Huynh-Feldt	3.167	11.928	6.169	.000
		Lower-bound	1.000	37.775	6.169	.016
Error(Tacton)	Accuracy	Sphericity Assumed	531.000	404.171		
		Greenhouse-Geisser	187.064	1147.280		
		Huynh-Feldt	198.924	1078.876		
		Lower-bound	59.000	3637.538		
	Confidence	Sphericity Assumed	531.000	.680		
		Greenhouse-Geisser	176.391	2.048		
		Huynh-Feldt	186.849	1.934		
		Lower-bound	59.000	6.123		
Syntax * Tacton	Accuracy	Sphericity Assumed	9.000	57.272	1.045	.403
		Greenhouse-Geisser	5.371	95.961	1.045	.393
		Huynh-Feldt	5.972	86.307	1.045	.396
		Lower-bound	1.000	515.447	1.045	.311
	Confidence	Sphericity Assumed	9.000	.123	1.449	.164
		Greenhouse-Geisser	5.149	.215	1.449	.205
		Huynh-Feldt	5.699	.195	1.449	.198
		Lower-bound	1.000	1.109	1.449	.233
Error(Syntax*Tacton)	Accuracy	Sphericity Assumed	531.000	54.801		
		Greenhouse-Geisser	316.913	91.820		
		Huynh-Feldt	352.364	82.582		
		Lower-bound	59.000	493.205		
	Confidence	Sphericity Assumed	531.000	.085		
		Greenhouse-Geisser	303.767	.149		
		Huynh-Feldt	336.259	.134		
		Lower-bound	59.000	.765		

Table 31
ANOVA for Classification Accuracy, Reaction Time, and Confidence for Syntax

Source			*df*	*MS*	*F*	*p*
Syntax	Accuracy	Sphericity Assumed	1.000	741.922	20.750	.000
		Greenhouse-Geisser	1.000	741.922	20.750	.000
		Huynh-Feldt	1.000	741.922	20.750	.000
		Lower-bound	1.000	741.922	20.750	.000
	RT	Sphericity Assumed	1.000	30210.133	.330	.568
		Greenhouse-Geisser	1.000	30210.133	.330	.568
		Huynh-Feldt	1.000	30210.133	.330	.568
		Lower-bound	1.000	30210.133	.330	.568
	Confidence	Sphericity Assumed	1.000	.003	.078	.780
		Greenhouse-Geisser	1.000	.003	.078	.780
		Huynh-Feldt	1.000	.003	.078	.780
		Lower-bound	1.000	.003	.078	.780
Syntax * Group	Accuracy	Sphericity Assumed	1.000	37.969	1.062	.307
		Greenhouse-Geisser	1.000	37.969	1.062	.307
		Huynh-Feldt	1.000	37.969	1.062	.307
		Lower-bound	1.000	37.969	1.062	.307
	RT	Sphericity Assumed	1.000	27060.033	.295	.589
		Greenhouse-Geisser	1.000	27060.033	.295	.589
		Huynh-Feldt	1.000	27060.033	.295	.589
		Lower-bound	1.000	27060.033	.295	.589
	Confidence	Sphericity Assumed	1.000	.006	.154	.696
		Greenhouse-Geisser	1.000	.006	.154	.696
		Huynh-Feldt	1.000	.006	.154	.696
		Lower-bound	1.000	.006	.154	.696
Error(Syntax)	Accuracy	Sphericity Assumed	58.000	35.756		
		Greenhouse-Geisser	58.000	35.756		
		Huynh-Feldt	58.000	35.756		
		Lower-bound	58.000	35.756		
	RT	Sphericity Assumed	58.000	91580.743		
		Greenhouse-Geisser	58.000	91580.743		
		Huynh-Feldt	58.000	91580.743		
		Lower-bound	58.000	91580.743		
	Confidence	Sphericity Assumed	58.000	.038		
		Greenhouse-Geisser	58.000	.038		
		Huynh-Feldt	58.000	.038		
		Lower-bound	58.000	.038		

Table 32
ANOVA for Classification Accuracy, Reaction Time, and Confidence for WI Groups

