DESIGN AND VALIDATION OF VIBROTACTILE COMMUNICATIONS FOR DYNAMIC ENVIRONMENTS

A Dissertation

by

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ABSTRACT

Vibrotactile displays are advantageous in task environments where visual and auditory channels are saturated or environmentally undesirable. These immediate, private stimuli are tied to our cognitive embodiment and well-suited for providing physical directions and speeded signals under cognitive workload and reducing competition for shared mental resources. However, these strengths depend on the development of robust communication systems. Highly dynamic domain environments necessitate error management, which pushes cognition into increasingly slow, reflective modes where touch is less beneficial. The design of vibrotactile displays should either focus development on more limited domains or face the sizeable challenge of developing an adaptable vibrotactile language to handle unanticipated changes.

This work advances the science of vibrotactile display development by demonstrating that superior resolution can be achieved through temporal overlap and the saltation illusion and, second, by establishing a method for the development of ordinal signals via subjective intensity ratings. It also demonstrates that more embodied interfaces, (i.e.: touch and gesture), provide shorter, more direct communication for speeded physical tasks by shortening the "Gulf of Action". Finally, it provides evidence that vibrotactile interfaces are useful as alerting systems under cognitive load, particularly for general aviation contexts, but also other highly demanding environments where graded warnings may improve situation awareness during demanding primary tasks.

DEDICATION

I would like to dedicate this research to my wife, Erin, and my daughter, Petra.

To Erin, for all the years of devotion: the support when I needed to persevere and criticism when change was needed. I could not ask for a better companion in all of this.

To Petra, who has brought so much joy into my life, and whose exuberant spirit and enthusiasm for all things lends purpose.

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I would like to thank my each of my committee members. Dr. Benden for teaching the skills and perspectives to be a professional. Dr. Quek for always being equally willing to discuss both the human and philosophical impacts of our work. Jim, for his years of wisdom in understanding where plans fail when facing reality and for providing support when I was most at risk. Finally, Dr. Ferris, for taking a chance on developing this enthusiastic undergrad and guiding him on the path he’d been seeking for so long.

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NOMENCLATURE

ART	Align-and-Rank Test
ERM	Eccentric rotating mass actuator
FAA	Federal Aviation Administration
GEE	Generalized Estimating Equations
GLMM	Generalized Linear Mixed Models
HFES	Human Factors and Ergonomics Society
HMI	Human-Machine Interaction, also sometimes referred to as Human Computer Interface (HCI)
IFR	Instrument flight rules
LRA	Linear resonant actuator
MRT	Multiple-resource theory, as initially described by Wickens (2002)
PEGASAS	Partnership to Enhance General Aviation Safety, Accessibility, & Sustainability
SRK	Skill, Rule, Knowledge Framework, a model to assess cognitive state by Rasmussen (1983)
TCAT	Texas Center for Applied Technology
VFR	Visual flight rules
VMC	Visual meteorological conditions

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CHAPTER I

INTRODUCTION

I.1 Motivation

In an increasingly complex world, humans connect to reality through varied information channels. While we have a strong understanding of how to design for our eyes and ears, we are still exploring effective uses for our sense of touch, the sense most closely linked to physical embodiment.

Vibrotactile technologies may improve both our understanding of both the world around us and the motion of our own bodies without disrupting other tasks. However, such technologies must communicate in a way that can be readily understood without labored, time-intensive cognition that can distract from the task at hand. To accomplish this, technologies must be timely, context appropriate, and adapt to any changes in the use environment.

I.2 Contribution

This thesis establishes evidence supporting the efficacy of vibrotactile systems design to support cognitive workload in challenging environments. Further, it establishes methods and processes for the design and evaluation of vibrotactile communication systems.

I.3 Organization

This thesis consists of nine chapters. Chapter II is a literature review focusing on the techniques and theoretical underpinnings of vibrotactile technologies and their current roles and limitations as communication devices. Chapter III covers research questions. Chapters

IV, V, & VI each cover a specific experiment to address these research questions. Chapter VII addresses important theoretical progress made following the work of previous chapters. Chapter VIII covers paired experiments to determine recommendations for the design and implementation of vibrotactile weather technology warning interfaces for general aviation pilots. Chapter IX summarizes the body of work and provides suggestion for future lines of inquiry.

I.4 Previous Publications

This work is the aggregate product of an extended research project and portions have been previously published. Chapter IV is adapted from work performed as an Undergraduate Research Scholars project and can be found in (T. Roady & Ferris, 2012) and (W. Roady, 2012). Chapter V has been adapted from (T. Roady & Ferris, 2013). Finally, Chapter VI is drawn from (T. Roady, Tippey, & Ferris, 2014).

CHAPTER II

LITERATURE REVIEW

The skin is not only the largest organ of the human body, but it is also the first sensory system to develop in most animals and in infants (Montagu, 1978). Touch mentally anchors our bodies in space, serving as a marker of where we stop and where our environment begins. It is also the sense we first use to explore our physical worlds and to soothe us when we are troubled, serving not only as a calibration for our developing visuo-spatial system (Hebb, 1949; MacLean, 2008; Piaget & Inhelder, 1956), but also serves to stimulate and encourage our physical development (Montagu, 1978).

Even the language we use conflates the sense of touch with relevance and closeness. We will say that something “touched us” when it has made a strong emotional impression, or that something “gave us chills”. It is difficult to consider something that immediately affects our sense of touch and yet remains distant or unrelated from us.

II.1 Uses of Touch

Touch is an ever-present source of environmental sensory data. Sensation is provided by thermoreceptors, which tell hot and cold; nociceptors, which determine pain from mechanical, thermal, or chemical stimuli; proprioceptors, which identify body location through muscle length and tension; and mechanoreceptors, which sense pressure, vibration, and texture. Mechanoreceptors come in four different varieties: Ruffini’s corpuscles, Merkel’s disks, Meissner’s corpuscles, and Pacinian corpuscles (Wickens, Hollands, Banbury, & Parasuraman, 2015). Pacinian corpuscles are sensitive to small, rapid changes in small areas of the skin, and have an optimal sensory frequency of around 250 hertz

(Makous, Friedman, & Vierck, 1995; Shimoga, 1992; Verrillo, 1966), and serve as the primary sensory organ for many vibrotactile interfaces, including those used here.

II.1.1 Exploration of Immediate Physical Space

Touch is not merely a passive sense, receiving information from the environment, but seeks out sensation to match our goals and to calibrates our other senses, demonstrating bi-directionality (Jones & Lederman, 2006). Exploratory, or active touch, is a key component of locating the body in physical space.

If tools perform this exploratory touch, the brain integrates these inanimate objects into its model of the body, extending peripersonal space (Cardinali et al., 2009; Farnè & Làdavas, 2000). This can be shown as a primary goal of haptics, shown in the "idealized teleoperator" of Lawrence and Chapel (1994).

This can be inverted as a form of communication, physically steering someone else, using the same sense as subject instead of object. This has been leveraged for snowboarding training (Spelmezan, Jacobs, Hilgers, & Borchers, 2009), kinesthetic learning (Lieberman & Breazeal, 2007), and to orient the attention of blind students in math instruction lectures by providing substituting visual attention direction cues with vibratory ones (Oliveira, Quek, Cowan, & Fang, 2012).

II.1.2 Interpersonal Coordination

Carrying a couch or dancing with a partner cannot simply be viewed as each individually performing their own action. Proprioception is used as a communication interface for dyads, allowing us to locate not only our bodies, but the bodies of others in space as a linked system (van der Wel, Knoblich, & Sebanz, 2011), with either participant taking turns between leading and following (Evrard & Kheddar, 2009). Research has shown that timing and coordination of actions is broken up into different tasks based on the task's characteristics. Even in cases where the cooperative linkage isn't proprioceptive, there is demonstrable improvement in motor function following a coordinated dyad task (Ganesh et al., 2014).

Work has shown promise in utilizing multimodal haptic feedback to provide coordination on cooperative motor and virtual tasks.(K. B. Reed et al., 2006; Simard & Ammi, 2010)

II.1.3 Attention Direction

The sense of touch also directly reorients attention, such as bumping into furniture while walking. This is also seen where individuals are mentally overloaded, going through shock, or otherwise experiencing cognitive tunneling. Touch can be used to help bring attention back to current conditions and to re-anchor the experience in the body through simple touching or shaking by another. When inattention is much larger, the physical sensation may also compensate, such as the cultural trope of a "slap to the face".

Many driving and flying studies use this component to compensate for operator workload (Ho, Tan, & Spence, 2005; Prewett, Elliott, Walvoord, & Coovert, 2012; Scott & Gray, 2008). Similar applications have been found for providing warning for inattentive pedestrians and into improve industrial worker safety through awareness of approaching forklifts (A. Marsalia, 2013; A. C. Marsalia, Ferris, Benden, & Zheng, 2016).

II.1.4 Symbolic Representation

While touch is not naturally used for pure symbolic, representational language, many different approaches have adapted it to that purpose, the most obvious being Braille and Morse code. Additionally, more recent creations such as Tadoma (C. M. Reed et al., 1985) and Vibratese (Geldard, 1957) have demonstrated effective language capability. While these methods have demonstrated breadth of their communication, they remain dependent on a high cognitive demand and substantial training, are inappropriate for performance-based applications, and focus heavily on a System 2 cognition that's largely artificial from the natural, evolved role of touch.

II.1.5 Navigation

While not enjoying widespread use, haptic navigation has been reasonably successful in experimental testing. Of particular interest are the offloading of visual resources onto those of touch, either due to the importance situational awareness maintenance in military tasks, for the blind, or for motorcycle navigation. (Cummings et al., 2012; Elliott, van Erp, Redden, & Duistermaat, 2010; Jones, Lockyer, & Piateski, 2006; Prasad, Taele, Goldberg, & Hammond, 2014; Tsukada & Yasumura, 2004; van Erp, van Veen, Jansen, & Dobbins, 2005). Some of the most heavily-validated work has been performed by the Army Research Lab and a decent overview can be found in Elliott, Schmeisser, and Redden (2011).

II.2 Dimensions of Vibrotactile Stimuli

While many haptic technologies exist, they may be broken down into several different interface categories: force-feedback, surface displays, tactile, and vibrotactile (Hayward & Maclean, 2007). While many different haptic applications are available for the former categories, this work will focus on evaluation of vibrotactile devices.

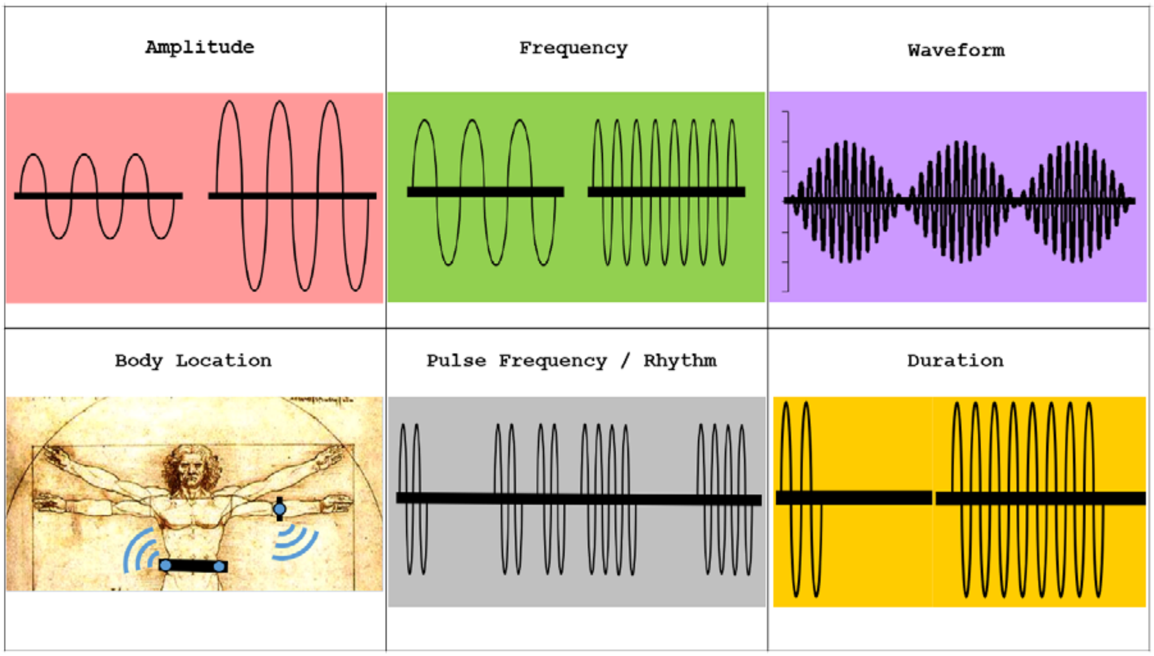

Figure 1. Dimensions of vibrotactile stimuli

Vibrotactile stimuli are distinguished by six different dimensions (Figure 1). While body location is self-explanatory, waveform properties are potentially best understood through musical analogy, in which signal development can be viewed as composition. Amplitude is the volume of the music, with a higher amplitude resulting in a “louder” signal. Each individual note has both a frequency, or pitch, and a duration. Pulse frequency / rhythm is how the notes are grouped. Finally, waveform can be viewed as the timbre of the instrument, itself. Manipulation of these components allows for designers to compose unique, recognizable vibrotactile stimuli for use in an interface.

II.3 Claims of Haptic Technology

Haptic technology promises to achieve several particular goals to improve interface design. While we’ve addressed Geldard’s (1957) claim that touch is attention-grabbing, but his claim remains true that touch is still an underutilized input system. Not only does it provide a remarkable amount of information in natural environments, but it is also the least applied in digital interactions.

Wickens's (2002) Multiple Resource Theory (MRT) suggests a differentiation in available mental resources for different types of cognitive tasks. The less these tasks overlap in demanded resources, the less they will interfere with each other. This explains, for instance, why one can have a conversation on the phone and cook dinner, while attempting the same conversation with background music may be more difficult. Likewise, if we provide information in a different sensory modality, the task of interpreting the information may prove less difficult to accomplish alongside related domain tasks. Also, if visual and auditory demands are offloaded onto the sense of touch, it may improve overall performance by balancing out demands across limited cognitive resources (T. Ferris & N. Sarter, 2011; Sklar & Sarter, 1999).

Touch also benefits from proximality: signals are presented directly to the body. Messages can be sent directly to the individual without those nearby sensing the same message (Jones & Sarter, 2008). Messages can be tailored directly to individuals within groups without confusion as to intended recipient.

When communicating information that requires spatial and temporal discrimination, it also shows a higher spatial resolution that audition and higher temporal resolution than vision (Sherrick & Cholewiak, 1986).

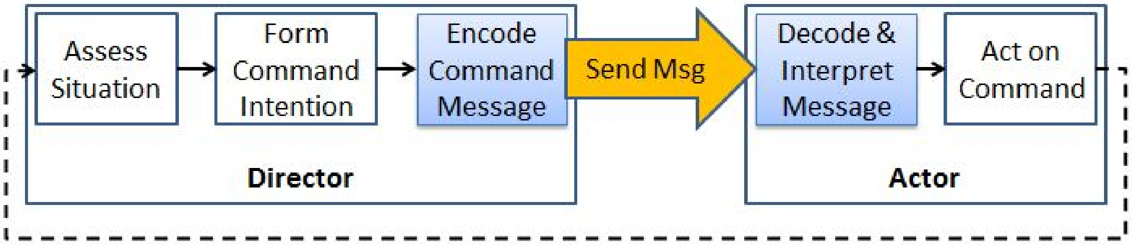

Figure 2. Message-driven communication model

Based off of the implications of the embodiment of touch, the initial claim of my first three studies, Chapters IV, V, and VI, is that touch is more effective for identifying physical tasks, easing the sensory transformation of messages by reducing the gulf of action (T. Roady & Ferris, 2013). If communication can be simply described as the sending and receiving of messages, in accordance with Figure 2, then this would manifest as the shortening of the message encoding and decoding components.

However, Chapter VI's results necessitate a conceptual reframing to account for engineering systems for a complex environment. This will be discussed in Chapter VII.

CHAPTER III

RESEARCH QUESTIONS

Vibrotactile interfaces are of interest for domains in which either of two things are true: mental resources are already highly saturated or there is a strong benefit for signal redundancy. For a vibrotactile system to effectively support multimodal communication, it must be timely, context-appropriate, and adapt to environmental changes while in use. For these reasons, I forward the following two central guiding questions:

Theme 1: What are the limits of vibrotactile communication as a function of cognitive workload?

Theme 2: Can psychophysical design methods be used to create a viable set of vibrotactile stimuli for an environment described by these traits?

However, as these are definitively general, it is necessary to specify them in more testable forms. While there may be other ways to define the first two questions, these reflect the thought process which was applied in the development of the included studies.

Question 1: How do you manipulate tactile dimensions to design perceptually distinguishable sets?

This was the focus for Chapter IV and the first study in Chapter VIII. The former measured the interaction of rhythm and body location, while the latter focused on rhythm, duration, and frequency. Better designed signal sets should result in performance improvements in application.

Question 2: Do more embodied communication systems improve performance in speeded, cooperative tasks?

Chapters V and VI addressed this by comparing gestural systems, graphical interfaces, vibrotactile stimuli, and verbal instructions. Using more natural, less symbolic interfaces should ease the amount of time and effort needed to interpret them.

Question 3: How does cognitive workload affect the perceptibility of vibrotactile displays?

Chapters V and VI looked at the viability for speeded cooperative action. The last study in Chapter VIII considered applications to weather information interfaces for GA. Vibrotactile interfaces should utilize different resources than other modalities and prevent interference with data from other interfaces.

CHAPTER IV*

SIGNAL INFORMATION AND TEMPORAL OVERLAP

IV.1 Introduction

For tactile navigation displays and other tactile messaging systems, most applications focus on the use of predefined symbols encoded in tactile patterns. These symbols must have a learned association, and the steepness of the learning curve reflects the complexity and abstractness of the pattern (MacLean, 2008). In addition to the need to consider training time and learning curve effects, these systems are relatively inflexible when the display system might be used for a different application, as this would require reprogramming of all stimuli and the retraining of users. An alternative approach to avoid existing systems limitations is to allow user-defined patterns to be created for each application.

Humans can be remarkably creative when they must improvise ways to communicate with each other through nontraditional channels. For example, high-level messages can be communicated between two people without a common spoken language through expressive body language and gesturing. Perhaps this creativity can be harnessed for person-to-person tactile communications by designing tactile displays that support open-ended and expressive patterns to be composed by a "director" and presented to a "actor". The communicator/receiver team may establish pattern meanings during a grounding session or

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can improvise by exploiting universal and intuitive conventions that are already firmly established in haptic communications. For example, very little, if any, training would be required for the communicator or receiver to direct the receiver's attention to an area of space by tapping them on the shoulder.