Source		*df*	*MS*	*F*	*p*
Intercept	Accuracy	1.00	981766.008	3159.473	.000
	RT	1.00	38400847.408	80.723	.000
	Confidence	1.00	5045.330	4372.421	.000
Group	Accuracy	1.00	100.833	.324	.571
	RT	1.00	2307136.008	4.850	.032
	Confidence	1.00	.034	.029	.864
Error	Accuracy	58.00	310.737		
	RT	58.00	475709.713		
	Confidence	58.00	1.154		

Table 33
ANOVA for Workload by Syntax

Source			*df*	*MS*	*F*	*p*
Syntax	MentalDemand	Sphericity Assumed	1	1171.875	10.892	.002
		Greenhouse-Geisser	1	1171.875	10.892	.002
		Huynh-Feldt	1	1171.875	10.892	.002
		Lower-bound	1	1171.875	10.892	.002
	PhysicalDemand	Sphericity Assumed	1	30.000	.240	.626
		Greenhouse-Geisser	1	30.000	.240	.626
		Huynh-Feldt	1	30.000	.240	.626
		Lower-bound	1	30.000	.240	.626
	TemporalDemand	Sphericity Assumed	1	.833	.008	.931
		Greenhouse-Geisser	1	.833	.008	.931
		Huynh-Feldt	1	.833	.008	.931
		Lower-bound	1	.833	.008	.931
	Effort	Sphericity Assumed	1	1505.208	9.969	.003
		Greenhouse-Geisser	1	1505.208	9.969	.003
		Huynh-Feldt	1	1505.208	9.969	.003
		Lower-bound	1	1505.208	9.969	.003
	Frustration	Sphericity Assumed	1	630.208	3.029	.087
		Greenhouse-Geisser	1	630.208	3.029	.087
		Huynh-Feldt	1	630.208	3.029	.087
		Lower-bound	1	630.208	3.029	.087
	Performance	Sphericity Assumed	1	725.208	17.154	.000
		Greenhouse-Geisser	1	725.208	17.154	.000
		Huynh-Feldt	1	725.208	17.154	.000
		Lower-bound	1	725.208	17.154	.000
	Global	Sphericity Assumed	1	403.443	11.726	.001
		Greenhouse-Geisser	1	403.443	11.726	.001
		Huynh-Feldt	1	403.443	11.726	.001
		Lower-bound	1	403.443	11.726	.001
Syntax * Group	MentalDemand	Sphericity Assumed	1	25.208	.234	.630
		Greenhouse-Geisser	1	25.208	.234	.630
		Huynh-Feldt	1	25.208	.234	.630
		Lower-bound	1	25.208	.234	.630
	PhysicalDemand	Sphericity Assumed	1	30.000	.240	.626
		Greenhouse-Geisser	1	30.000	.240	.626
		Huynh-Feldt	1	30.000	.240	.626
		Lower-bound	1	30.000	.240	.626
	TemporalDemand	Sphericity Assumed	1	120.000	1.083	.302
		Greenhouse-Geisser	1	120.000	1.083	.302
		Huynh-Feldt	1	120.000	1.083	.302
		Lower-bound	1	120.000	1.083	.302
	Effort	Sphericity Assumed	1	175.208	1.160	.286
		Greenhouse-Geisser	1	175.208	1.160	.286
		Huynh-Feldt	1	175.208	1.160	.286
		Lower-bound	1	175.208	1.160	.286