With this design philosophy in mind, we've pursued the development of the Creative Haptic Interaction At-a-Distance (CHIAD) communication to allow two users to create and communicate quick, intuitive messages and support speeded interpretation and initiation of response for a cooperative task. By supporting haptic communication from both the message sender (via gesture-based controls) and the receiver (via spatially- and intensity-mapped vibration patterns), this system will shorten the instruction/response loop for time-critical coordination. Example applications for such a system include military or emergency firefighting operations. Commanders can use natural gesturing to quickly and intuitively relay navigation instructions to deployed soldiers/firefighters, who can then quickly and intuitively act on them. The seconds or fractions of seconds that can be saved during both the message encoding/sending and receiving/interpreting ends of the communication timeline could be the difference between safe navigation of a hostile environment and putting the soldier/firefighter at great risk of harm.

The first design iteration of the CHIAD display system focuses on navigation applications. In developing this system, there are some questions that need to be addressed. Of primary concern is how performance will relate to the level of signal complexity that is possible, for example, whether only single cardinal/intermediate directions or a complex sequence of such directions can be effectively interpreted. Another consideration is which vibration patterns best support signal perception and interpretation. Finally, if presentations of various levels of complexity are best supported by specific patterns, is there a tradeoff in the required signal duration? In other words, if a signal must be presented over a longer duration in order to assure it is reliably communicated, how does this affect the overall communication time?

Several studies have addressed these questions individually but few, if any, have looked at their combination. Additionally, most previous studies have measured the effectiveness of vibrotactile patterns in terms of accuracy; however, few have analyzed both accuracy and response time measures. This study will look at both measures to infer the efficiency of presenting such signals, as the CHIAD system is designed to support both accurate and speeded responses. It is expected that some signals will be more accurately interpreted than others, yet at the cost of longer presentation and response times, and therefore may not be the most efficient ways to communicate within time constraints.

This initial study in the development of the CHIAD system analyzes the ability of human subjects to recognize, interpret, and identify a series of vibrotactile patterns which employ three different display methods: static, dynamic, and saltatory. The results will be used to inform ongoing development of this system, by presenting encoded messages in maximally efficient manner, dependent upon both interpretation accuracy and response time. Future studies will investigate other dimensions of the signal, such as the frequency, waveform, and/or intensity of the signal, and will also investigate the benefits and communication strategies developed by pairs of communicators interacting with each other through the CHIAD system.

In addition to informing the CHIAD system design, the results of this study will advance knowledge of tactile information processing, by exploring signals that are both reliably and quickly interpretable with minimal effort. These aspects of “transparency” in tactile communications (MacLean, 2008) are critical to consider in designing haptic/tactile displays to support the attention and task management of human operators in complex environments, such as military operations, air traffic control, firefighting, leisure sports, and many others which require fast interpersonal communication and action.

IV.2 Methods

Six study participants were recruited from the student body of Texas A&M University via mass email (IRB approval: IRB2011-0915). After consenting to participate, participants experienced and practiced identifying examples of each presentation type. This fifteen-minute training session assured that participants could correctly identify presentation patterns at each complexity level by performing the required responses, which involved drawing the presentation on a paper worksheet. Participants then completed eighteen different blocks of experimental trials. Participation in the study took approximately an hour and a half.

The eighteen experimental blocks represented a full factorial design of each of the three primary variables of interest: presentation method (static, dynamic, and saltatory, explained below); signal complexity (C1 and C2), and presentation duration (500 ms, 750 ms, and 1000 ms), with the order of presentation and method balanced between participants. C1 complexity involved basic cardinal and intermediate directions; trials in the C2 level of complexity included the same basic signals as in C1 complexity, but also included sequential combinations of two directional presentations (e.g., up, then left). C1 blocks consisted of thirty trials and C2 blocks consisted of sixty trials (thirty single direction presentations and thirty sequenced combinations of two directions). Participants always completed C1 blocks before C2 blocks. The script of presentation pattern order was identical for each participant, though each participant received the patterns with different presentation method and durations.

Static signaling is the most basic of the three presentation methods analyzed. It consists of the simultaneous activation of one or more tactile presentation devices (so-called “tactors”) for the given duration. All spatial information is communicated through the physical location of the stimulus in regard to the individual (e.g., a vibration on the right side of the body relates to the right, etc.). The second method, dynamic signaling, consists of non-overlapping temporally sequenced activations of successive tactors. This allows both the spatial emphasis utilized by the static method and an additional temporal component of perceived motion direction and provides a larger potential range of expression than static signaling, but at the expense of time. The third presentation method used sensory saltation, sometimes referred to as the “cutaneous rabbit phenomenon”, an illusion created by rapidly stimulating multiple body locations in sequence. Instead of sensing separate presentations solely at each actuator site, the observer additionally perceives stimulation at intermediate locations between the actuators, resulting in the apparent perception of a moving vibration source (Sherrick, 1968). The signal parameters used for the saltatory presentation method (duration of stimulus and stimulus onset asynchrony) were derived from the literatureto best elicit the apparent motion illusion (Niwa, Lindeman, Itoh, & Kishino, 2009). The advantage of this presentation method is that it can allow a user to perceive higher-resolution linear signals from point stimuli and may also make movement direction more discernible.

Signal generation and data collection were carried out via a simple console application developed for this study. The presentation of each individual trial was activated via a simple interface. After the presentation, participants responded by drawing on a printed paper response form – with a pen – the pattern they felt. Following each presentation, participants had an option of pressing one of two buttons to repeat the signal or advance to the next signal. Participants were instructed to advance as soon as possible once they were certain of their response, since both accuracy and response time per trial were performance measures of interest. After the end of each block a short break could be taken before starting the next block. A new response sheet was used for each block.

IV.2.1 CHIAD 1.0 Display Design

Signals were administered to participants by way of two Engineering Acoustics, Inc.© C2 systems and sixteen solenoid-based tactile actuators (*tactors)* mounted on a polyester/spandex compression shirt with strips of hook-and-loop fastener. The tactors were arranged in a concentric square array with a minimum inter-tactor distance of roughly ten cm (see Figure 3). This system allows a lightweight arrangement of equipment to be worn over a thin undershirt while ensuring adequate contact pressure, so that each presentation is clearly perceptible. The positions of the tactors were arranged to accommodate participants of various sizes, such that the four corners of the outermost square were slightly outside and at the same height as the shoulder blades and slightly above and at the same width as the iliac crest on either side of the pelvis.

Tactors were arranged in two concentric squares to provide greater signal redundancy for cardinal and ordinal directions (for example, both Tactors 5 and 6 could be activated for a “right” signal; see Figure 3), and also greater expressiveness for complex patterns. Static signals could therefore be communicated with multiple tactors radiating from the center, and the sequences of vibrations for dynamic and saltatory presentations could follow many different paths.

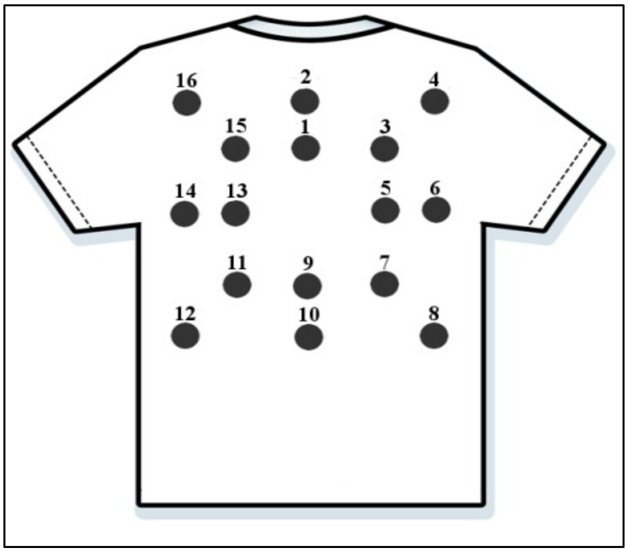

Figure 3. Tactor shirt array layout

IV.2.2 Signal Design

All vibrotactile stimuli in this study were displayed with a frequency of 250 hertz for maximum sensitivity (Shimoga, 1992) and at the maximum hardware-supported gain (1 mm displacement of the actuator against the skin). Static presentations involved simultaneous activation of all involved tactors for the specified duration. Dynamic presentations involved sequential presentations from the individual tactors such that the duration of stimulus (DOS) for each was equally represented in the total presentation duration, and the stimulus onset asynchrony (SOA) was 0 (see Figure 4). For the saltatory signals, the duration of each stimulus was also equal and fit within the total presentation duration, but the stimuli temporally overlapped (see Figure 4). In order to best evoke the apparent motion illusion, the DOS was twice that of the SOA (Niwa et al., 2009).

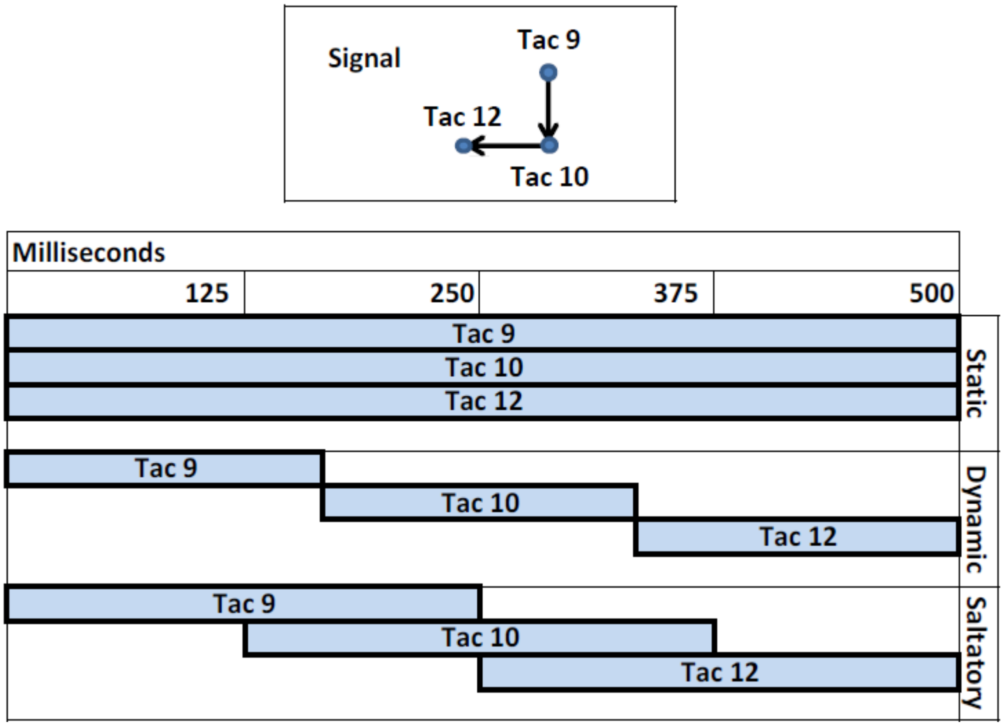

Figure 4. Example time sequence for each presentation method (500 ms duration)

IV.3 Results

One of the six initial participants reported discomfort with the display system and took an extended break which resulted in vastly inflated response times. Therefore, data for this participant were removed from the analysis.

IV.3.1 Response Accuracy

The measure of response accuracy was significantly affected by both presentation method (F(2,72)=6.63; p=0.002) and complexity (F(1,72)=149.79; p<0.001). Surprisingly, presentation duration did not reach significance. Figure 5 shows the mean accuracy for each presentation method and complexity.

More complex presentations (C2: mean overall accuracy 69.2%) had lower accuracy than relatively simple presentations (C1: accuracy 93.4%). Post-hoc tests for presentation method showed that dynamic presentations (overall accuracy: 73.7%) were significantly worse than both static (78.0%; p=0.044) and saltatory (79.8%; p=.023) presentations. Static and saltatory presentations did not differ overall, however, a trend favoring saltatory responses in more complex presentations could be observed. The interaction between presentation method and complexity was marginal (F(1,46)=3.21, p=.080), and may have reached significance with more participants. Further analysis of this effect showed that while the accuracy of static and saltatory signals did not differ for low-complexity (C1) signals (95.3% and 94.2%, respectively), saltatory signals were interpreted significantly more accurately (73.1%) than static signals (69.2%; p=0.037) for higher-complexity (C2) signals.

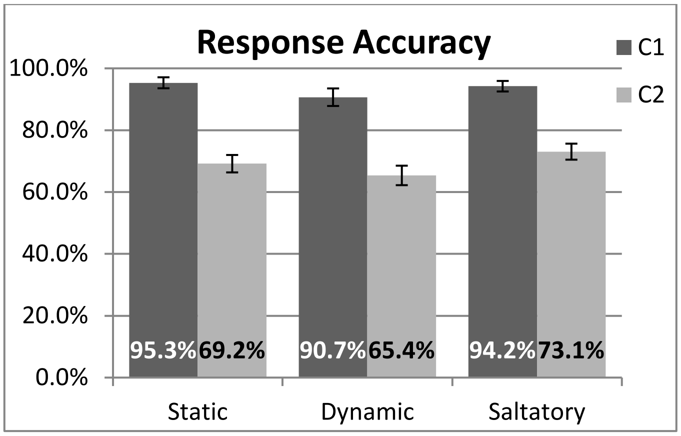

Figure 5. Response accuracy for each presentation method at each complexity level

IV.3.2 Response Time

Response times per trial were also significantly affected by both presentation method (F(2,72)=4.90; p=.010) and signal complexity (F(1,72)=44.94; p<.0001). Again, presentation duration was not found to be a significant factor. Post-hoc comparisons between presentation methods found that dynamic presentation trials (mean response time: 5658 ms) took significantly longer to complete than both static (4823 ms; p = 0.009) and saltatory presentation trials (4867 ms; p=0.023). Figure 6 shows the relationship between response times for blocks with each presentation method and level of signal complexity. No significant interaction effects were found.

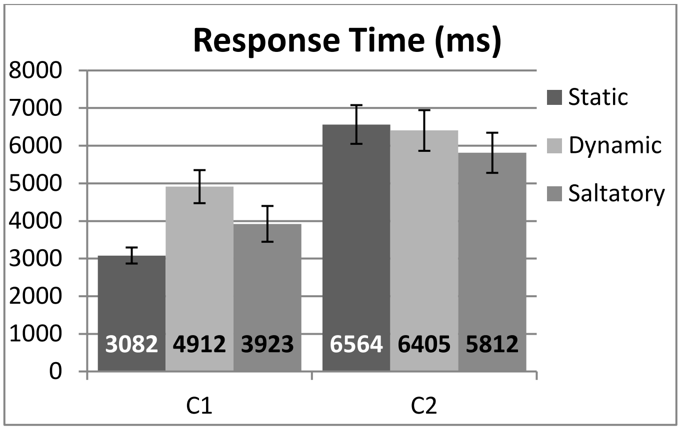

Figure 6. Average response time per trial (in ms) for experimental blocks with each presentation method and complexity level

IV.3.3 Requested Repeats

The number of requested repeats for trial presentations was significantly affected only by the signal complexity ($p<.0001$), with on average 5.7 repeat requests for C1 blocks and 47.2 requests for C2 blocks (Figure 7). It should be noted that C1 blocks included thirty trials and C2 blocks included sixty. Therefore, repeats were requested, on average, roughly once every five trials in C1 blocks, and five times for every six trials in C2 blocks.

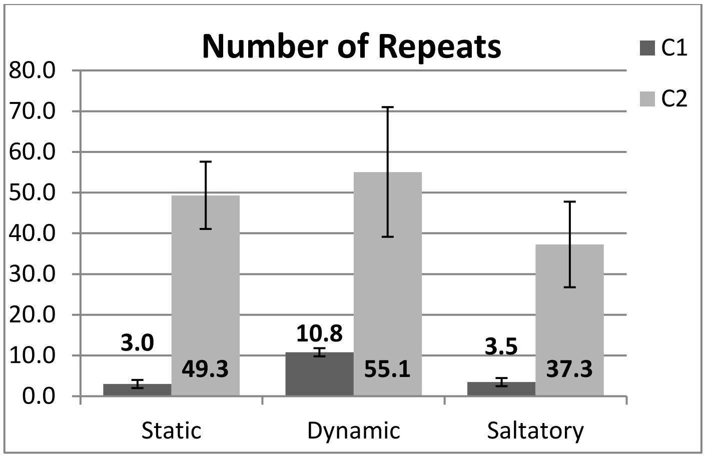

Figure 7. Average number of user-initiated presentation repeats for experimental blocks with each presentation method and complexity level

IV.4 Discussion

The sense of touch is uniquely suited for communicating immediately relevant spatial information, such as navigation instructions. One limitation of existing tactile display systems, for navigation or otherwise, is that they require learning a set of pre-defined signals without provision for context. As an alternative approach, the current research involves the development of a novel system – Creative Haptic Interaction At-a-Distance (CHIAD) – to support human-to-human communications via the haptic channel in a way that utilizes the natural human creative ability to communicate in an open-ended, improvisational way.

As part of the ongoing development of the CHIAD system, the goals of this study were: to understand the relationship between subject performance and signal complexity; to determine which vibrational presentation patterns best support signal perception and interpretation; and to investigate possible tradeoffs in efficiency (defined by both accuracy and time factors) that relate to signal duration. Of particular interest was the possible interaction effect between signal complexity and presentation method.

The results show differences in performance due to presentation method among static, dynamic, and saltatory signals. Generally, and especially with more complex signals (C2 blocks), the saltatory presentations showed the greatest accuracy. Saltatory presentations also showed faster response times than dynamic displays and trended toward being the fastest responses among all presentation methods for more complex signals. Though the differences did not always reach significance, it is important to note that a speed-accuracy tradeoff was not observed for the saltatory signals, thus we can conclude that this presentation method may be one of the most efficient ways to relay a tactile message.

The results clearly present a case for the importance of considering signal complexity when developing transparent tactile display systems. Clearly, lower signal complexities (C1) are easily identified, with accuracy scores between 90 and 95%. However, to support reliable and fast interpretation of more complex signals, additional steps should be taken to better support accuracy, which may come at the cost of longer presentation times or reduced expressiveness. One potential solution which will be further investigated could be to employ redundant encoding methods for communicating the signal, for example, recruiting a greater number of tactors to get greater resolution in the pattern shape. The reasoning for this solution comes from the fact that for C1, two tactors were used to redundantly communicate a single direction (instead of one tactor) in a reliable way. In this study, C2 presentations which involved the sequenced presentation of two directions with a shared vertex only activated three tactors, rather than two tactors for each individual direction in the sequence.

For all of the presentation types, participants exhibited few problems sensing the signal and determining whether it was a single direction or sequenced combination of directions. One interesting piece of anecdotal evidence was that participants generally reported that the main problem in signal recognition was in determining the precise location and/or the *order* of locations in the presentations. For example, some reported difficulty under certain conditions in distinguishing a left-to-right pattern from a right-to-left one. This suggests that further investigation of the spatial and temporal properties of the presentation may result in even better performances. While tactors were placed at a minimum of 10 cm apart, it could be assumed that location recognition would be improved by greater tactor spacing, which should not affect the apparent motion illusion induced by the saltatory displays (Sherrick, 1968). Also, the range of presentation duration windows used in this study (500 ms – 1000 ms) were longer than those used in the literature, which were within the order of 100 ms, e.g. (Niwa et al., 2009; Sherrick, 1968). It is possible that a shorter duration (or longer duration, for that matter) could improve the results as well.

A clear limitation of this study was that only five participants' data were analyzed in this initial study, after data removal. Though a large number of trials were used, the low participant sample size may have led to the lack of some differences reaching significance.

In conclusion, the results from this study demonstrate the importance of signal method and complexity for the design of haptic communication systems. Higher signal complexities are better supported by the greater perceived resolution and apparent motion of the saltatory vibrational signals, in terms of both response accuracy and time measures. This method of presenting complex patterns is likely the best alternative for expression via the CHIAD system and will be employed to investigate the benefits and communication strategies developed by pairs of communicators interacting with each other via CHIAD. Finally, the results provide evidence to inform the design of “transparent” tactile communications, e.g.(MacLean, 2008), which is an important descriptor to strive for in the design of haptic/tactile displays to support the attention and task management of human operators in complex environments.

CHAPTER V[*]

SPEEDED COOPERATIVE NAVIGATION

V.1 Introduction

Figure 1 highlights the two elements of a communication model that the CHIAD system may, in some cases, support more effectively than other forms of communication, such as verbal instruction. Gestures may allow a faster encoding of a navigation message and vibrotactile display of the message may support faster and potentially more accurate message interpretation. The result is a shortened communication control loop (the dashed line in Figure 1). Shortening this loop can be beneficial for tasks that require one person to assess a dynamically-changing situation and issue commands or instructions to other operators, who must then interpret the instructions and act appropriately as quickly as possible.

The present study tests the effectiveness of the CHIAD system by addressing two specific questions. First, can navigation instructions be encoded more quickly and/or accurately via gestural input than via verbal commands or graphical interface-based commands? Also, can navigational information be more quickly decoded, interpreted, and used when it is expressed via vibrotactile patterns than via auditory verbal instructions?

To test these questions, three interfaces were analyzed with cooperating dyads in a speeded navigation task. For this task, instructions were limited to binary (“left” / “right”) directions so that the first test of this system was with a very basic instruction set. This

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[*] Reprinted with permission from “Supporting Speeded Navigational Communication via Gesture-Controlled Vibrotactile Displays” by Roady, T., & Ferris T.K., 2013. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 57, pp 1144-1148, Copyright 2013 by SAGE Publications.

decision was also driven by previous research which demonstrated that simpler directional vibration patterns are interpreted faster and more accurately than more complex signals (T. Roady & Ferris, 2012).

Specifically, the following hypotheses were evaluated: Hypothesis 1: the natural gesture-based interface will out-perform the graphical button interface in both completion time and accuracy for the navigation task. This performance benefit was expected due to the gesture-based interface allowing more intuitive ease in encoding instructions, and also allowing a communicator to keep their eyes on the environment (rather than on a graphical display). Hypothesis 2: vibrational communication methods will outperform verbal communication in task completion time and accuracy. This hypothesis tests the expectation that vibrotactile displays of simple navigation instructions will be decoded more efficiently.

V.2 Methods

Fourteen participants were recruited from the Texas A&M University student body via mass email (IRB approval: IRB2012-0456D). After consenting to participate, subjects were paired into dyads and were given a short training session to familiarize themselves with the task course and the three communication systems: verbal communication via radio, vibrotactile signals activated by a GUI, and vibrotactile signals activated by a natural gesture system.

The study was conducted in the lobby of a large campus building. Within dyads, participants assumed specific roles: a director who communicated navigational instructions and an actor who received the instructions and moved according to them. The actor was located on the first floor, where a 2x15 field of multicolored traffic cones represented the navigation course; the director was located on the second floor in a glass-walled room that allowed a superior vantage point above the course but which prevented extraneous communication (see Figure 8). Each trial involved the actor continuously moving away from the director along the course (never reversing directions or stopping), while the director communicated the required path. The director learned of the appropriate path in real-time via a series of cues presented by experimenters. Cues consisted of colored cards with matching black text which corresponded to the color of "target" cones the actor needed to navigate around. Cards were used as cues to prevent potential cross-communication when director-actor instructions were communicated verbally. Cue order was pseudo-randomized but the order was consistent for each pair of participants, independent of the order of experimental treatments.

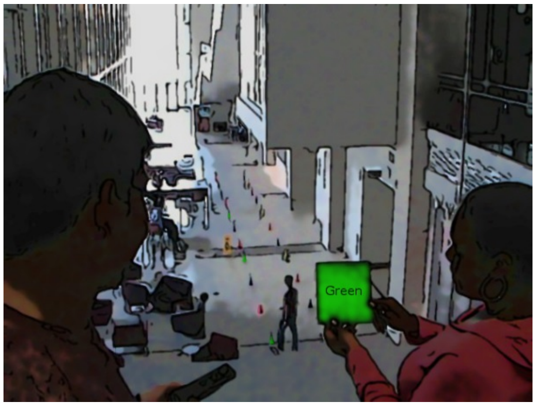

Figure 8. Experiment 2 setup

The navigation course consisted of cones in six different colors (red, blue, green, yellow, orange, and purple). The cones were arranged 5.5 feet apart from each other in 2 x 3 "units" which were always arranged as shown in Figure 9. Each unit consisted of a single target cone which was communicated to the director prior to the actor entering the unit. To avoid confusion between the red and orange cones and the blue and purple cones, easily confused colors were placed at opposite corners to provide the reinforcement of a reliable pattern (i.e., directors knew that orange cones were always on the left, while red were always on the right). For each cone unit, only one of the six cones were designated as the target, and the dyad was tasked with making sure the actor walked around the target cone in each unit, and then returned to the center of the two columns of cones. To accomplish this, the director needed to interpret the cues presented by the experimenters, judge which side the cue was associated with, and communicate the navigation instructions to the actor via the method specified for the experimental treatment. Actors were instructed to walk continuously at a fast pace, not to jog, and told to complete the course as quickly as possible while focusing on accurate cone selection.

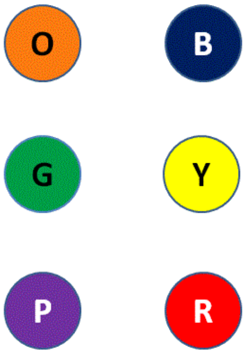

Figure 9. Cone "unit"

There were five cone units over the length of the course (Figure 10), which constituted one “run”, and three runs were performed with each experimental treatment (communication method). Colored electrical tape was placed between cone units to aid in scoring the participants, and to serve as a reference point for experimenters, who would present the next cue immediately after a navigation instruction was issued by the director. Run completion time and accuracy (calculated as the percentage of cone units in which the actor travelled around the target cone) were collected as measures. Please note that the first row of cones in the first unit is not visible in Figure 9 because an opaque layer in the glass obscured it.

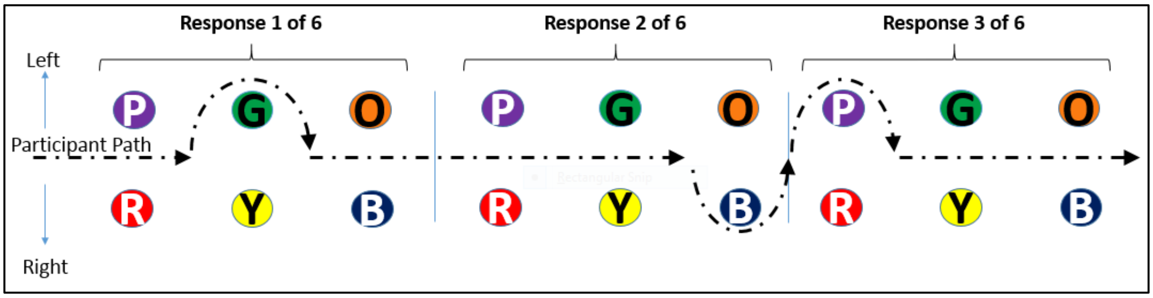

Figure 10. Study 2 response example

Dyads completed each of three experimental treatments by performing three runs with one participant performing as director and the other as actor, and then by repeating the process with the director/actor roles reversed. This resulted in a total of eighteen trials per dyad. Training runs were used to familiarize participants with the physical sensations of each treatment and allowed them to practice and calibrate the timing of their communications. Upon completion of the experiment, participants filled out a feedback questionnaire that rated the comfort of the vibrational system and allowed participants to rate their experience with each interface on a ten-point Likert scale. Participation took approximately an hour and a half.

V.2.1 Communication Methods

Three experimental treatments were used in this study: the verbal (V) treatment which acted as a baseline and two vibrational treatments which only differed in the way directions were encoded: by button-presses (B) or by gestures (G). In the verbal treatment, the director provided verbal guidance to the actor using two-way radios. Allowable instructions were limited to “left” and “right”. Because the experimenter indicated the target cone by waving a colored card, confusion or interference resulting from listening and speaking simultaneously was reduced (Wickens, 2002). This also ensured that instructions given by experimenters to the directors were not overheard through the radio channel.

In the vibrational treatments (B and G), the actor was fitted with an elastic weightlifting belt containing eight solenoid-based tactile devices (C-2 “tactors” developed by Engineering Acoustics, Inc.), four on the left and four on the right (see Figure 11). These four-tactor groups were activated simultaneously to indicate direction. Tactors were set at maximum gain and activated with a summed signal combination of 250 and 240 hertz, to provide a highly-salient “beat pulse” sensation that was easily detected. Signals were therefore restricted to simple “left” and “right” commands, just as they were in the V treatment.

Figure 11. Tactile display; tactor arrangement underneath belt highlighted

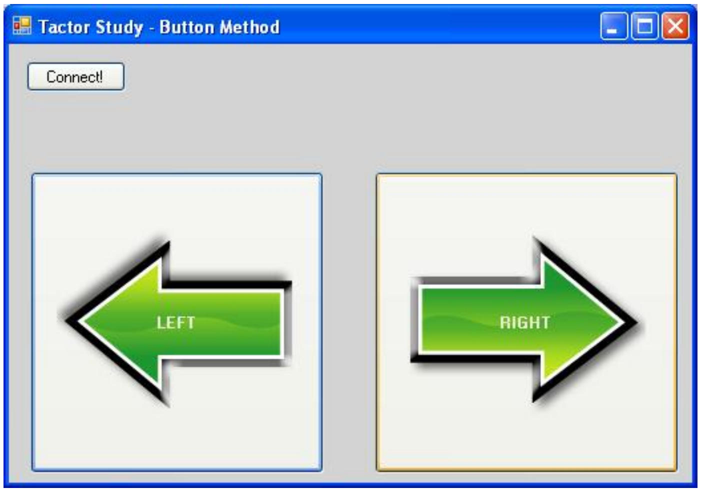

Figure 12. Button interface, (B) condition

In the button treatment (B), the director was given a laptop with a standard optical mouse. Vibrational signals were sent to the actor by clicking on either a “left” or “right” button in a graphical display (see Figure 12). Buttons were oversized, central, and indicated by both text and arrows, to minimize errors and workload due to Fitt’s target selection.

In the gesture-based treatment (G), the director used a Nintendo Wii remote ("Wiimote") to guide the actor. The remote was programmed to send "left" and "right" signals based on the degree of roll, or y-axis rotation. Threshold levels were set at ± 20º from neutral (see Figure 13). Signals were sent only after the threshold was reached and the director was provided with vibrational feedback from the remote to indicate when the signal was active. This provided a feedback source for the director that wasn't filtered through the actor's perception.

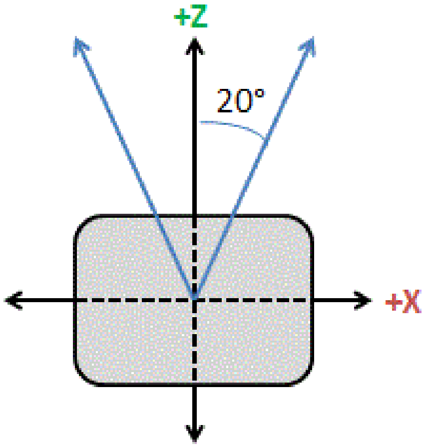

Figure 13. Wiimote roll threshold

V.3 Results

One participating dyad mentioned consistent issues with technical performance and a distinct lag in the tactor system. Due to possible technical error and participant confusion, their results were not considered. Therefore, twelve dyads were statistically analyzed.

V.3.1 Run Accuracy

Run accuracy is expressed as the percentage of cone units in which the actor passed around the “target” cone. Accuracy was significantly affected by communication interface method (F(2,35)=5.37; p=0.013). Button (B) and verbal (V) supported equivalent accuracy scores of 79.4%, while gesture (G) supported an improved accuracy score of 88% (Figure 14). A post-hoc Tukey comparison test showed that accuracy for the V and G conditions were significantly different (F(1,23)=8.8; p=.013), as were the G and B conditions (F(1,23)=8.19;p=.015). Accuracy did not differ between the V and B treatments.

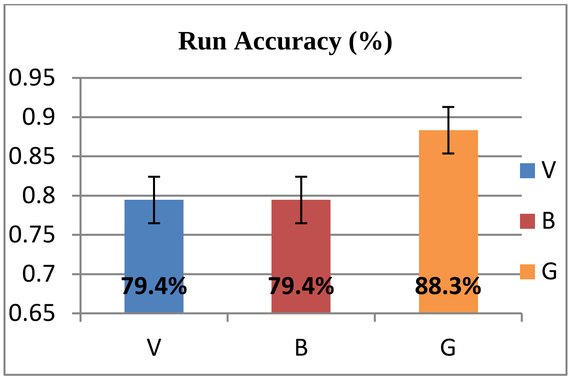

Figure 14. Run accuracy (% of cone units in which actors walked around the outside of the target cone) vs. communication method. Errors bars represent standard error.

V.3.2 Run Completion Time

Run completion time was not significantly affected by treatment (F(2,35)=1.11; p=0.348). However, pairwise comparisons were made between individual communication methods to test the hypotheses individually. These comparisons found completion times to be significantly different between V (mean run completion time: 27.9 s) and G treatments (27.4 s; F(1,23)=5.85; p=0.034). The average run completion times for each treatment are shown in Figure 15.

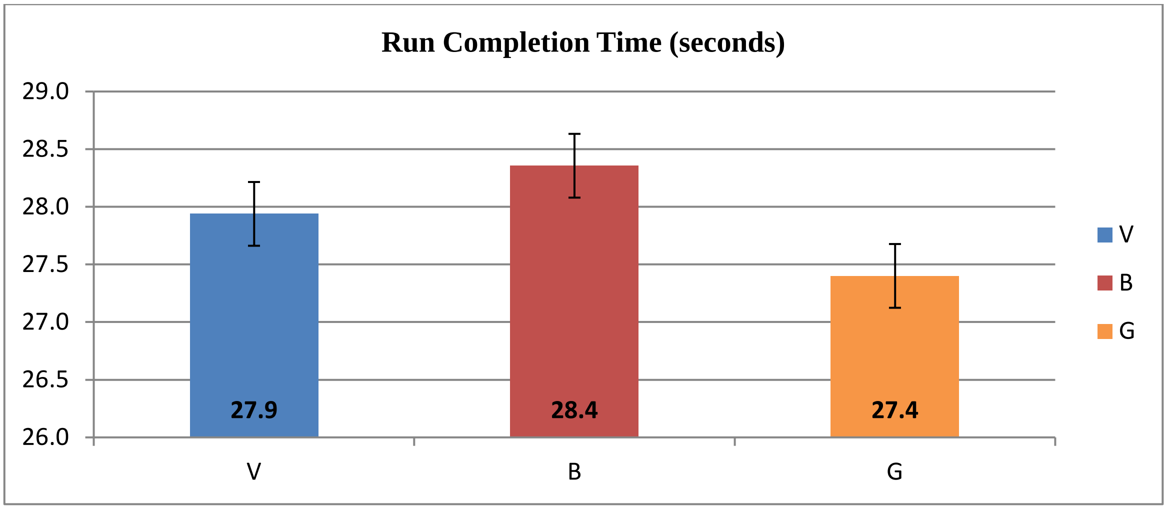

Figure 15. Run completion time vs. communication method; error bars represent standard error

V.3.3 Subjective Perception of Effectiveness

User feedback questionnaires were used to rate the efficacy of each interface. Subjective effectiveness was significantly affected by communication interface method (F(2,35)=5.07; p=0.015). The mean results for V, B, and G were 6.5, 6.4, & 8.4, respectively (see Figure 16). The gesture method was rated very favorably by many participants, receiving "10" (most effective) ratings 4 times, and a singular low rating of 5. Both V and B received minimum ratings of 3, with maximum ratings of 10 for B and 9 for V.

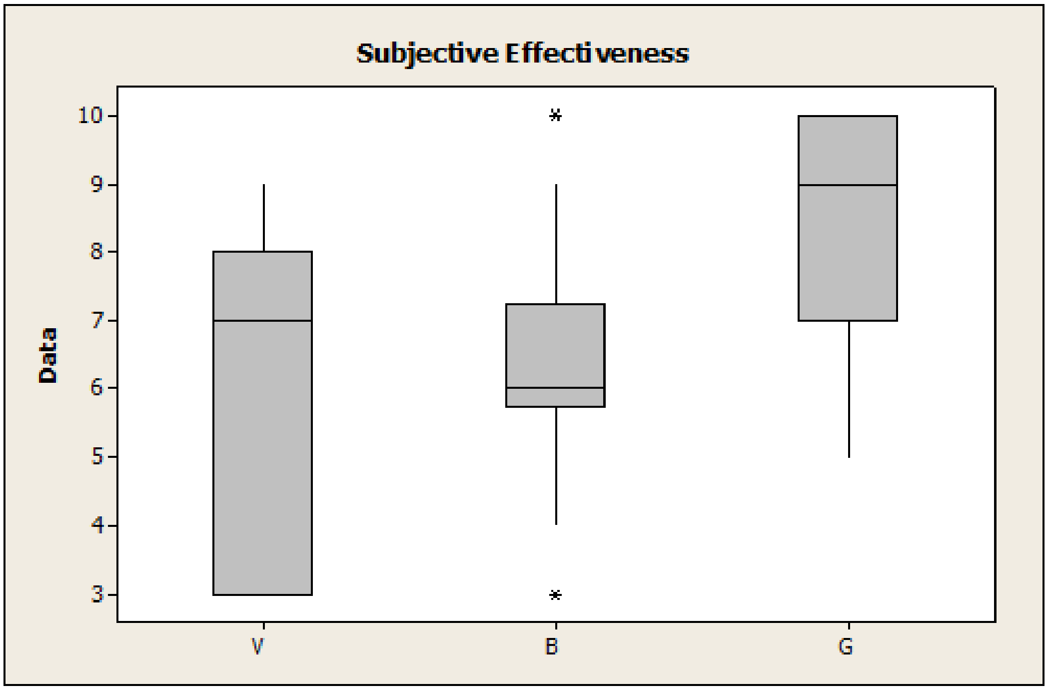

Figure 16. Box plots of subjective effectiveness ratings by communication method

V.4 Discussion

The CHIAD system tested in this study includes two design features that support speeded communication of navigation instructions. Natural gesture methods allow a "director" to intuitively encode navigation instructions and to keep their eyes on the task, rather than on a graphical interface. Presenting these instructions via vibrotactile signals supports fast reception and intuitive decoding of signals by an "actor", reducing higher cognitive process engagement during signal interpretation. These two features make the CHIAD system well-suited for tasks which require fast and reliable communication of navigation information, especially when operators are under stress and/or time pressure.