	Frustration	Sphericity Assumed	1	91.875	.442	.509
		Greenhouse-Geisser	1	91.875	.442	.509
		Huynh-Feldt	1	91.875	.442	.509
		Lower-bound	1	91.875	.442	.509
	Performance	Sphericity Assumed	1	385.208	9.111	.004
		Greenhouse-Geisser	1	385.208	9.111	.004
		Huynh-Feldt	1	385.208	9.111	.004
		Lower-bound	1	385.208	9.111	.004
	Global	Sphericity Assumed	1	51.130	1.486	.228
		Greenhouse-Geisser	1	51.130	1.486	.228
		Huynh-Feldt	1	51.130	1.486	.228
		Lower-bound	1	51.130	1.486	.228
Error(Syntax)	MentalDemand	Sphericity Assumed	58	107.593		
		Greenhouse-Geisser	58	107.593		
		Huynh-Feldt	58	107.593		
		Lower-bound	58	107.593		
	PhysicalDemand	Sphericity Assumed	58	124.828		
		Greenhouse-Geisser	58	124.828		
		Huynh-Feldt	58	124.828		
		Lower-bound	58	124.828		
	TemporalDemand	Sphericity Assumed	58	110.848		
		Greenhouse-Geisser	58	110.848		
		Huynh-Feldt	58	110.848		
		Lower-bound	58	110.848		
	Effort	Sphericity Assumed	58	150.984		
		Greenhouse-Geisser	58	150.984		
		Huynh-Feldt	58	150.984		
		Lower-bound	58	150.984		
	Frustration	Sphericity Assumed	58	208.024		
		Greenhouse-Geisser	58	208.024		
		Huynh-Feldt	58	208.024		
		Lower-bound	58	208.024		
	Performance	Sphericity Assumed	58	42.277		
		Greenhouse-Geisser	58	42.277		
		Huynh-Feldt	58	42.277		
		Lower-bound	58	42.277		
	Global	Sphericity Assumed	58	34.406		
		Greenhouse-Geisser	58	34.406		
		Huynh-Feldt	58	34.406		
		Lower-bound	58	34.406		

Table 34
ANOVA for Workload by WI Group

Source		*df*	*MS*	*F*	*p*
Intercept	MentalDemand	1	471880.208	390.028	.000
	PhysicalDemand	1	94640.833	100.593	.000
	TemporalDemand	1	255763.333	229.992	.000
	Effort	1	398476.875	368.203	.000
	Frustration	1	189210.208	113.338	.000
	Performance	1	75751.875	69.409	.000
	Global	1	224326.527	418.864	.000
Group	MentalDemand	1	21735.208	17.965	.000
	PhysicalDemand	1	22140.833	23.533	.000
	TemporalDemand	1	9187.500	8.262	.006
	Effort	1	17641.875	16.302	.000
	Frustration	1	1300.208	.779	.381
	Performance	1	460.208	.422	.519
	Global	1	9421.901	17.593	.000
Error	MentalDemand	58	1209.864		
	PhysicalDemand	58	940.833		
	TemporalDemand	58	1112.055		
	Effort	58	1082.220		
	Frustration	58	1669.432		
	Performance	58	1091.386		
	Global	58	535.560		

Table 35
ANOVA of Classification Accuracy for Sentences

Source		*df*	*MS*	*F*	*p*
NonDirectional	Sphericity Assumed	5.000	2619.772	2.427	.035
	Greenhouse-Geisser	3.175	4125.622	2.427	.063
	Huynh-Feldt	3.377	3879.274	2.427	.059
	Lower-bound	1.000	13098.859	2.427	.125
Error(NonDirectional)	Sphericity Assumed	295.000	1079.584		
	Greenhouse-Geisser	187.325	1700.131		
	Huynh-Feldt	199.221	1598.614		
	Lower-bound	59.000	5397.921		
Directional	Sphericity Assumed	3.000	590.497	3.464	.018
	Greenhouse-Geisser	2.761	641.644	3.464	.021
	Huynh-Feldt	2.910	608.775	3.464	.019
	Lower-bound	1.000	1771.491	3.464	.068
Error(Directional)	Sphericity Assumed	177.000	170.462		
	Greenhouse-Geisser	162.891	185.227		
	Huynh-Feldt	171.686	175.738		
	Lower-bound	59.000	511.386		
NonDirectional*Directional	Sphericity Assumed	15.000	276.961	1.309	.189
	Greenhouse-Geisser	9.850	421.765	1.309	.223
	Huynh-Feldt	11.984	346.669	1.309	.208
	Lower-bound	1.000	4154.422	1.309	.257
Error(NonDirectional*Directional)	Sphericity Assumed	885.000	211.559		
	Greenhouse-Geisser	581.155	322.168		
	Huynh-Feldt	707.047	264.805		
	Lower-bound	59.000	3173.384		

APPENDIX N: SUMMARY OF ALL TABLES FOR EXPERIMENT TWO

Table 36
Classification Accuracy for Individual Tactons

Syntax	Tacton	*M*	*SD*
TS	Attention	90.83	24.92
	East	96.76	5.90
	Enemy In Sight	92.36	17.65
	Move Out	87.64	22.42
	North	97.31	6.90
	Rush	84.04	29.09
	South	96.94	6.89
	Vee Formation	93.61	13.92
	Wedge Formation	89.58	13.25
	West	95.74	7.26
ST	Attention	90.21	25.12
	East	98.54	4.66
	Enemy In Sight	95.00	15.64
	Move Out	88.33	23.11
	North	97.50	6.83
	Rush	85.21	30.66
	South	95.00	11.78
	Vee Formation	92.50	19.82
	Wedge Formation	90.83	18.54
	West	96.25	7.39

Table 37
Confidence Scores for Individual Tactons

Syntax	Tacton	*M*	*SD*
TS	Attention	6.55	0.97
	East	6.59	0.71
	Enemy In Sight	6.49	1.02
	Move Out	6.23	1.28
	North	6.67	0.62
	Rush	6.16	1.33
	South	6.60	0.68
	Vee Formation	6.33	1.07
	Wedge Formation	6.30	1.10
	West	6.60	0.68
ST	Attention	6.52	1.19
	East	6.71	0.58
	Enemy In Sight	6.49	0.99
	Move Out	6.21	1.31
	North	6.66	0.66
	Rush	6.16	1.41
	South	6.63	0.66
	Vee Formation	6.48	0.94
	Wedge Formation	6.34	1.02
	West	6.70	0.57

Table 38
Classification Accuracy, Reaction Time, and Confidence for Syntax Sessions and WI Groups

		M	*SD*
Accuracy TS	WI Absent	89.44	17.25
	WI Present	86.49	13.71
	Total	87.96	15.52
Accuracy ST	WI Absent	93.29	11.74
	WI Present	92.58	8.36
	Total	92.94	10.11
Reaction Time TS	WI Absent	457.92	486.25
	WI Present	705.20	618.51
	Total	581.56	565.51
Reaction Time ST	WI Absent	396.15	565.13
	WI Present	703.50	442.96
	Total	549.83	526.73
Confidence TS	WI Absent	6.50	0.87
	WI Present	6.46	0.66
	Total	6.48	0.77
Confidence ST	WI Absent	6.50	0.85
	WI Present	6.48	0.68
	Total	6.49	0.77

Table 39
Workload for Syntax Sessions and WI Groups

Workload Subscale	WI Group	*M*	*SD*
Mental Demand TS	Absent	52.83	31.64
	Present	78.83	14.60
	Total	65.83	27.73
Mental Demand ST	Absent	45.67	33.65
	Present	73.50	16.98
	Total	59.58	29.92
Physical Demand TS	Absent	14.50	17.88
	Present	40.67	26.48
	Total	27.58	26.00
Physical Demand ST	Absent	14.50	17.49
	Present	42.67	28.37
	Total	28.58	27.34
Temporal Demand TS	Absent	36.50	28.17
	Present	56.00	23.02
	Total	46.25	27.33
Temporal Demand ST	Absent	38.33	25.10
	Present	53.83	22.19
	Total	46.08	24.75
Effort TS	Absent	47.83	32.58
	Present	74.50	16.83
	Total	61.17	29.01
Effort ST	Absent	43.17	28.54
	Present	65.00	17.52
	Total	54.08	25.93
Frustration TS	Absent	37.83	35.40
	Present	46.17	26.22
	Total	42.00	31.17
Frustration ST	Absent	35.00	34.72
	Present	39.83	24.69
	Total	37.42	29.96
Performance TS	Absent	23.83	23.84
	Present	31.33	25.39
	Total	27.58	24.71
Performance ST	Absent	22.50	24.42
	Present	22.83	21.40
	Total	22.67	22.76
Global Workload TS	Absent	35.56	19.45
	Present	54.58	13.64
	Total	45.07	19.22
Global Workload ST	Absent	33.19	19.86
	Present	49.61	13.46
	Total	41.40	18.75

Table 40
Classification Accuracy for Tactile Sentences by Non-Directional Component

Non-Directional Sentences	*M*	*SD*
Attention	90.00	25.06
Enemy In Sight	91.39	17.63
Move Out	85.83	23.18
Rush	82.78	29.27
Wedge Formation	90.56	15.83
Vee Formation	87.22	14.51

Table 41
Classification Accuracy for Tactile Sentences by Directional Component

Directional Sentences	*M*	*SD*
East	88.06	16.83
North	89.26	15.68
South	88.33	16.23
West	86.20	15.99

LIST OF REFERENCES

Anderson, R., & Ross, V. (2001). *Questions of Communication: A Practical Introduction to Theory*. New York, NY: Bedford/St. Martin's.