The performance measures and subjective feedback results support the first hypothesis of this study: the natural-gesture treatment provided the most effective of the three communication methods. The significant difference between the gesture (G) and button (B) interfaces– found in the measures of run accuracy and run completion time – implies a distinct director performance improvement, due to identical actor conditions between B and G. This likely occurs because natural gestures allow the director to maintain focus on the actor as they navigated the course. In contrast, the button method, while simple in nature, required the director to shift visual focus between the task and the interface. Interestingly, it appears that fewer errors in the gesture method actually occurred as a result of over-anticipation and early response rather than late-reactions and misinterpretation. Perhaps this is because actors assumed the same delay in instruction delivery that was present in the button method.

While verbal communication methods didn't significantly differ from both vibrotactile methods, they did differ from the gesture condition, suggesting a distinct decoding advantage for vibrotactile communication and a validation of the second hypothesis. Therefore, it is reasonable to assume that vibrotactile signals are reasonably intuitive.

Performance similarities between button and verbal were likely due to similar processing structure challenges. In verbal, both parties had to expend more effort to quickly encode and decode directions, leading to lower accuracies that may be due to either misspoken directions or actions opposite of instruction. In the button condition, the director's visual resources faced interference effects from two different visual tasks: observing the actor's location on the course relative to the target cone and visually locating the button associated with the desired instruction. Because the two visual tasks could not be easily performed in parallel, it was difficult to time sending the navigation messages with the actor’s motion.

Though the individual comparison between verbal and gesture was found to differ in completion time, the time measure did not reach significance overall among the treatments. This is likely explained by participant behavior in the given task: participants usually maintained a fairly consistent pace throughout each run. Though participants moved slightly faster for gesture trials, this appears to be because of subjective interface preferences. They did not slow down to increase accuracy, leading to an overall lack of variation between methods. This does not necessarily mean that reaction time itself is not affected by the methods analyzed here, just that the study as performed, with its current simple paradigm, did not provide significant measure. The lack of significance suggests that the effects of accuracy were not the result of a speed-accuracy tradeoff. Further task complexity and information density would likely have made the measure of run time more sensitive to the different communication methods, as previous studies have shown that signal complexity affects the relative benefits of tactile display (T. K. Ferris & N. Sarter, 2011; T. Roady & Ferris, 2012).

The subjective ratings showed overwhelmingly that the gesture method was acceptable and preferred over the other communication methods for the given task. However, the experimental task was designed to emphasize the strengths of the CHIAD system and involved a very simple task with simple instructions. Likely, as complexity in the task increases, there would be greater benefit for descriptive verbal communications versus gesture-based tactile interfaces.

In conclusion, these results highlight the viability of natural gesture systems and vibrotactile communication for reducing encoding and decoding workload in navigation tasks.

CHAPTER VI[*]

SPEEDED COOPERATIVE NAVIGATION UNDER INCREASED COMPLEXITY

VI.1 Introduction

Previously, in Chapter V (T. Roady & Ferris, 2013), we demonstrated a significant performance advantage for vibrotactile communication driven by gestures over verbal communication during a simple navigational task. We attributed this to decreased encoding time due to ease of gesturing for the directing party and to decreased decoding time for the acting party due to the shared physical nature of task and stimuli, as highlighted in Figure 1.

The present study expands on the previous paradigm by expanding the available problem space and incrementally increasing the task complexity by increasing the potential responses from two (navigate to the left or to the right) to five, significantly increasing the information content of the communicated message from 1 bit to 2.3 bits. Does the increase task information cause a similar performance advantage for the simple vibrotactile system over verbal communication methods?

In the following study, pairs of participants cooperated to complete a navigation task that required one party (the "director") to assess the situation and relay speeded instructions to the other party (the "actor"), who then moved according to these instructions through the designed course. The following hypotheses were evaluated: Hypothesis 1: the vibrotactile-gesture system will outperform the verbal system in the accuracy of the path followed by the actor. Hypothesis 2: the vibrotactile-gesture system will result in faster course completion

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times than the verbal system. These are expected due to the reduction in both encoding for the gesture system and in decoding for vibrotactile stimuli.

VI.2 Methods

Eight participants were recruited from the Texas A&M University student body via mass email (IRB approval: IRB2012-0456D). After consenting to participate, subjects were paired into dyads and were given a short training session to familiarize themselves with the task course and the two communication systems: verbal communication via radio and vibrotactile signals activated by a gesture system.

The study was conducted in the same building space as Chapter V. Within dyads, participants assumed specific roles: a *director* who communicated navigational instructions and an *actor* who received the instructions and moved according to them. The actor was located on the first floor, where a field of multicolored traffic cones represented the navigation course; rows were spaced ten feet apart and consisted of cones that were two feet apart, respectively. The director was located on the second floor in a glass-walled room that allowed a superior vantage point above the course but which prevented extraneous communication between the cooperating participants. Each trial involved the actor continuously moving away from the director along the course (never reversing directions), while the director communicated the required path. The director learned of the appropriate path in real-time via a series of cues presented by experimenters. Cues consisted of colored squares with matching black text (see Figure 17) which corresponded to the color of “target” cones the actor needed to navigate around. For instance, a green and orange card would denote the path shown in Figure 18. The relative location of colors on the cue card was randomized to eliminate spatial encoding and prevent the director from simply reading the left-hand color without needing to locate the right color. Cues were provided immediately after actor selection of the target path. Experimenters displayed the cards to the directors as opposed to verbally describing them to prevent potential cross-communication when director-actor instructions were communicated verbally. Cones of perceptually similar colors were modified with white stripes to aid in discrimination; cue cards were similarly modified to be visually similar to their target cone. Cue order was pseudo-randomized but the order was consistent for each pair of participants, independent of the order of experimental treatments. Communication methods were balanced between subjects.

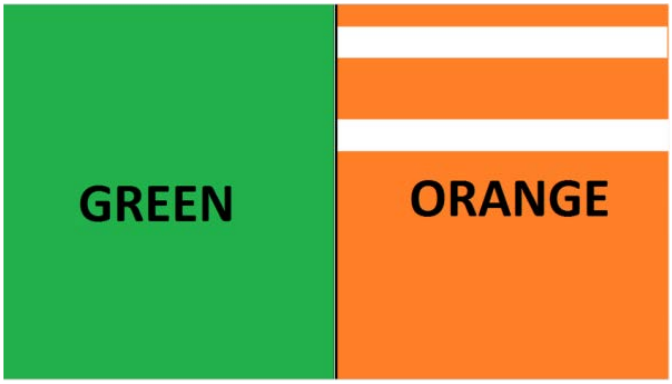


Figure 17. Example cue card

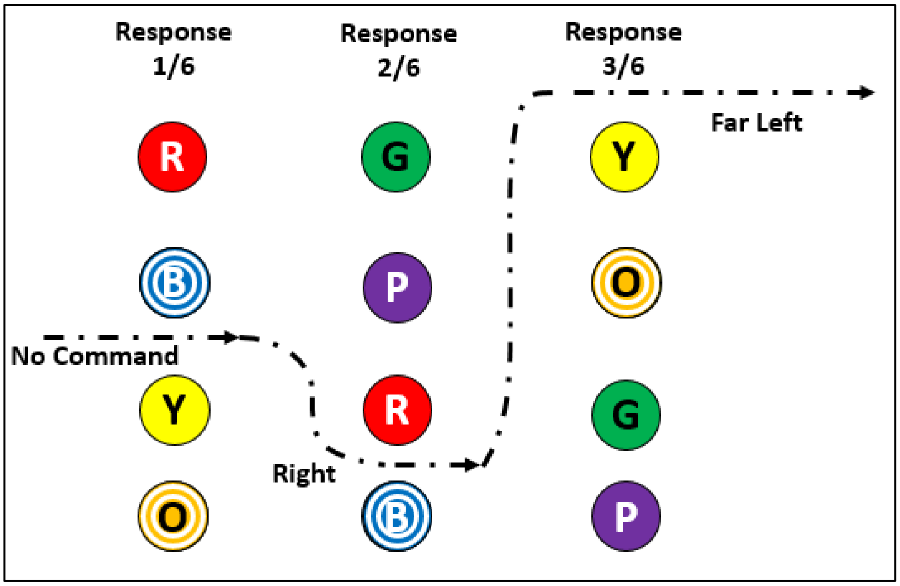


Figure 18. Cone path example

There were 8 rows of cones over the length of the response areas, which constituted one "course". Five courses were performed with each experimental treatment (communication method) with each participant serving as first a director, then an actor, or vice-versa. Course completion time and accuracy (calculated as the percentage of cone units in which the actor travelled around the target cone) were collected as measures, along with background information regarding participants' physical fitness and virtual environment experience.

Tactile signals were presented to the actors by way of a tactile belt fitted with Engineering Acoustic Instruments© C2 solenoid tactors. As in Chapter V, 4 tactors were placed on the left and 4 on the right (see Figure 11).Tactors were set at maximum gain and a frequency of 250 hertz, to ensure maximum sensitivity, in accordance with Verrillo (1966). Two levels of left/right signal were available: a "strong" signal produced by activating the tactors with 150 millisecond pulses, and a "weak" signal produced by activating the tactors with 60 millisecond pulses for the duration of the gesture. Signals were developed for easy discrimination through pilot testing.

The vibrotactile cues were activated by specific gestures conducted with a Nintendo Wii© remote (Wiimote). Signals were sent if the remote was rotated beyond the signal threshold at 20 degrees (see Figure 13). The “strong” signal, accomplished by holding both the A & B buttons on the top and underside of the baton-like remote (akin to gripping the Wiimote more forcefully for the stronger instruction). In addition to presenting the strong signals to the actor, a continuous activation of the Wiimote’s eccentric motor provided immediate strong state feedback for the director. The “weak” signal was accomplished by holding only the A button (akin to a weaker grip), and director feedback was sent as a pulse activation of the Wiimote’s eccentric motor for 125 milliseconds with a gap of 15 milliseconds. Participants were easily able to identify differences between the two levels during pilot testing.

VI.3 Results

All statistical analysis was performed in SAS 9.3 using Proc GLM MANOVA with $\alpha=0.05$. Mauchley’s test for sphericity was not significant, indicating that no correction to the univariate output was necessary. Initial tests suggested that a relationship existed between the two dependent measures (accuracy and time); hence a combined metric was formed to better evaluate performance. Due to restrictions from the small sample size (and the use of a balanced experimental design), data was not additionally evaluated for sequence or order effects. All post-hoc tests were performed using Tukey’s HSD.

VI.3.1 Course Completion Time

Initial results suggest that completion time was not significantly different for the vibrotactile and verbal conditions. However, multivariate analysis indicated a potential interaction between course and communication method (F(4,4)=5.31, Wilk's Λ=0.1584, p=0.0674).

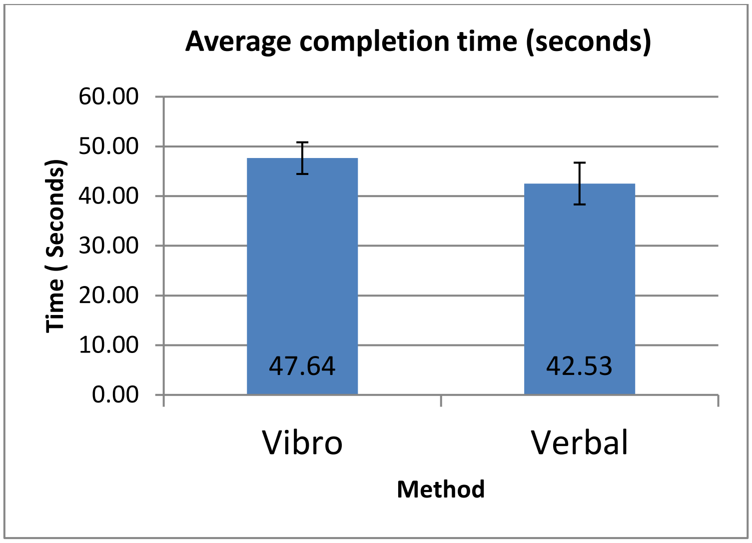


Figure 19. Average completion time (s) vs. condition. Error bars represent standard error.

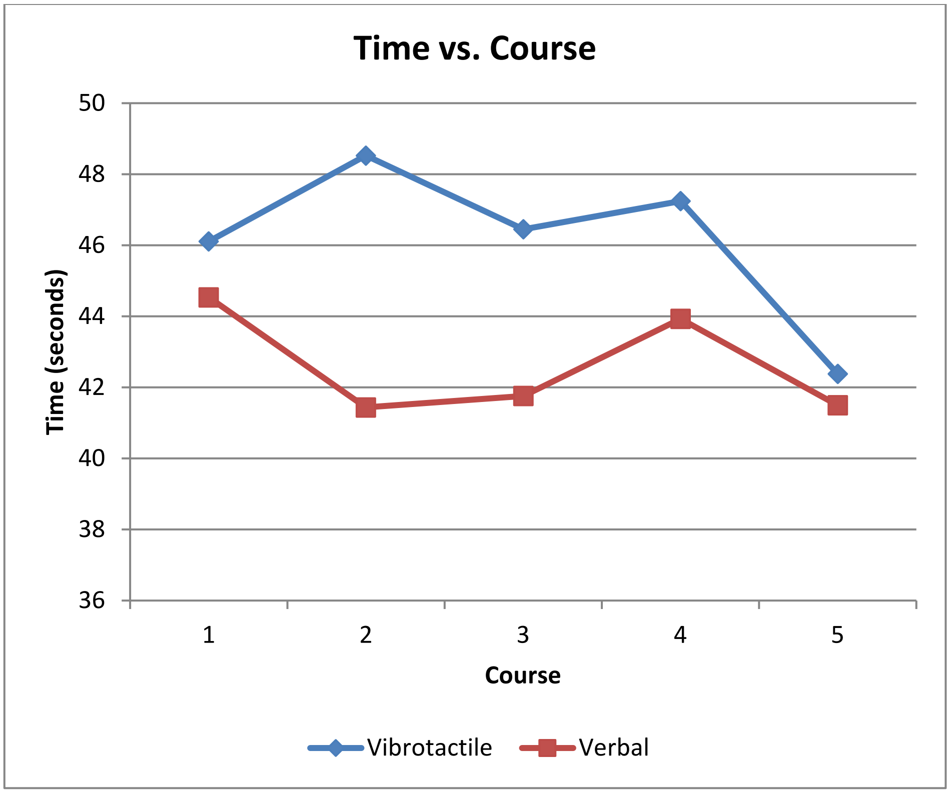


Figure 20. Completion time vs. course by conditions

VI.3.2 Accuracy versus Time

Both graphical and statistical analysis indicated a negative relationship between the dependent measures (time and accuracy, shown in Figure 21), which was consistent with expectations following from Fitts (1954).

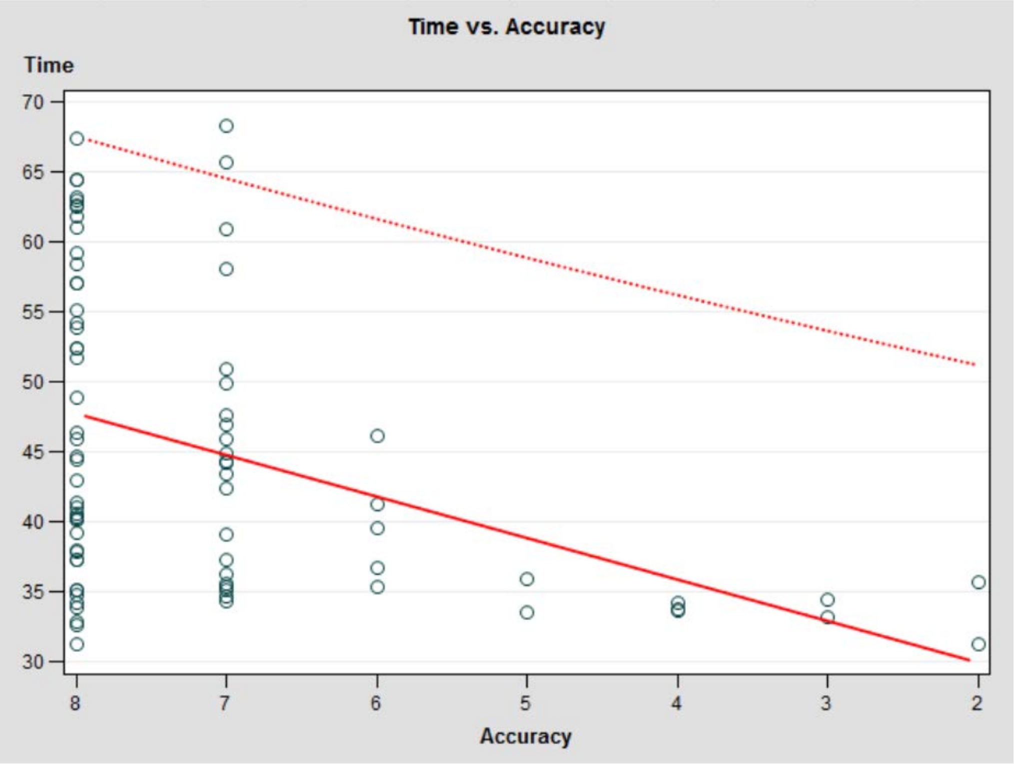


Figure 21. Time vs. accuracy; top line is vibrotactile, bottom line is verbal

Analysis of time when adjusting for the level of accuracy (using a metric of time divided by accuracy), suggested that no significant difference exists between the verbal and vibrotactile conditions across any courses (Figure 22).