Barber, D. J., Leontyev, S., Sun, B., Davis, L., Nicholson, D., & Chen, J. Y. (2008). The Mixed Iniative Experimental (MIX) Testbed for Collaborative Human Robot Interactions. *Army Science Conference.* Orlando: DTIC.

Barnes, M., & Jentsch, F. (Eds.). (2010). *Human-Robot Interactions in Future Military Operations.* Ashgate.

Barnlund. (1986). *Interpersonal Communication: Survey and Studies.* Boston, MA: Houghton Mifflin.

Behrmann, M., & Ewell, C. (2003). Expertise in Tactile Pattern Recognition. *Psychological Science, 14*(5).

Berlo, D. (1960). *Process of Communication: An Introduction to Theory and Practice.* Harcourt School.

Bischoff, R., & Graefe, V. (2002). Dependable Multimodal Communication and Interaction with Robotic Assistants. *11th IEEE International Workshop on Robot and Human Interactive Communication* (pp. 300-305). IEEE.

Bowers, C., Braun, C., & Morgan, Jr., B. B. (1997). Team Workload: Its Meaning and Measurement. In M. T. Brannick, E. Salas, & C. W. Prince (Eds.), *Team Performance Assessment and Measurement: Theory, Methods, and Applications* (pp. 85-104). Psychology Press.

Brewster, B., & Brown, L. M. (2004). Tactons: Structured Tactile Messages for Non-Visual Information Display. *Austrailian User Interface Conference*, (pp. 15-23). Dunedin, New Zealand.

Brewster, S., & King, A. (2005). The Design and Evaluation of a Vibrotactile Progress Bar. *First Joint Eurohaptics Converence and Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems.* Pisa.

Brown, L. M., Brewster, S. A., & Purchase, H. C. (2006). Multidimensional Tactons for Non-Visual Information Presentation in Mobile Devices. *Eigth Conference on Human-Computer Interaction With Mobile Devices and Services*, *159*, pp. 231-238. Helsinki, Finland.

Bunt, H. (1998). Issues in Multimodal Human-Computer Communication. In H. Bunt, R. J. Beun, & T. Borghuis (Eds.), *Multimodal Human-Computer Communication: Systems, Techniques, and Experiments* (Vol. 1374, pp. 1-12). Berlin: Springer-Verlag.

Campbell, K., & Burkholder, T. (1996). *Critiques of Contemporary Rhetoric.* New York, NY: Wadsorth.

Carruthers, P. (2002). The cognitive functions of language. *Behavioral and Brain Sciences, 25*, 657-726.

Cholewiak, R., & Collins, A. (2003). Vibrotactile Localization on the Arm: Effects of Place, Space, and Age. *Perception & Psychophysics, 65*(7), 1058-1077.

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

Chomsky, N. (1957). *Syntactic Structures* (Vol. 4). The Haugue: Mouton Publishers.

Chomsky, N. (1965). *Aspects of the Theory of Syntax.* Cambridge, Massachusetts: MIT Press.

Clark, E. (1973). What's in a Word? On th Child's Acquisition of Semantics in HIs First Language. In T. Moore (Ed.), *Cognitive Development and the Acquisition of Language* (pp. 65-100). New York, NY: Academic Press.

Cohen, P., & McGee, D. (2004). Tangible Multimodal Interfaces for Safety-Critical Applications. *Communications, 47*(1), 41-46.

Collins, A., & Quillian, M. (1969). Retrieval Time from Semantic Memory. *Verbal Learning & Verbal Behavior, 8*(2), 240-247.

Cosenzo, K., Capstick, E., Pomranky, R., Dungrani, S., & Johnson, T. (2009). *Soldier Machine Interface for Vehicle Formations: Interface Design and an Approach Evaluation and Experimentation.* Aberdeen Proving Ground: U.S. Army Research Laboratory.

Dance, F. (1967). *Human Communication Theory: Original Essays.* Holt, Rinehart & Winston.