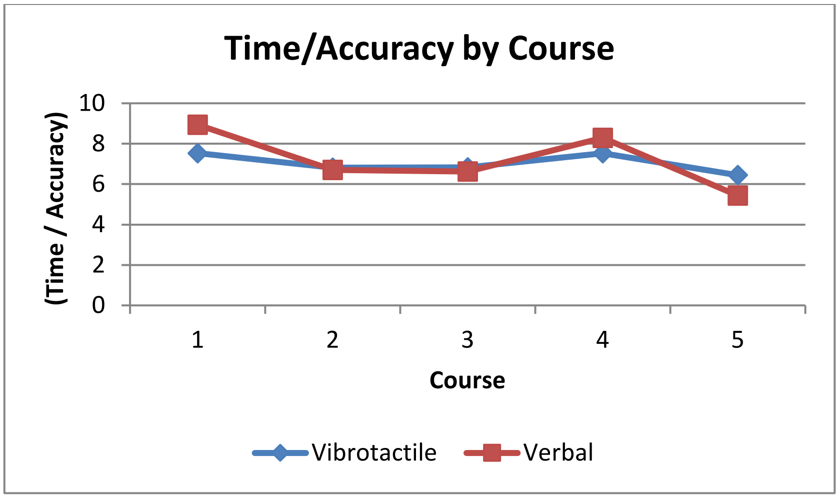


Figure 22. Time/accuracy participant performance for each course for each treatment condition

VI.4 Discussion

The system and paradigm tested in this study were intended to be simple extensions of Roady & Ferris (2013) by increasing response options from 2 possibilities to 5 and system redesign to allow for “strong” and “weak” magnitude stimuli.

Performance measures and statistical analysis are inconclusive in the case of Hypothesis 1, likely due to wide variation between subjects. It is, however, entirely possible that the nature of the task was not challenging enough to provide a clear difference in responses.

Hypothesis 2 is distinctly rejected, with results showing faster completion times for the Verbal treatment. While this could be considered as an indicator for the prevalence of verbal modality over the vibrotactile modality, there are other probable explanations. Three primary considerations can be considered problematic: insufficient discriminability in Wiimote feedback increases in task complexity, and subject expectation in cone layout.

Previously, remote feedback was sufficiently salient to indicate tactor activation. While this study developed two vibrational patterns that were sufficiently discriminable in an isolated pilot study, subjects expressed confusion during the study itself, instead increasingly opting to focus on the use of the extreme signal.

Wide variation was also observed between subjects on the visual task, with some directors responding to cues well after their response window and others responding almost immediately. The previous study had no such problems, suggesting that reduction in the difficulty of the visual task will likely result in less variation. In the previous study, participant response was evaluated by a set of cones set up in three rows of two. This required participants to forego potentially correct responses to indicate their choice. In the present study, all responses were gathered together in one row. This gave participants the awareness of each exact evaluation point and resulted in pausing just prior to target selection, rather than the continuous motion of the first study. This clear, discrete evaluation point favored the easy, direct categorization afforded by verbal tasks, relieving time pressure.

This tradeoff can also be seen in the significant difference between verbal and vibrotactile (Figure 20). Subjects were significantly faster with verbal than with vibrotactile in the second and third conditions. This is likely due to familiarity with verbal and acclimation to the research task. In the last two courses, it appears that subjects become more effective with the vibrotactile system, reducing differences in performance. This is further supported by completion time significance between subjects but not within subjects, suggesting that sequence, and growing task familiarity, may have impacted performance. Likewise, while participants were with the verbal condition, they didn’t actually perform more accurately when the two were considered together.

CHAPTER VII

HAPTIC DESIGN FOR COMPLEX, DYNAMIC ENVIRONMENTS

VII.1 Lessons Learned in Previous Chapters

The preceding studies (Chapters IV, V, & VI) depended upon a simple model of communication, as shown in Figure 2. This model assumes that communication between an actor, who was performing an action, and the director who guided them, was a matter of simple message sending. It was posited that the use of gestures could shorten the time for encoding a message and vibrotactile stimuli could do the same for the decoding of the message.

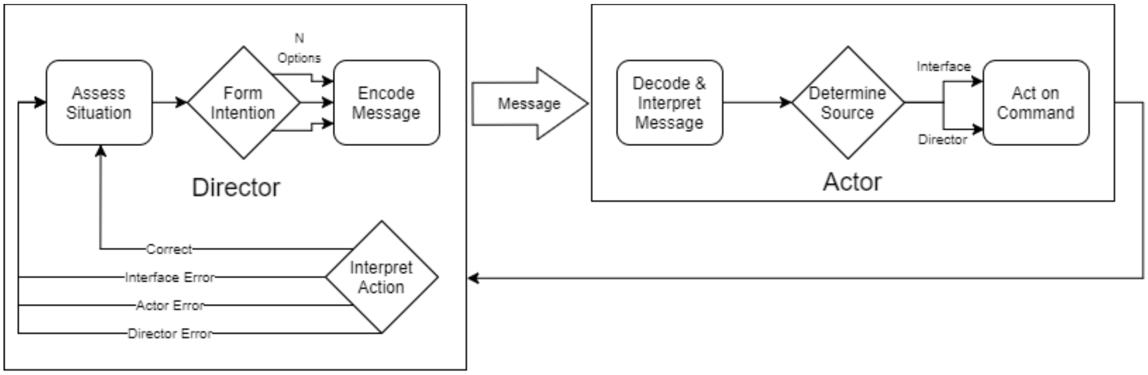


Figure 23. Updated communication model. Expanded from Figure 1.

This seemed a reasonably powerful model for explaining behavior in Chapter V under a simple signal set. However, as consistent with Hick-Hyman Law's prediction that decision time increases with the number of available options (Hick, 1952; Hyman, 1953), expanding the number of options for the study caused a distinct performance breakdown, as shown in Figure 23. Participants were no longer confident about the messages. This lead directors to second guess how they sent the messages and actors to revert to a stuttering process of pausing and waiting for confirmation. When the message was simple, there was trust that any error was small and easily corrected. Participants became increasingly uncertain that the signal they sent or received was the one intended by their partner, resulting in perceived unreliability and distrust of the system, which may lead into many of the facets of trust-in-automation (e.g.: use, disuse, and abuse) as identified by Parasuraman and Riley (1997) and Lee and See (2004), among others. Participants began to anticipate and correct for errors, a meta-language process that is seen more in language than simple signal sets.

VII.1.1 The Challenge of Language

Imagine a piano. Two people sit down at it and play a duet, each trading off sections, marking tempo against each other. Now, if you were to separate them into two rooms and ask them to play the same piece, the result would not be a duet. The duet is a joint action, where the whole is greater than its parts.

According to Clark, “language use is really a form of joint action. A joint action is one that is carried out by an ensemble of people acting in coordination with each other. As simple examples, think of two people waltzing, paddling a canoe, playing a duet…” (1996). So, while the design of vibrotactile systems may not first seem to be a linguistic one, Clark’s perspective clearly places it as such. Actions must be determined from a shared understanding of common ground. For two people to collaborate, they must understand that they are referring to the same thing.

It is also important to realize that joint action happens on many levels. While a firefighter may be moving through a burning building and locating points of interest, they must also prioritize them while keeping situational awareness for their own safety.

For laboratory conditions, it is easier to create a basic language for coordination of action. Because the testing domain is limited, there is less need to establish a robust communication model. When vibrotactile technologies are developed for application, they must be able to adapt to naturally occurring contexts, increasing design difficulty.

To define an effective language, as Riddle and Chapman (2012) suggest, it is not enough to establish a set of important message characteristics for communication. For a truly effective system, there must be meta-language characteristics to allow for identification of error and to establish not only the reliability of the system, but to prevent confusion arising from both human errors and system breakdowns.

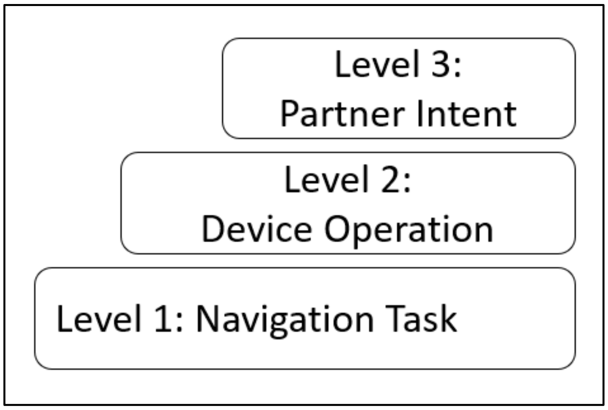


Figure 24. Common ground analysis of message decoding.

Applying this to Chapter VI, we can dissect an error according to Figure 24. When the messages were clearly mapped to the observed task, actors were confident in their motion. However, when the message became unclear, they had to attribute the error to one of three levels: their partner's intent, the device itself, or instructions for the navigation task.

When they were no longer able to reliably depend on the device, they used their actions within the navigation task to try and communicate understanding and bridge the limited expression available. For instance, if the actor received a “far-left” instruction, they would frequently pause and begin to move slowly left, waiting for either a confirming “left” command, silence, or disconfirming “right” command. They no longer trusted the magnitude of the signal and instead depended on being moved right or left one step at a time.

VII.2 Two Views of Human-Machine Interaction and Planning

Performance inconsistencies demonstrated in Chapter VI are based on the strengths and weaknesses of vibrotactile interfaces, which may be best understood in the context of HMI and human automaticity.

One of the most historically dominant views in human-machine interaction, information processing or, as some critics call it, the "cognitivist" tradition, emphasizes the role of the mind as a logical symbol processor that serves as sole intermediary between environmental stimulus and behavioral response. Several notable examples are the Card, Moran, and Newell (2005) "Model Human Processor", a predecessor to the heavily-used GOMS model, or the Simon (1996) model of the computationally satisficing ant. In any case, cognition is viewed as a mathematical process performed on symbols stored in the mind to solve environmental challenges. Improvements in action are caused by either improving the quality of the model or in algorithmic efficiency. However, if the internal representation is constantly increasing, due to complexity of the natural environment, then how does the mind possess the computational power to search through all of the features and possible interactions to find a solution? To find the proverbial needle, the expert adds more hay.

Two particular theories stand in contrast to cognitivism, those of situated and embodied cognition. Embodied cognition insists that:

> Biological brains are first and foremost the control systems for biological bodies. Biological bodies move and act in rich real-world surroundings. (A. Clark & Chalmers, 1998)

Likewise, it is erroneous to consider the mind purely separate-and-apart from the body, as even "higher" cognitive functions are the product of evolutionary processes on the body. Similarly, situated cognition takes the view that:

> Human knowledge and interaction cannot be divorced from the world. To do so is to study a disembodied intelligence, one that is artificial, unreal, and uncharacteristic of actual behavior. What really matters is the situation… One cannot look at just the situation, or just the environment, or just the person: To do so is to destroy the very phenomenon of interest. (Norman, 1993)

Both of these perspectives draw heavily from ecological psychology, which focuses on how the environment affords various actions to the organism (Gibson, 1966). However, as Wilson (2002) points out, while cognition may have an embodiment origin, the mind certainly does possess "offline", reflective capabilities that are highly cognitivist in nature, though they can, and do, interact with more embodied processes.

VII.2.1 HMI Model Reconciliation

The disparate cognitivist and embodied philosophies are reconcilable, as first indicated by Sheridan (2001) through Rasmussen's Skill, Rule, Knowledge (SRK) Framework (Rasmussen, 1983) and dual-process theory, as typified by the dual-process theory and the heuristics & biases model (Kahneman, 2011), as demonstrated in Figure 25. In dual-process theory, the mind has two components: slow, purposeful, conscious, off-line processes (System 2), and our more automated, subconscious, on-line processes (System 1). For a more detailed evidentiary treatment, see Evans (2003). From this perspective, the cognitivist tradition can be said to focus on System 2 while the embodiment tradition identifies more with System 1. In line with Box's aphorism: "all models are wrong but some are useful" (1979) both describe behavior in different contexts.

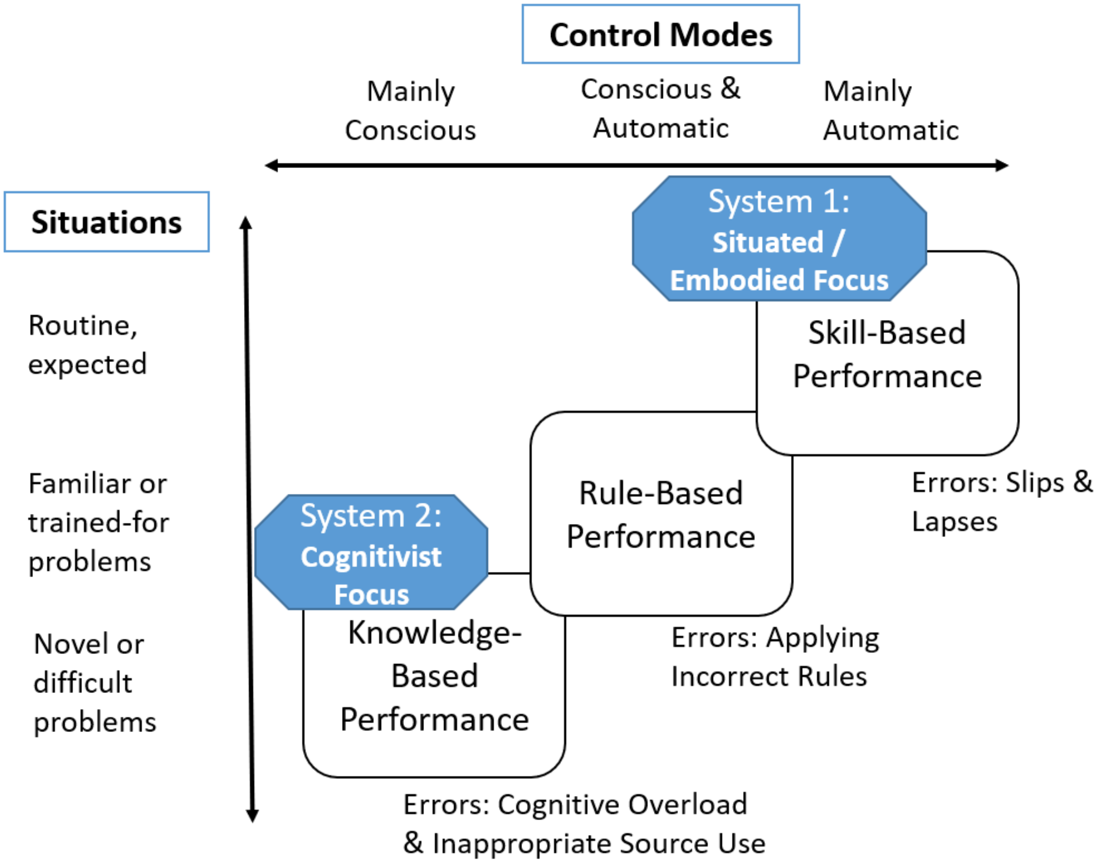


Figure 25. SRK, dual-process theory, and HCI. Adapted from Flight Safety Foundation (2010), System 1 & System 2 labels added.

From the SRK perspective, as we learn new domains, we start from base *knowledge* of a subject, modeling and deriving potential actions with heavily conscious System 2 usage. A beginner's action is slow, considered, and frequently awkward. As we gain more practice, we develop *rules* to govern how to respond and categorize our domain, quickly applying rules that match our familiarity. When we meet with novel arrangements, we modify our rules from our base knowledge of the subject. Finally, after we have practiced and pruned our rules, we begin to operate in the range of *skill*, with highly automated actions and responses in System 1, little governed by conscious, considered action.

Additionally, as System 2 resources have greater access to themselves, it is easier to apply conscious analysis to System 2 resources. When operating at a *knowledge* level, it is easy to explain to someone else why you perform a specific action and exactly how. However, when operating at a *skill* level, one can implicitly understand an action without being able to explain it, articulate its purpose, or even recognize that it is happening at all! Likewise, it's possible to explain all of the necessary components, but to not have the understanding to perform the actions oneself.

Wilson (2002) suggests a linkage between "online" and "offline" processes by noting that highly skilled experts, such as jugglers or drivers, maintain a greater degree of control over their situation, demonstrating clarity instead of chaos. Wilson accredits this to the expert's more sophisticated internal task representation. While I agree that the two components may operate cooperatively, expertise is not a matter of increasingly complex representations. Experts are simply better at identifying relevant components. The conscious System 2 mind offloads more and more from its limited capability to the more automated practices of System 1, freeing up limited cognitive resources.

This logic suggests that experts do not have significantly more detailed mental models, but rather a greater experience of ***recognizing discrete usable components***, in line with expertise literature such as Naturalistic Decision Making (Klein, 2008). This also describes results such as Gobet & Simon's (1998) comparison of mental model chunking between chess-masters and amateurs. While an expert may understand a system at a greater level of detail, they are more efficient at priming the components that are important to them while ignoring those that are irrelevant to the task. This is also seen in the neurological motor control level, as shown by Naito and Hirose (2014). While primarily a case study, they demonstrated that, when compared with several less experienced football players and athletes skilled in other areas, Neymar da Silva Santos Júnior, a notable Brazilian forward, demonstrated less medial-wall recruitment. Likewise, in a study of brain-computer interfaces, Nam found that fully paralyzed subjects were less effective than able-bodied participants at engaging purely motor-cortex controlled technology, with the latter showing more targeted neurological activation. This suggests that the brain, itself, may actually improve some types of performance by improving efficiency.

If we are to design technologies to use the sense of touch, we have to appreciate that it is highly embodied and more closely connected with System 1 strategies than with System 2.

VII.3 Domain Complexity, Design Envelope, & Challenges to Vibrotactile Communication

The real challenge is more inherent: an attempt to address multi-dimensional open worlds, not the carefully bounded closed worlds of the laboratory. As Woods (1988) notes, this problem of unanticipated variability is particularly difficult in contexts which are "highly dynamic and highly coupled, when the degree of uncertainty is high and when there are significant consequence[s] to potential outcomes". For vibrotactile design, this creates a conundrum: domains where vibrotactile systems are more desirable are more subject to unanticipated variation, which is addressed through error management and a more deliberate use of cognitive resources. As shown in Figure 25, haptics is primarily advantageous in the context of System 1's skill-based performance; however, error correction pushes operation into knowledge-based performance to account for dynamic shifts.

Haptics effective for immediate sensory feedback & attention directing, especially when coupled in a multi-modal environment where more detailed information can be presented through another sense. However, trying to develop an interface to present a larger amount of information becomes a tricky design challenge because of the need to account for the complexity of the domain.

This means that there are two potential approaches to developing more advanced vibrotactile systems: develop a scalable, extensible vibrotactile language or focus on domain problems that are more easily bounded.

CHAPTER VIII

IDENTIFICATION OF ORDINAL VIBROTACTILE ICONS UNDER COGNITIVE LOAD

VIII.1 Introduction

For General Aviation (GA) pilots, adverse weather is a significant threat, with fifty weather-related GA accidents occurring in 2012, thirty-eight of which proved fatal (Nall, 2012). Visual Flight Rules (VFR) is the base GA accreditation level, which limits pilots to flying only within Visual Meteorological Conditions (VMC). Moving beyond these parameters transitions flight into that of Instrument Flight Rules (IFR), which requires further training and accreditation. Previous work demonstrates that many weather-related GA accidents are caused by a pilot's inability to adequately perceive and assess actual meteorological conditions, essentially missing the VFR / IFR transition (Aarons, 2014; Pearson, 2002).