DARPA. (2007 йил 3-November). *Urban Challenge*. Retrieved 2010 йил 15-11 from DARPA: http://www.darpa.mil/grandchallenge/index.asp

Derryberry, D., & Reed, M. (2002). Anxiety-Related Attentional Biases and Their Regulation by Attentional Control. *Journal of Abnormal Psychology, 111*(2), 225-236.

Ekstrom, R. B., French, J. W., Harman, H. H., & Dermen, D. (1976). *Manual for Kit of Factor-Referenced Cognitive Tests.* Princeton, New Jersey: Educational Testing Service.

Elliot, L. R., Coovert, M. D., Prewett, M., Walvord, A. G., & Saboe, K. (2009). A Review and Meta Analysis of Vibrotactile and Visual Information Displays. 1-36. Aberdeen Proving Ground, MD, USA: U.S. Army Research Laboratory.

Elliot, L. R., Duistermaat, M., Redden, E., & Van Erp, J. (2007). *Multimodal Guidance for Land Navigation.* Aberdeen Proving Ground: U.S. Army Research Laboratory.

Endsley, M. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors, 37*(1), 32-64.

Feil-Seifer, D. J., & Matarić, M. J. (2009). Human-Robot Interaction. In R. A. Meyers (Ed.), *Encyclopedia of Complexity and Systems Science* (Vol. LXXX). Springer.

Fernald, A., & Kuhl, P. (1987). Acoustic Determinants of Infant Preference for Parentese Speech. *Infant Behavior and Development, 10*, 278-293.

Gilson, R. D., Redden, E. S., & Elliott, L. R. (2007). *Remote Tactile Displays for Future Soldiers.* Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Gleason, J. B. (2005). *The Development of Language.* Boston, MA: Pearson/Allyn and Bacon.

Gogate, L., Bahrick, L., & Watson, J. (2000). A Study of Multimodal Motherese: The Role of Temporal Synchrony Between Verbal Labels and Gestures. *Child Development, 71*, 878-894.

Goodwyn, S., Acredolo, L., & Brown, C. (2000). Impact of Symbolic Gesturing on Early Language Development. *Journal of Nonverbal Behavior*, *24*(2), 81-103.

Grey, A. A., Redden, E. S., Coovert, M. D., & Elliot, L. R. (2008). Empowering followers in virtual teams: Guiding principles from theory and practice. *Computers in Human Behavior, 24,* 1884-1906.

Griffiths, R. (1992). Speech Rate and Listening Comprehension: Further Evidence of the Relationship. (G. Weinstein-Shr, Ed.) *TESOL Quarterly, 26*(2), 385-390.

Haas, E. C. (2007). Integrating Auditory Warnings with Tactile Cues in Multimodal Displays for Challenging Environments. *13th International Conference on Auditory Displays,* (pp. 127-131). Montreal.

Haas, E. C., & Van Erp, J. B. (2010). Multimodal Research for Human-Robot Interactions. In F. Jentsch, & M. Barnes (Eds.), *Human-Robot Interactions in Future Military Operations* (pp. 271-292). Ashgate.

Hancock, P. A. (1996). On Convergent Technological Evolution. *Ergonomics in Design The Quarterly of Human Factors Applications, 4*(1), 22-29.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. (P. A. Hancock, & N. Meshkati, Eds.) *Human mental workload, 1*(3), 139-184.

Hearst, M., Allen, J., Guinn, C., & Horvitz, E. (1999). Mixed-Initiative Interaction: Trends & Controversies. *IEEE Intelligent Systems*, 14-23.

Hoff-Ginsberg, E. (1990). Maternal Speech and the Child's Development of Syntax: A Further Look. *Journal of Child Language, 19*, 85-99.

Hutchins, S., Cosenzo, K., McDermott, P., Feng, T., Barnes, M., & Gacy, M. (2009). An Investigation of the Tactile Communication Channel for Robotic Control. *Human Factors and Ergonomics Society Annual Meeting*, *53*, pp. 182-186.

iRobot. (2012, 04 20). *iRobot 510 PackBot*. Retrieved 04 20, 2012, from iRobot: http://www.irobot.com/us/robots/defense/packbot.aspx

Jackon, H., & Amvela, E. (2000). What is Lexicology? In *Words, Meaning and Vocabulary: An Introduction to Modern English Lexicology* (p. 1). New York, NY: British Library Cataloging Publication Data.

Jones, L., & Sarter, N. (2008). Tactile Displays: Guidance for Their Design and Application. *Human Factors, 50*(1), 90-111.

Kaaresoja, T., & Linjama, J. (2005). Perception of Short Tactile Pulses Generated by a Vibration Motor in a Mobile Phone. *First Joint Europhaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems,* (pp. 471-472). Pisa, Italy.

Kalat, J. (2008). *Introduction to Psychology.* Belmot, CA, USA: Wadsworth Publishing.

Kinsbourne, M., & Wallace, L. S. (1974). *Hemispheric Disconnection and Cerebral Function.* C. C. Thomas.

Knecht, S., Deppe, M., Drager, B., Bobe, L., Lohmann, H., Ringelstein, E. B., et al. (2000). Language Lateralization in Healthy Right-Handers. *Brain, 123*(1), 74-81.

Kowalski, R., & Westen, D. (n.d.). *Psychology.* John Wiley & Sons.

Kvale, K., Wrakagoda, N., & Knudsen, J. (2003). Speech Centric Multimodal Interfaces for Mobile Communication. *Telektronikk, 2*, 104-117.

Lackey, S. J., Barber, D. J., Reinerman-Jones, L., Badler, N., & Hudson, I. (2011). Defining Next-Generation Multi-modal Communication in Human-Robot Interaction. *Human Factors and ERgonomics Society Conference.* Las Vegas: HFES.

Louwerse, M. M., Jeuniaux, P., Hoque, M. E., Wu, J., & Lewis, G. (n.d.). Multimodal Communication in Computer-Mediated Map Task Scenarios. In R. S, & N. M (Ed.), *28th Annual Conference of the Cognitive Science Society* (pp. 1717-1722). Mahwah, NJ: Erlbaum.

Magnuson, S. (2011, February 2). *"Robot Army" in Afghanistan surgest past 2,000 units.* Retrieved 04 15, 2012, from National Defense Magazine: http://www.nationaldefensemagazine.org/blog/Lists/Posts/Post.aspx?ID=300

Marcotte, A., & Morere, D. (1980). Speech Lateralization in Deaf Populations: Evidence for a Developmental Critical Period. *Brain and Language*, *39*(1), 134-152.

Mariani, J. (2000, 04 05). *Spoken Language Processing and Multimodal Communication : A View from Europe.* Retrieved 04 14, 2011, from http://www.ifp.illinois.edu/nsfhcs/talks/mariani.html

McDonald, J. (1997). Language Acquisition: The Acquisition of Linguistic Structure in Normal and Speical Populations. *Annual Review of Psychology, 48*(1), 215-241.

Merlo, J. L., Terrence, P. I., Stafford, S., Gilson, R., Hancock, P. A., Redden, E. S., et al. (2006). Communicating Through the Use of Vibrotactile Displays for Dismounted and Mounted Soldiers. *25th Army Science Conference.* Orlando.

Messer, D. (1994). *The Development of Communication: From Social Interaction to Language* (1 ed.). New York, NY: John Wiley & Sons.

Mohebbi, R., Gray, R., & Tan, H. (2009). Driver Reaction Time to Tactile and Auditory Rear-End Collision Warnings While Talking on a Cell Phone. *The Journal of the Human Factors and Ergonomics Society, 51*(1), 102-110.

Mortimer, B. J., Zets, G. A., & Cholewiak, R. W. (2007). Vibrotactile Transduction and Transducers. *Acoustical Society of America, 121*(5), 2970-2977.

Mortimer, B., Zets, G., Mort, G., & Shovan, C. (2011). Implementing Effective Tactile Symbology for Orientation and Navigation. In J. A. Jacko (Ed.), *HCI 3* (Vol. 6763, pp. 321-328). Orlando, Florida, United States of America: Springer.

Newport, E. (1990). Maturational Constraints on Language Learning. *Cognitive Science, 14*, 11-28.

Nigay, L., & Coutaz, J. (1993). A Design Space for Multimodal Systems: Concurrent Processing and Data Fusion. *INTERACT'93 and CHI'93 Conference on Human Factors in Computing Systems*, (pp. 172-178).