These effects are attributable to four different possibilities: 1.) the pilot doesn't receive the weather information; 2.) the pilot receives the information but doesn't understand it, due to being over-stressed and overloaded; 3.) the pilot receives the information, but it is incorrect; or 4.) the pilot receives and understands the message but decides to continue anyways. This study is focused on the second case, particularly in establishing whether or not vibrotactile interfaces can help reduce this risk.

Vibrotactile interfaces clearly cannot display the wide range of information that is communicated through vision, such as displaying an entire weather map. They can, however, provide levels of urgency mapping for interruption management, prioritizing the pilot's attention based on increasing stimuli. These sorts of ordinal signals are ubiquitous in other domains for graded warnings (e.g.: red, green, and yellow traffic lights). We wish to determine how the number of ordinal vibration levels a pilot can interpret under the cognitive workload of flight.

As discussed previously in Chapter XII, vibrotactile interfaces may be particularly useful in a well-defined domain. Previous work by Tippey et al. (2018) on GA weather interfaces established that vibrotactile is effective for directing pilot attention and improving situational awareness. However, the lack of statistical power made it difficult to provide concrete vibrotactile design recommendations, necessitating a follow-up study with a vibrotactile focus.

This chapter will demonstrate two things: how to design a discriminable signal set of ordinal vibrotactile signals, and how to evaluate their performance under a cognitive load.

VIII.1.1 Haptic Research Background

van Erp and Spapé have established that people are capable of identifying between vibrotactile signals with up to three levels of amplitude, five levels of frequency, & ten levels, if combined (2003). This finding has two primary limitations for direct application: cognitive load and performance standards. This was completed in-lab as a primary, uninterrupted task. While this demonstrates ideal performance conditions for the recognition of signals, vibrotactile signal development is frequently multimodal and must interact with other domain tasks, such as flying a plane, the stress and workload of which can lead to perceptual and cognitive tunneling (Stokes & Raby, 1989), a form of inattentional blindness (Mack & Rock, 1998). Additionally, the success measure for in-lab participants is recognition accuracy beyond random chance. However, the performance standard for a safety application must be higher.

Melody is more useful for detailed encoding than monotone rhythms. (Swerdfeger, Fernquist, Hazelton, & MacLean, 2009). The design of large sets of vibrotactile signals, perhaps even so large as 70 or 80 signals, may be possible by manipulating temporal components of *note length* and *unevenness* (Ternes & MacLean, 2008). Likewise, Azadi and Jones (2014) demonstrate an effectiveness of between 73% and 83% for five to six icons. As in the case of van Erp & Spapé, it is unclear if these effects are reliable under cognitive load and stress.

The first goal of this study is to define ordinal vibrotactile signal sets for use in the task environment. Similarly, ordinal haptic interfaces have been tested under cognitive load using a one degree-of-freedom torque-knob configuration, with "detent-wall", torque differential, and hapticon mappings resulting in average recognition rates of 83.9%, 92.9%, and 74.6%, respectively (Tang, McLachlan, Lowe, Saka, & MacLean, 2005). Unfortunately, all conditions consisted of a five-signal set, limiting recommendations over the number of levels to be used. While useful for determining haptic viability for ordinal presentation, similar work should address current GA domain vibrotactile interfaces.

VIII.1.2 Musical Recognition

Vibrotactile stimuli are most analogous to audition, possessing qualities such as pitch / frequency, amplitude / volume, and temporal timing. This has not been lost on researchers, who have developed several systems for the display of vibrotactile music, primarily as an avenue for providing musical experiences for the deaf (Branje, Maksimouski, Karam, Fels, & Russo, 2010; Nanayakkara, Taylor, Wyse, & Ong, 2009). However, as compelling as these prototypes are, there appears to be no case where their performance has been validated.

Because of this, it remains unclear to what degree people are capable of recognizing music presented solely through vibrotactile stimuli.

Vibrotactile melody recognition has the practical advantage of expanding potential icon sets. If people demonstrate an emergent capability of recognizing familiar melodies, it may be possible to create a functionally infinite set, similar to the range of ringtones available for cellphones. If this recognition is particularly strong, it may improve recognition accuracy and speed, compared to mappings that are more arbitrary.

VIII.1.3 Target Technologies

Many different vibrotactile actuators are used for GA interfaces, with new approaches currently in development. To provide effective guidance for FAA recommendations, we identified three categories: eccentric rotating mass (ERM), linear resonant actuator (LRA), and variable frequency actuators. These categories can be viewed as previous-generation, current-generation, and near-future technologies.

ERMs are the ubiquitous choice for vibrotactile interfaces. Cheap, widely available, and simple, they are present in almost any product that shakes, including children’s toys. ERMs are motors with off-center mounted weights. As the motor spins faster, the centripetal force causes a displacement that is felt as vibration. This leads to three primary application concerns: 1.) coupled frequency and amplitude; 2.) slow start-up and settling times; and 3.) inefficient power-consumption.

LRAs are composed spring-mounted mass, driven by an electromagnet. Cycling the magnet caused vibration from the oscillating mass. This allows for more rapid starts and stops, within a range of 5-10 ms, compared to the ERM’s 20-50 ms, along with independent control of signal amplitude (Bala, 2106). However, because this assembly relies upon a spring, the response is limited to a specific resonance frequency, with sharp decreases in amplitude outside of it.

Solenoid-based variants on the LRA, such as the EAI C2 tactors used throughout this research, allow for a wider range of frequency expression as they are not resonance limited. Likewise, piezoelectric actuators contract in response to an electrical current and provide a much faster response at a wider range of frequencies than LRAs. However, as novel electrical components, they're not as readily available as the other devices mentioned, and the use of such devices at a production scale may be cost prohibitive, but this is unlikely to be a factor of concern in near-future applications.

VIII.1.4 Signal Design

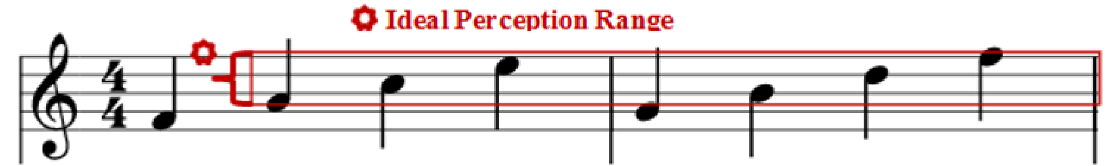
The C2 tactors have a frequency response range between 100 and 350 Hz. This compares favorably with both the ideal range of vibrotactile perception and the musical notes between middle A and high F, as shown in Figure 26, with 250 Hz (middle B) serving as the most salient. Therefore, it is reasonable to consider the design of musically-analogous vibrotactile icons using musical notation.

Note (L to R)	F	A	C	E	G	B	D	High F
Frequency (Hz)	174.6	220	261.6	329.6	196	246.9	293.7	349.2

Figure 26. Tactor tuning. Ideal vibrotactile perception range from (Makous et al., 1995; Shimoga, 1992; Verrillo, 1966)

The resonant frequency of LRAs is a major constraint for hapticon design, limiting signals to a single frequency and reducing discriminability (Swerdfeger et al., 2009). In this study, such icons were targeted at middle B for maximum saliency and are referred to as "Syncopated", as the variation in timing and duration of stimuli is similar to the musical concept of syncopation, or Ternes & MacLean's (2008) "note length & unevenness".

Other developing vibrotactile technologies such piezo-electric haptics and the EAI C2 tactor system combine more precise temporal control with frequency variation. Per Swerdfeger et al. (2009), we expect this addition increase perceptual signal distance and improve performance. Signals developed with both variable frequency and temporal variation will be referred to as "Melodic".

Finally, as ERMs are slower to respond to signals, resulting in "muddier" seeming icons, we present a "Counted" condition based on the number of signals provided within a one-second window. This allows for subjects to identify signals both on the duration of individual signals and by counting them.

Figure 29 demonstrates differences between signal types, please see Figure 30 in Results of details over the specific signals chosen.

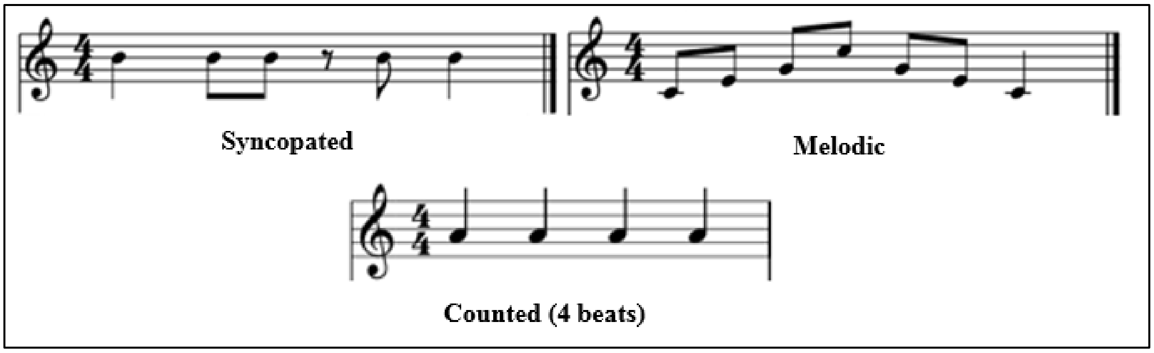


Figure 27. Signal presentation Methods.

VIII.1.5 Hypotheses

The expectation of this work is that musically-analogous signals can be used to develop perceptually distinguishable ordinal sets. The two studies test the following assertions.

Verification Study

H1: Participants will report a wider range of between-signal differences for melodic signals than for syncopated signals

H2: Participants will perform better than chance at recognizing familiar vibrotactile melodies

Cognitive Load Study

H3: Participant recognition performance will favor the following presentation methods, in order, Melodic, Syncopated, and then Counted.

H4: The Melodic presentation method will be more robust to Levels and MATB induced cognitive workload.

VIII.2 Methods of Verification Study

Twenty-five participants were recruited from the student body of Texas A&M University through flyers and email recruitment; one participant's data was dropped from consideration due to loss-of-data from technical issues, resulting in a study size of twenty-four (IRB approval: IRB2016-0825D). After initial consenting protocol, participants were outfitted with an EAI C2 tactor fastened tightly to the inside of their wrist and a pair of noise-cancelling headphones to prevent auditory interference.

Participants completed a multiple-choice response survey of unforced pairwise comparisons between every signal within each treatment set, resulting in forty-five questions per treatment. (10 signals, C(10,2)) . Valid responses were: a.) Signal A > Signal B; b.) Signal A = Signal B; and c.) Signal A < Signal B. Participants were able to repeat signals as desired. Half of participants started with the Syncopated condition, and the other half with Melodic.

After completion of the first treatment, participants participated in a four-choice identification quiz for ten different snippets of common melodies. This served as both as means of testing musical recognition and as a buffer between treatments.

VIII.2.1 Signal Set Selection

Subject pairwise comparison answers, $x_{n,i,j}$, were coded as follows: -1, A > B; 0 A = B; and 1 A < B, where n is the subject number, and *i* and *j* are the signal numbers. Total between-subject agreement for each comparison was calculated according to Equation 1. $X_{A,B}$ measures the relationship between A and B on (-1,1), with -1 being complete subject agreement that A > B, and 1 that A < B. Signal sets of 3, 4, and 5 were selected according to the following algorithm:

1. Calculate average between-subject agreement ($X_{i,j}$) for each signal comparison

$$X_{I,J} = \sum_n \left(x_{n,i,j}\right) \Big/ N$$

$$Signals: i, j \in \{1, \ldots, 10\}; i < j$$

Equation 1. Average between-subject agreement

2. For each signal set size, (3 signals, 4 signals, and 5 signals) enumerate every signal order permutation. In this instance, permutations were calculated using the *gtools* package (Warnes, Bolker, & Lumley, 2014) Calculate the total "set strength" of each by summing all between-subject agreement scores, respecting their signs. For example, in Figure 28, the relationship X_{BC} would be positive, indicating that C > B. If this order were reversed, the BC relationship would change sign, reducing the overall set strength.

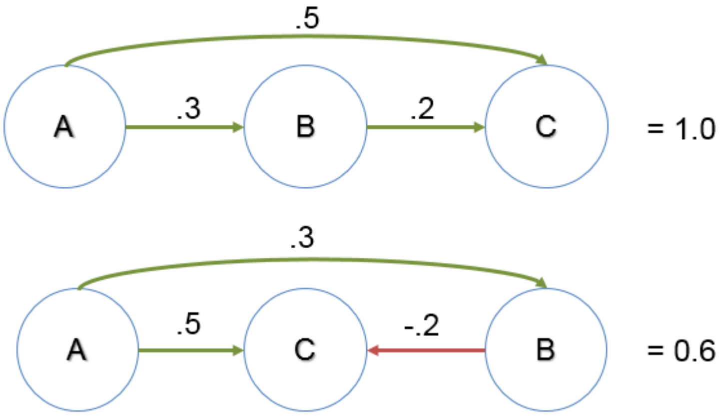


Figure 28. Total set strength calculation

3. Divide these top candidate scores by σ, the standard deviation of X_{ij} along the signal set's path. The path of a signal set, Figure 29, is defined as the relationships that are specifically between each level of signal. For example, the set [A, B, C] would consider X_{AB} and X_{BC} as "path" relationships, but not X_{AC}.

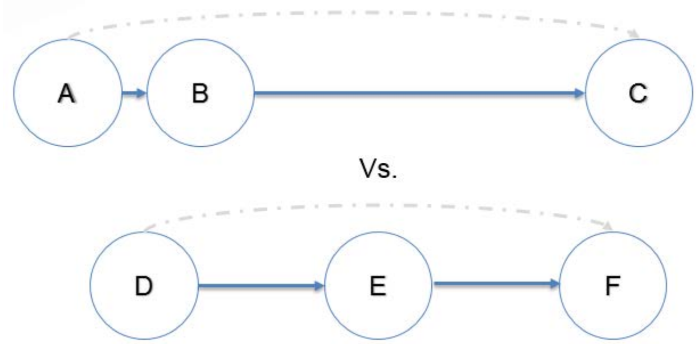


Figure 29. Signal path.

The objectives of this algorithm are two-fold: 1.) to find the signal set with the strongest subjective underlying ordinal relationship, and 2.) to find a set whose components are discriminable from each other.

In regards to resolution of the subject-agreement index, if one participant were to rate a relationship one level different (e.g. giving it a 0, instead of -1), the index would change by .04. By this logic, the real difference between top candidate sets may be partially obscured by noise. In regards to the first goal, it is important to consider a reasonably wide collection of candidate sets.

Based entirely on the first objective, there are many ties in set strength that are differentiated by only a handful of responses. Step 4, the scaling of set strength by path standard deviation, was undertaken as a tie-breaker to fulfill the secondary objective. Initial calculations of set strength did not account for the possibility that several strong relationships might dominate the set strength scoring and result in discrimination difficulty, as in the case of [D,E,F] in Figure 29.

VIII.3 Results of Verification Study

As shown in Table 1, sets selected for Syncopated conditions were [3,5,1], [3,5,9,1], and [3,4,5,7,1]. Sets selected for the Melodic conditions were [6,9,5], [6,8,4,5], and [6,8,9,1,5]. For illustration of identified signals, please see Figure 30.

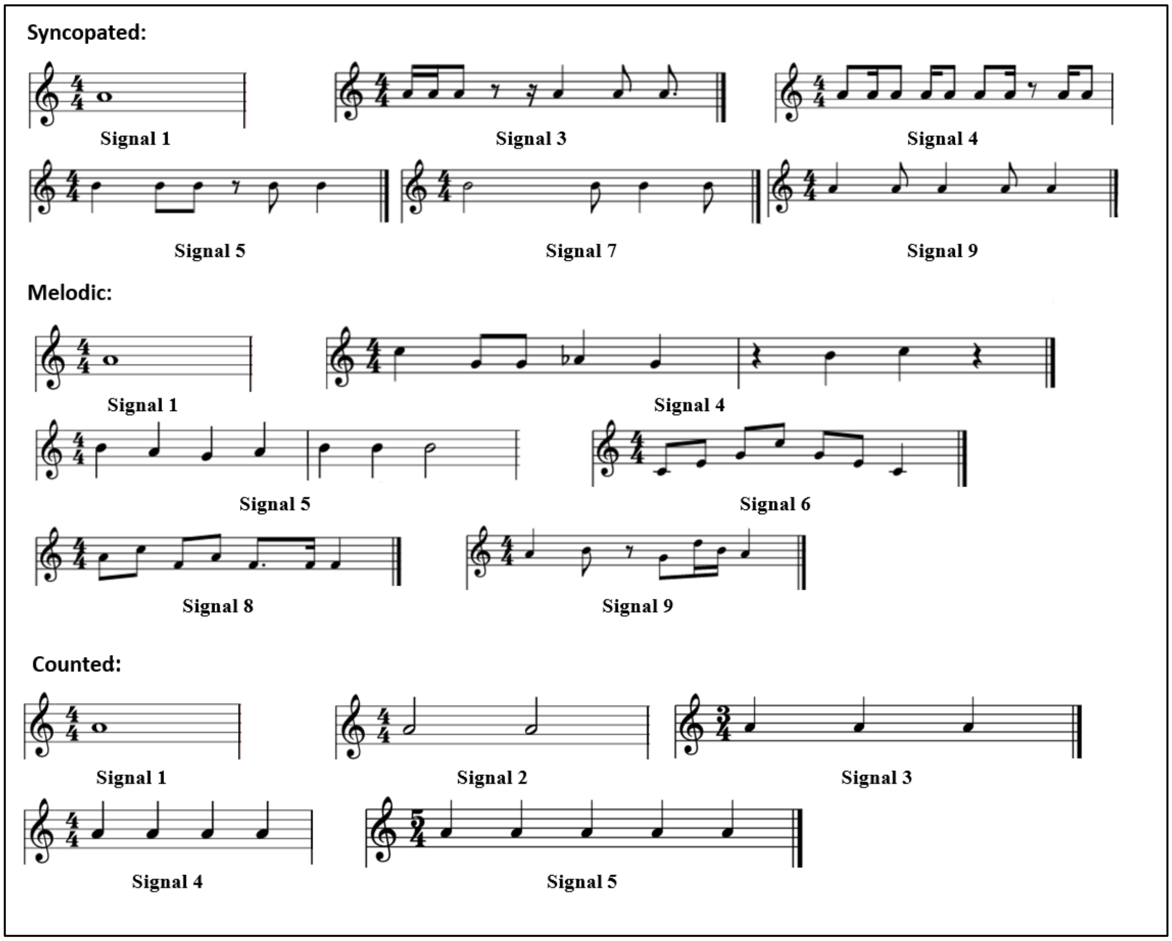



Figure 30. Signals chosen for cognitive load study. Tuning based on Figure 26. Signal sets chosen according to Table 1.

Syncopated Signals				**Melodic Signals**			
Signal Set	**Set Strength**	**Path σ**	**Strength /σ**	**Signal Set**	**Set Strength**	**Path σ**	**Strength /σ**
3 Signals							
[4, 6, 7]	0.646	0.029	21.92	[6, 8, 5]	1.104	0.133	8.33
[3, 6, 7]	0.646	0.044	14.61	[6, 4, 5]	1.083	0.030	36.77
[3, 5, 1]	**0.617**	**0.015**	**41.86**	[6, 7, 5]	1.083	0.030	36.77
[3, 1, 6]	0.533	0.200	2.66	[6, 1, 5]	1.063	0.162	6.56
[3, 6, 1]	0.533	0.029	18.102	**[6, 9, 5]**	**1.063**	**0.015**	**72.13**
4 Signals							
[3, 4, 6, 7]	1.146	0.098	11.64	[6, 8, 1, 5]	2.083	0.098	21.16
[4, 3, 6, 7]	1.063	0.098	10.79	**[6, 8, 4, 5]**	**2.000**	**0.032**	**62.85**
[3, 5, 9, 1]	**1.054**	**0.084**	**12.52**	[6, 8, 9, 5]	1.938	0.048	40.27
[3, 5, 7, 1]	1.033	0.087	11.91	[6, 8, 3, 5]	1.938	0.126	15.43
[8, 3, 6, 1]	0.971	0.110	8.81	[6, 7, 1, 5]	1.938	0.073	26.48
5 Signals							
[3, 4, 6, 7, 1]	1.617	0.111	14.58	[6, 8, 9, 3, 5]	3.083	0.095	32.36
[3, 4, 5, 7, 1]	**1.554**	**0.073**	**21.31**	**[6, 8, 9, 1, 5]**	**3.063**	**0.040**	**76.77**
[3, 4, 5, 6, 7]	1.542	0.082	18.90	[6, 7, 8, 1, 5]	3.021	0.143	21.15
[3, 4, 6, 5, 7]	1.542	0.107	14.44	[6, 8, 4, 1, 5]	3.021	0.100	30.29
[3, 4, 1, 6, 7]	1.533	0.085	18.03	[6, 8, 9, 2, 5]	3.021	0.077	39.34

Table 1. Signal set scoring between-subject agreement for Syncopated and Melodic stimuli for top five candidates. Bold indicates selected sets.

When comparing Syncopated and Melodic conditions, it appears the latter has greater signal distance (Figure 31). In Table 2, the strongest Syncopated relationship, .283, would only be in the Melodic 3rd quartile, while the median Syncopated score, .083, would fall into the bottom quartile of the Melodic condition.

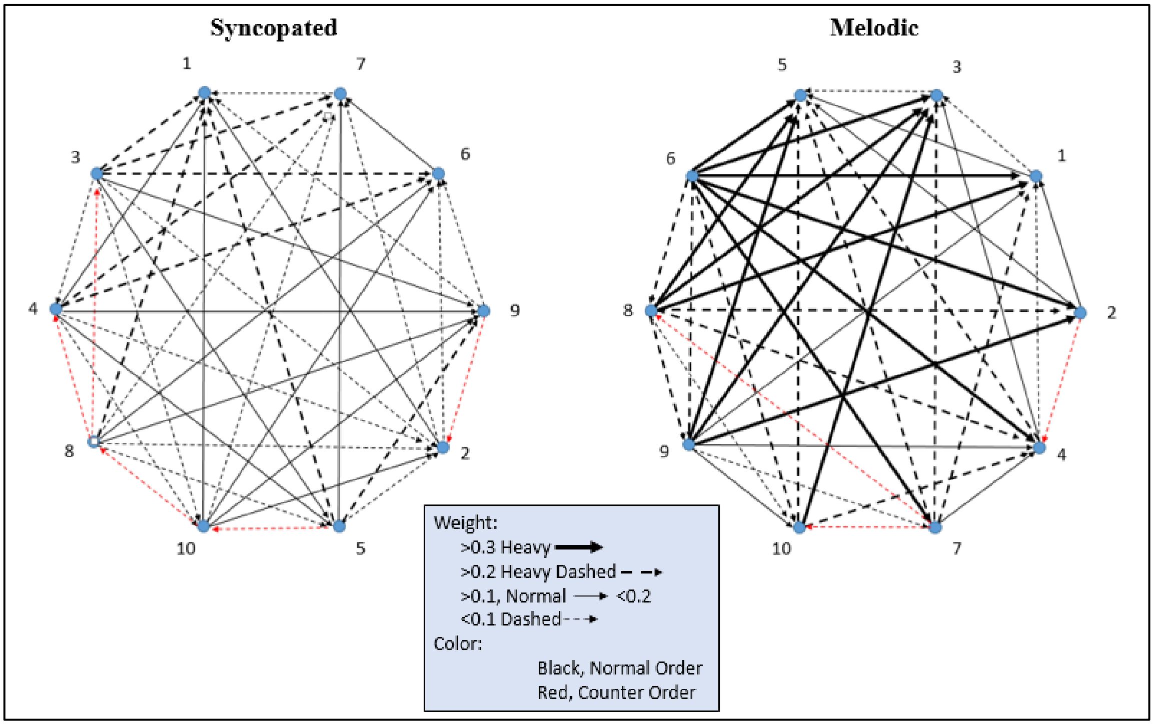


Figure 31. Syncopated and Melodic Comparisons, K10 Graphs. Decreasing subject-rated intensity moving clockwise from top-left signal. Red indicates counter-order relationships.

	Min	**1st Quart.**	**Median**	**Mean**	**3rd Quart.**	**Max**	**Std. Dev.**
Syncopated	0.000	0.042	0.083	0.109	0.1670	0.283	0.079
Melodic	0.021	0.146	0.229	0.2306	0.313	0.458	.116

Table 2. Summary statistics for between-subject ratings of Syncopated and Melodic signals

VIII.3.1 Musical Recognition

Song	% Correct
Mary Had a Little Lamb	73.1
Here We Go ‘Round the Mulberry Bush	38.4
Ring Around the Rosy	76.9
Twinkle Twinkle Little Star	50.0
Frere Jacques	61.5
Bingo	50.0
Old MacDonald	80.8
The Wheels on the Bus	57.7
The Itsy-Bitsy Spider	50.0
The Imperial March (Vader’s Theme)	69.2

Table 3. Musical recognition

Using a t-test for proportions, there was sufficient evidence (T= 4.41, n = 18, p = .0002) to reject the assumption that participant identification of melodies was no better than random chance (25%), suggesting that the true recognition performance is actually greater, somewhere between 43% and 83%.

VIII.4 Discussion of Verification Study

Results appear consistent with the first hypothesis. The apparent signal distance shown between Syncopated and Melodic suggests that the latter condition should demonstrate a larger performance benefit, due to easier recognition.

This analysis method is not adapted from previous studies, and it is unclear whether the reported magnitudes of average between-subject agreement scores are particularly strong or weak. While it is a reasonable claim that the Melodic condition demonstrates a larger signal-distance than the Syncopated condition, it is unclear whether the overall relationship is strong enough to affect performance.

Data suggests that participants were also capable of recognizing familiar melodies purely through vibrotactile stimuli. Following the completion of the study, it is also clear that instead of depending on user background to define song familiarity, it would have been more direct to simply ask participants whether they were familiar with each song at the end of the study.

VIII.5 Methods of Cognitive Workload Study

Following the signal set selection from the verification study above, twenty-one participants were recruited from Texas A&M University via mass email (IRB approval: IRB2017-0269D) to participate in a study identifying vibrotactile signals while performing in the NASA's Multi-Attribute Task Battery II (MATB) environment (Santiago-Espada, Myer, Latorella, & Comstock Jr, 2011). Eighteen participants were necessary to complete the Latin-squares partial counterbalance study design. Two withdrew from the study due to unexpected scheduling conflicts and one participant was dropped from analysis due to failure to follow instructions.

MATB was chosen due to the strength of between-subject replicability, focus on cognitive workload during flight, previous familiarity with treatment design (Rodriguez-Paras, Yang, & Ferris, 2016; Rodriguez-Paras, Yang, Tippey, & Ferris, 2015; Rodriguez Paras, 2015), and its use other in other established studies, for instance: (Caldwell Jr, Caldwell, Brown, & Smith, 2004; Gutzwiller, Wickens, & Clegg, 2014).

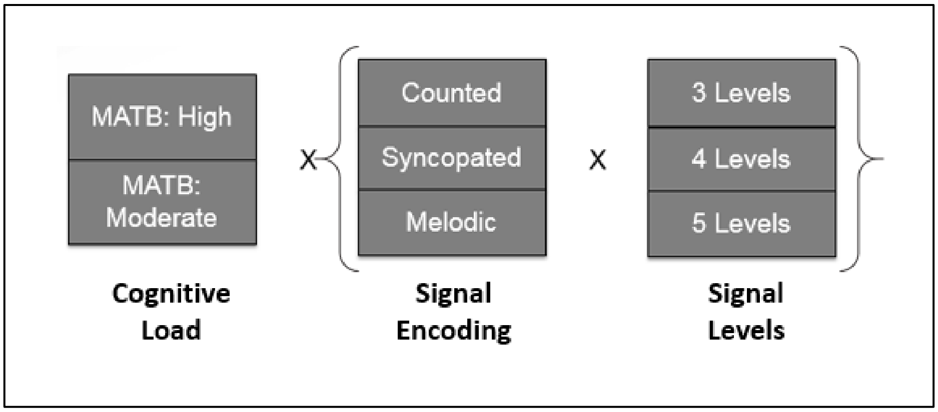


Figure 32. Cognitive workload study design

The study followed a 2 x 3 x 3 full factorial repeated-measures model, as per Figure 32. Treatments were presented in partial counter-balanced blocks of nine treatments (Signal Encoding by Signal Level). MATB levels were presented in alternating order, starting with Moderate difficulty. Treatments that were assigned to one MATB condition in the first nine treatments were then presented under the other MATB condition, preventing clustering of participant observations in conditions with High or Moderate MATB conditions. This was done to prevent uneven participant fatigue due to extended high workload conditions. Treatment order was assigned according to a Latin-square partial counterbalance to prevent order effects.

Trials were four minutes long, and consisted of fourteen signals, in which each signal was represented as evenly as possible, favoring more repetitions for lower-intensity signals. For instance, a signal set with four levels would consist of the following: four level 1 signals, four level 2 signals, three level 3 signals, and three level 4 signals. Each signal was presented twice, with a one-second gap between to aid in recognition. Time between signals was generated from a triangular distribution with a minimum of fifteen and a maximum of twenty-five. This provided some unpredictability to each individual signal but allowed each treatment to consistently have fourteen signals.

All data were analyzed within R (R Core Team, 2017). Analysis can be found in Appendix E. In the analysis of signal identification, the dependent variable demonstrated a high degree of non-normality (Shapiro-Wilk Normality Test, W= 0.907, p= 3.166e-13), violating both the normality and sphericity assumptions for repeated-measures ANOVA. Four candidate methods were identified that could handle full-factorial, repeated-measures designs: Generalized Linear Mixed Models (GLMM), Generalized Estimating Equations (GEE), Kaptein's Method, and Aligned Rank Transform (ART). Two were chosen: GLMM and ART.

GLMM was analyzed with the *afex* package (Singmann, Bolker, Westfall, & Aust, 2015), which utilizes *lme4* (Bates, Maechler, Bolker, & Walker, 2014) to perform linear mixed models analysis (also known as mixed effects), in accordance with Winter (2013) and Singmann and Kellen (2017), as logit mixed models are more appropriate for categorical data analysis, particularly binomially distributed outcomes (Jaeger, 2008). We use fixed effects of MATB, Levels, and Method, with all interactions and random-slopes to adhere to the maximal model and reduce anti-conservative tendencies (Barr, Levy, Scheepers, & Tily, 2013), as per direct recommendation from the creator of the *afex* package(Singmann, 2018; Singmann & Kellen, 2017). Subject was used as the random effect. A further, reduced random-intercepts model is also provided in Appendix E for reference to the maximal model. P-values and interaction effects were obtained through least likelihood ratio tests of the full model without the effect in question. Follow-up testing was accomplished through estimated marginal means in the *emmeans* package (Lenth, 2016).

ART was chosen to provide a non-parametric method to compare against GLMM and account for potential sphericity and normality considerations. Analysis was performed using Wobbrock et al’s (2011) Aligned-Rank Tool. Significant pairwise interactions were analyzed with Wilcoxon signed-rank post-hoc tests.

VIII.6 Results of Cognitive Workload Study

The overall mean for correct identification of signal was 72%. Count provided the best performance across all Levels (83.4%) and 3 Levels provided the best performance across all Methods, as shown in Table 4. A cross-over effect was observed between Melodic and Syncopated signals, with Melodic out-performing Syncopated at 3 Levels and 5 Levels but underperforming at 4 Levels (Figure 33). The effect of Levels, Method, and MATB conditions on signal recognition can be seen in Figure 34.

		Levels			
		3	**4**	**5**	
Method	**Sync**	76.8%	69.2%	56.3%	67.4%
	Mel	79.6%	56.5%	59.7%	65.3%
	Count	88.9%	83.5%	77.9%	83.4%
		81.7%	69.7%	64.7%	72.1%

Table 4. Mean correct identification, by Levels and Method.

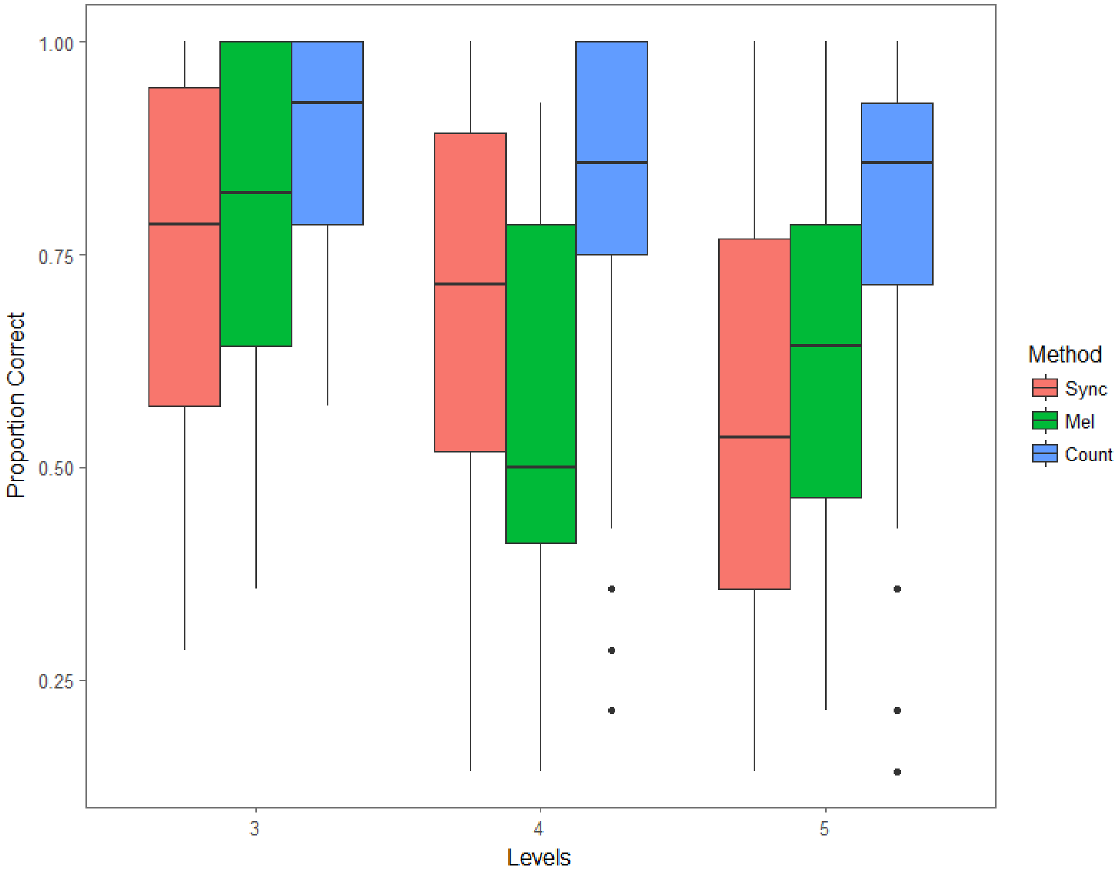


Figure 33. Correct signal identification vs. Levels by Method. Points represent outliers

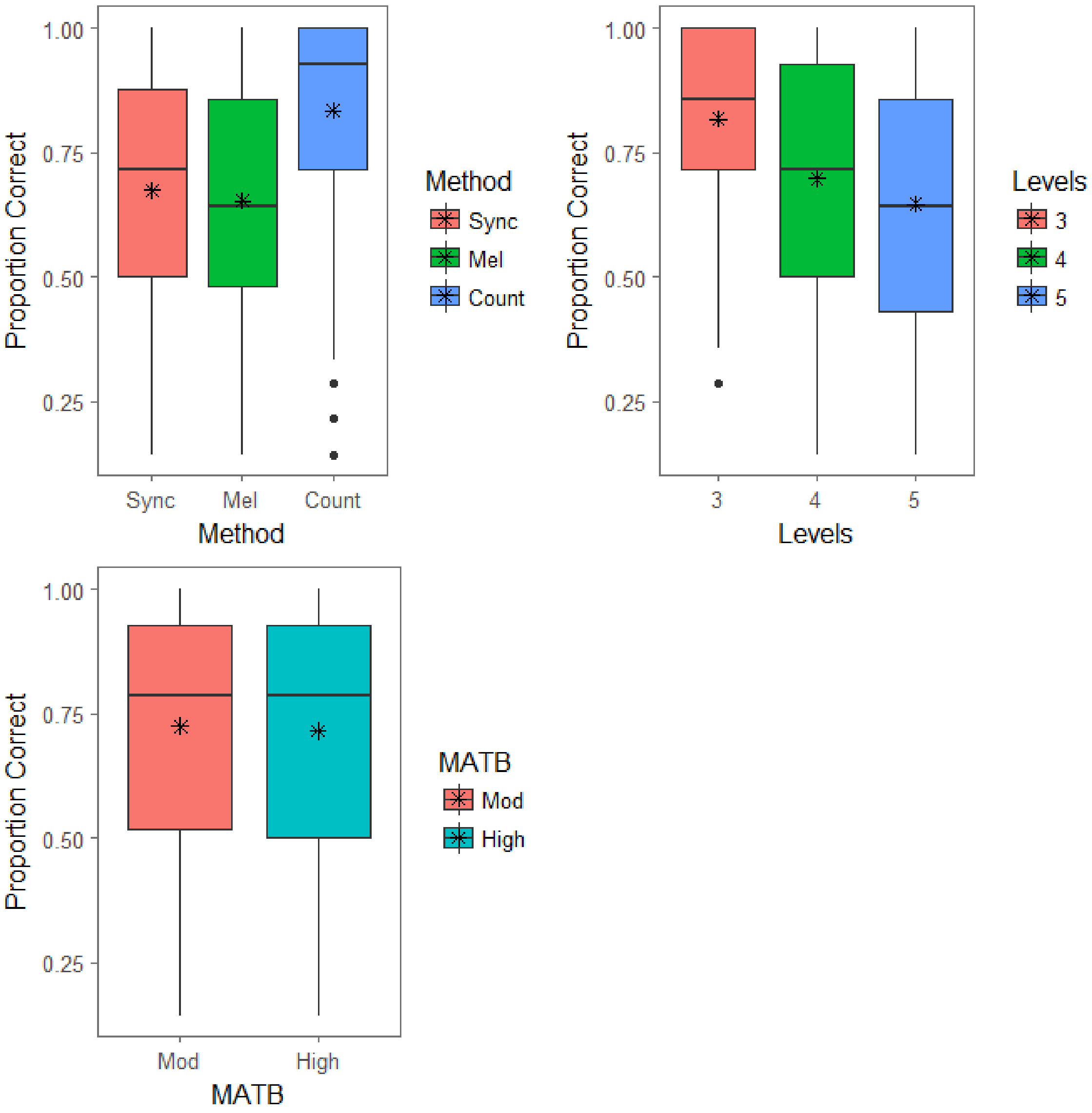


Figure 34. Proportion of signals correctly identified vs. Method, vs. Levels, and vs. MATB. Black stars represent means.