Office of the Secretary of Defense. (2007). *Unmanned Systems Roadmap: 2007-2032*. Office of the Undersecretary of Defense for Acquisition, Technology, and Logistics, Unmanned Warfare Division. U.S. Department of Defense.

Oviatt, S. (2002). Breaking the Robustness Barrier: Recent progress on the design of robust multimodal systems. *Advances in Computers*, *56*, 305-341.

Parr, L. (2004). Perceptual Biases for Multimodal Cues in Chimpanzee (Pan troglodytes) Affect Recognition. *Animal Cognition*, *7*, 171-178.

Partan, S., & Marler, P. (1999, February 26). Communication Goes Multimodal. *Science, 283*(5406), 1272-1273.

Pettitt, R., E.S., R., & Carsten, C. (2009). Scalablity of Robotic Controllers: Speech-based Robotic Controller Evaluation (ARL-TR-4858). *Aberdeen Proving Ground, MD: US Army Research Laboratory*, 1-46.

Pettitt, R., Redden, E. S., & Carstens, C. (2006). *Comparison of Army Hand and Arm Signals to a Covert Tactile Communication System in a Dynamic Environment.* Aberdeen Proving Grounds: U.S. Army Research Laboratory.

Raisamo, R. (1999). Multimodal Human-Computer Interaction: A Constructive and Empirical Study. Tampere, Finland: University of Tampere.

Redden, E., & Elliot, L. (2010). Robotic Control Systems for Dismounted Soldiers. In F. G. Jentsch, & M. J. Barnes (Eds.), *Human-Robot Interactions in Future Military Operations* (pp. 335-352). Ashgate.

Rehfeld, S. A. (2006). The Impact of Mental Transformation Training Across Levels of Automation On Spatial Awareness in Human-Robot Interaction. *The Impact of Mental Transformation Training Across Levels of Automation On Spatial Awareness in Human-Robot Interaction*. Orlando, FL, USA: University of Central Florida.

Tanenhaus, M. (1988). Psycholoinguistics: an overview. (F. Newmeyes, Ed.) *3*, 1-37.

Thiran, J.-P., Marqués, F., & Bourlard, H. (2009). *Multimodal Signal Processing: Theory and applications for human-computer interaction.* San Diego, CA: Academic Press.

U.S. Army. (1987, September 30). Visual Signals. *Visual Signals: FM 21-60*. Washington, DC: U.S. Army.

U.S. Army Research Laboratory. (2011, June 1). *Robotics.* Retrieved April 20, 2012, from U.S. Army Research Laboratory: http://www.arl.army.mil/www/default.cfm?page=392

U.S. Congress. (2001). National Defense Authorization Act for Fiscal Year 2001. *National Defense Authorization Act for Fiscal Year 2001*. Washington, D.C.

Varcholik, P., Barber, D., & Nicholson, D. (2008). Interactions and Training with Unmanned Systems and the Nintendo Wiimote. *Interservice/Industry Training, Simulation, and Education Conference.* Orlando: (I/ITSEC).

Vitello, M. P., Ernst, M. O., & Fritschi, M. (2006). An Instance of Tactile Suppression: Active Exploration Impairs Tactile Sensitivity for the Direction of Lateral Movement. *EuroHaptics Conference*, (pp. 351-355). Paris.

Wexelblat, A. (1995). An approach to natural gesture in virtual environments. *ACM Transaction on Computer-Human Interaction, 2*(3), 179-200.

White, T. (2010). *Suitable Body Locations and Vibrotactile Cueing Types for Dismounted Soldiers.* Aberdeen Proving Grounds, MD: U.S. Army Research Laboratory.

White, T. (2011). *The Perceived Urgency of Tactile Patterns.* Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Wickens, C. D., & Hollands, J. G. (2000). Attention, Time-Sharing, and Workload. In C. D. Wickens, J. G. Hollands, N. Roberts, & B. Webber (Eds.), *Engineering Psychology and Human Performance* (Vol. 3, pp. 439-479). Upper Saddle River, New Jersey, USA: Prentice-Hall Inc.

Williams, J. R. (1998). Guidelines for the Use of Multimedia in Instruction. *Human Factors and Ergnomics Society Annual Meeting*, *42*, pp. 1447-1451.

Write, R., Thompson, W., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review*, *15*(4), 763-771.