VIII.6.1 Non-Parametric Analysis

The three-way, within-subjects Aligned-Rank omnibus test for interactions indicate a significant interaction effect between Method and Levels (F=5.131, p <.001), as well as main effects of both Method (F = 54.322, p<.001) and Levels (F = 35.213, p < .001). No significant effects were found for any effects containing MATB.

A Wilcoxon signed-rank post hoc test for simple main effects on the Method and Levels interaction is displayed in Table 5, alongside their Bonferroni-correction adjusted p-values. Of particular note, Counted was significant from other methods at all Levels. Within Levels, the results are less clear. For Syncopated the comparison between 3 Levels and 4 Levels did not reach significance, but between 4 Levels and 5 did. For Melodic, the comparison between 3 levels and 4 Levels is significant, as it performs worst at 4 Levels.

	P-Values			**Bonferroni Adjusted**		
	Within Levels					
Method	**in 3**	**in 4**	**in 5**	**in 3**	**in 4**	**in 5**
Sync v Mel	0.2983	0.003995	0.2885	0.5771	0.0160*	0.5771
Sync v Count	0.00062	0.004421	2.84E-05	0.0043*	0.0160*	0.0002*
Mel v Count	0.002856	1.23E-05	0.0006583	0.0143*	0.0001*	0.0043*
	Within Method					
Levels	**in Sync**	**in Mel**	**in Count**	**in Sync**	**in Mel**	**in Count**
3v4	0.1141	1.19E-06	0.01034	0.228	0.000*	0.041*
4v5	0.002129	0.2776	0.04149	0.011*	0.278	0.124
3v5	1.89E-05	3.32E-05	0.0007321	0.000*	0.000*	0.004*

Table 5. Wilcoxon signed-rank test p-values for signal identification Method:Levels interaction

VIII.6.2 Logistic Mixed-Models Analysis

The maximal logistic mixed-models analysis, via least likelihood ratio tests, found significant effects for the interaction of Method and Levels ($\chi2 = 10.19$, $p = .04$). Interaction effects for Method-by-MATB ($\chi2 =1.87$, $p = .39$), Levels by MATB ($\chi2 = 1.56$, $p = .46$), and the three-way interaction ($\chi2 =3.02$, $p = .56$) were not significant. Main effects were found for Method and for Levels ($\chi2=20.14$, $p < .0001$; $\chi2 = 28.93$, $p < .0001$). For calculation details, including interaction effects, please see A.2.2.

Figure 35 shows the estimated marginal means for post-hoc testing. The left side demonstrates the logit-transformed data that is used for hypothesis testing, resulting in much wider confidence intervals. The right side demonstrates the same scale when back-transformed, presented for the reader to help interpret scale. However, it is not advisable to use back-transformation for hypothesis testing.

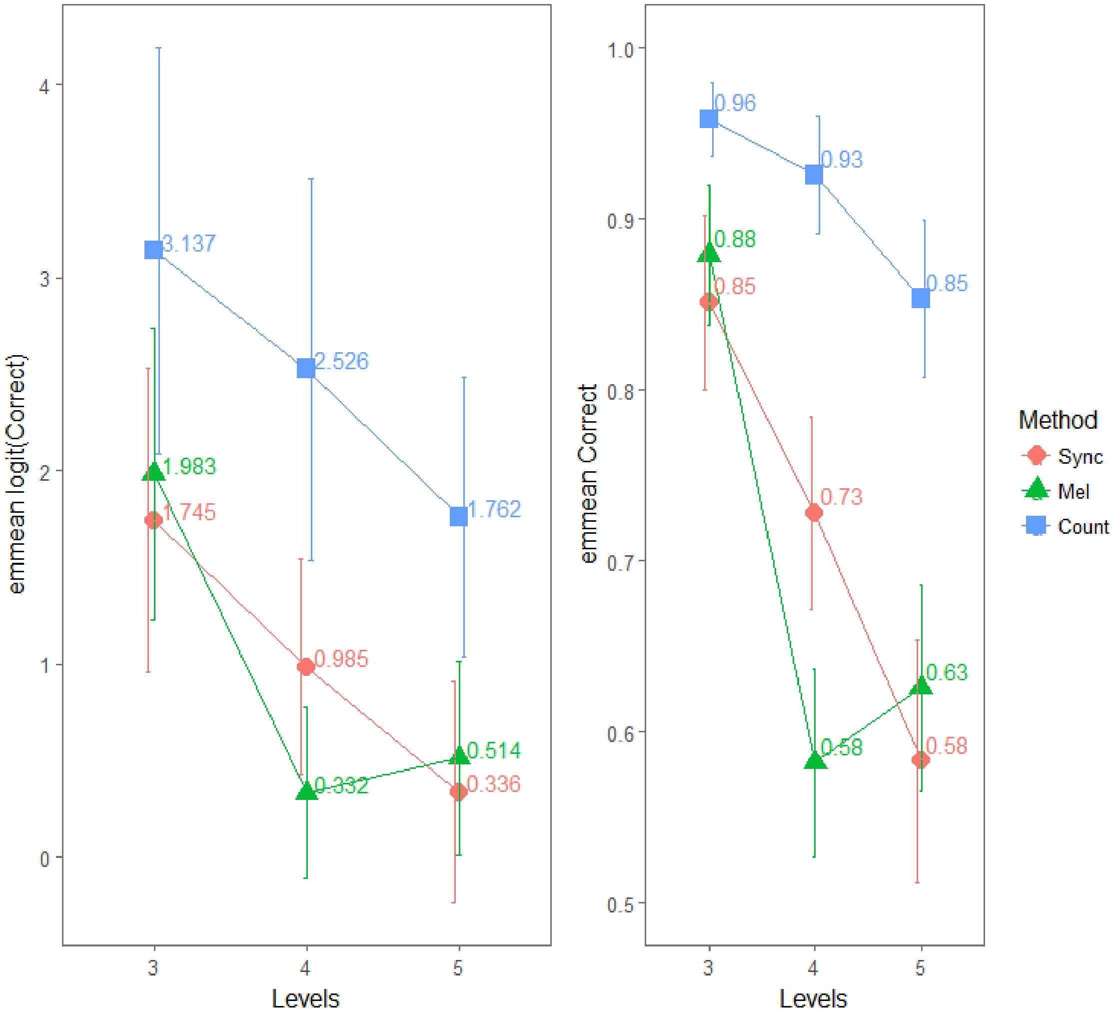


Figure 35. Maximal logistic mixed-model. Left, logit-transformed data used in hypothesis testing. Right, back-transformed data for readability, not used for hypothesis testing.

VIII.7 Discussion

Pilots currently report very little interest in smartwatch technologies, but simultaneously demonstrate a high level of comfort with in-cockpit technology. (Johnson, Pokodner, & Caldwell, 2016). The barrier to implementation of in-cockpit vibrotactile wearables is high; manufacturers of these devices must take care to not only develop effective devices, but to provide convincing evidence of device efficacy. Incremental interface development through a series of public releases might damage user acceptance, so a viable implementation strategy must be sure to first establish efficacy.

Our data indicates that Hypothesis 3 should be rejected. Of the vibrotactile encoding methods tested, musically analogous hapticons (Melodic & Syncopated) show an insufficient effect on pilot performance to justify their use in the communication of alert levels. The mixed-model results show a difference between 3 Levels and 5 Levels, but not step-wise between Levels. Counted is distinguished from the other two Methods only at Level 5, and marginally overlaps at 4 Levels. Additionally, this model predicts higher averages for Counted than the raw scores. The ART is more optimistic, recommending a distinct difference between Counted and the other two conditions (Table 5), but didn't discriminate between Melodic and Syncopated as much. This difference is potentially due to ART's greater robustness to non-normality and the intentionally more conservative nature of the maximal mixed-model. Regardless, there is sufficient evidence to reject Hypothesis 4; of any of the methods, Counted is most likely to be robust to workload and number of Levels.

While musical icons were expected to provide a greater improvement on recognition, in line with van Erp and Spapé (2003) and Ternes and MacLean (2008), two factors must be considered: acceptable recognition performance and cognitive load. First, what counts for an acceptable level of recognition in the context of the laboratory depends on recognition being better than chance, which is not nearly reliable enough for ensuring safety. Second, previous laboratory conditions were focusing on unstressed, single-task recognition, thus why it was important to test and see if increased cognitive workload provides a cognitive tunneling effect. Unfortunately, as the MATB factor did not significantly affect performance, it is difficult to conclude on the magnitude of effect that cognitive load played in this case. Further analysis of the biometric data will be necessary to establish workload differences.

The unexpected performance improvement provided by the Counted signal condition may be due to an increase in redundant elements within the signal. In the case of Syncopated and Melodic, the participants were depending on the subjective intensity of the signal and their memorization of the icon order. However, in the Counted condition they had the benefit of being able to both feel the difference in pulse-length and count the number of pulses in each signal. The latter also provided a clear index over the signal's ordinal rank, without having to remember its relationship to the other signals.

The cross-over effect between the Syncopated and Melodic condition in Figure 33 is particularly surprising. The verification study led us to expect a clear performance benefit for Melodic in comparison with Syncopated. However, the inconsistency between performances at different signal levels suggests that, in this study, the differences between the two conditions were not substantial enough to have a reliable effect. This may be due to two different considerations: cognitive workload's weak effect on performance and the large amount of between-subject variance. Regardless, the hypothesis of improved perceptual signal distance is not supported by these results.

This study focused on the analysis of a single, wrist-worn tactor. While appropriate for the context of current GA wearables, this data does not consider the possibility of using arrays of tactors. However, such large devices would certainly be a departure from the form factors used for GA devices and would likely be of consideration only for commercial and military application. Likewise, there was not a focus on sustained training, as extended training to familiarize with a device is also undesirable within a GA domain.

Further, this study is prone to similar population errors found in much of academic psychology in its use of a student population. Pilots are a relatively small population and expensive to recruit. While students are convenient, most are not pilots and substantial differences should be expected due to experience and training. Additionally, the student population is substantially younger than the average GA pilot, so age effects may also be significant. The results discovered here are useful, however, for defining future analyses of pilots and setting baseline performance standards to make for more effective use of GA pilot subjects in the design of experiments.

Future work should focus on the testing of Counted signal sets in less artificial, more ecologically valid flight conditions with pilots. Additionally, there is merit in establishing the reliability of auditory icons under similar domain conditions to establish cross-comparison criteria for acceptable performance levels.

CHAPTER IX

CONCLUSIONS

IX.1 Research Questions

The studies presented here aim to expand understanding of the design and evaluation of vibrotactile interfaces in dynamic environments and may be viewed in light of the research questions established in Chapter III.

Question 1: How do you manipulate tactile dimensions to design perceptually distinguishable sets?

As established in Chapter IV, if there are multiple body locations available, it is possible to utilize the saltation illusion to provide a greater sense of motion. This may reduce the number of tactors necessary and provide another dimension of signal redundancy.

In the case of graded warnings, it is possible to develop sets of signals based on subjective user feedback by using the method demonstrated in the verification study of Chapter VIII. While it is unclear whether the specific signal sets developed in this study were differentiated enough to be beneficial for direct application, the same method may be useful with other signals.

Question 2: Do more embodied communication systems improve performance in speeded, cooperative tasks?

The cooperative navigation tasks discussed in Chapters IV and V provide some evidence for the efficacy of embodied interfaces. When the experimental apparatus was reasonably reliable and participants were confident in it, interfaces using gesture and vibrotactile provided performance benefits, suggesting that using physical tasks for physical instruction may make it easier to connect intention and action. Unfortunately, these benefits were not forthcoming when applied to a more complex environment, as participants had difficulty assigning error to either the other participant, their own action, or the apparatus itself.

Question 3: How does cognitive workload affect the perceptibility of vibrotactile displays?

The signal recognition rates demonstrated in Chapter VIII's cognitive workload study are within the values predicted by preceding work, providing evidence that vibrotactile systems are robust to cognitive workload. However, as the workload manipulation, itself, was not significant, it is difficult to establish the scale of effectiveness without analyzing other data, such as biometric markers or flight performance.

IX.2 Work in Context

Interpreting the preceding experimental results is partly a matter of establishing where these and related studies fit in regards to Figure 25. Where does each study lie on the continuum between Skill and Knowledge? Such distinctions are partly subjective but are mostly a matter of arbitrariness and abstraction. Do the stimuli used link directly to the action, or is interpretation necessary? A tap on the shoulder is more direct and intuitive than an arrow pointing in the needed direction, which is still more intuitive than an unrelated snippet of music.

Previous work by the same individual can frequently can be placed on different ends of the continuum. For instance, vibrotactile counter-measures for spatial disorientation in pilots (van Erp, Groen, Bos, & van Veen, 2006) could be viewed as more Skill-focused, where van Erp and Spapé (2006) demonstrates more of a Knowledge-focused context of signal interpretation.

This is also the case here, as roughly-illustrated in Figure 38. Chapter IV's use of body location to provide cues places it more in the territory of Skill, where communication breakdowns pushed subjects into error-correction during Chapter V. Chapter III's focus on how to pack consistently more information into a signal meant that performance decrements between low and high complexity signals are due to increasing need for interpretation. Finally, Chapter VIII's signals were decidedly symbolic, depending on subjective evaluations of "intensity".

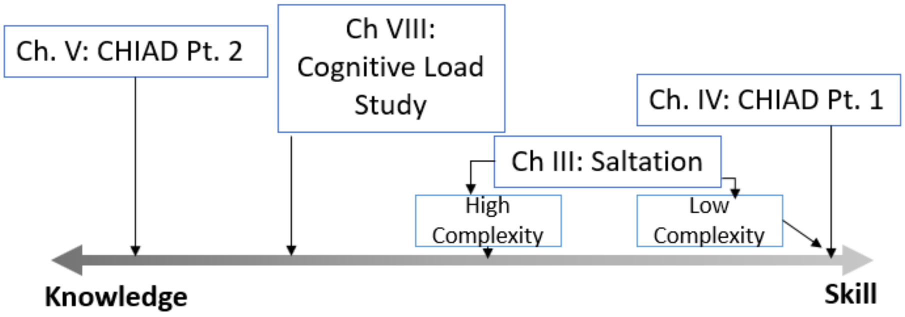


Figure 36. Chapters compared on SRK continuum.

IX.3 Future Work

We are continuing analysis of the cognitive workload study data. While we collected flight performance and biometric data, this work focuses solely on signal recognition. Further efforts will explore whether signal recognition was accompanied by tradeoffs in flight performance and whether or not reported cognitive workload and task difficulty can be objectively measured using biometric data, potentially to identify if participants were operating close to a “cognitive redline”, or the limit of their mental resources.

As mentioned, there may also be benefit in analyzing the effectiveness of auditory icons under similar cognitive workload conditions to allow for cross-comparison. Auditory icons clearly must contend with masking effects from engine noise, and while their use is much more commonly accepted, it may be that their actual performance and recognition rates are not nearly as favorable.

The signals tested in this work are just one variation among many. New tools such as Haptic Jazz (Schneider & MacLean, 2014) allow for more nuanced control in the development of vibrotactile icons. More advanced icons may improve recognition and support an expansion of available signal sets but would need to be similarly tested against cognitive load.

Likewise, the phonetic alphabet may also serve as an analog for signal development, as it was developed to account for between-subject uncertainty and the limitations of auditory confusion of stimuli. Similar methods might be applied in a haptic sense to improve recognition rates.

While I argue that meta-language components, such as error handling, are important for the design of highly dynamic vibrotactile applications, it is unclear at what level these features must be implemented. Clark’s (1996) treatment of common ground theory suggests that three levels of meta-knowledge are necessary for effective cooperative action. This may be empirically testable for purely vibrotactile communication. Some promising interfaces, such as COMMAND, (Elliott et al., 2011) address this through providing visual interfaces which may be useful for error management, but other domains, such a Haptimoto's (Prasad et al., 2014) focus on motorcycle navigation, make visual error handling untenable.

Finally, there is an opportunity for the analysis of design domains. Many diverse, dynamic design environments exist, but it can be difficult to establish, at the outset, what features are the most important. To be able to accomplish this, there is value in a taxonomy of features, to establish where domains are analogous and divergent. For example, the coordination of a team of deep water divers and that of wildfire management. There are many similarities in regards to team communication, stress, visibility, and limited resources. However, one is concerned about depth and the other about wind conditions. How do these challenges create similar design requirements and where do they differ?

IX.4 Final Thoughts

The sense of touch is remarkable. It ties us to the here-and-now in our own skin. This immediacy and privacy provides a tempting avenue for the design of novel interfaces to both offload work from overloaded visual and auditory channels and to provide direct feedback for physical tasks.

Overall, while a generalizable, creative vibrotactile communication system is appealing, the dream is a distant one. Touch is a valid method for directing individuals in time-sensitive or stressful conditions, but it is exceedingly difficult to design a system for more dynamic environments, as the natural human processes for error management are in conflict with these benefits. Such a system might require the design of a linguistically complex, vibrotactile language. For the time being, purely vibrotactile interfaces should focus on applications in well-specified domains with a limited design envelope. It's possible that more effective, limited designs may later combine into more elaborate systems.

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APPENDIX A

SUPPORTING DOCUMENTS, SIGNAL INFORMATION AND TEMPORAL OVERLAP

A.1. Consent Form

Introduction

The purpose of this form is to provide you information that may affect your decision as to whether or not to participate in this research study. If you decide to participate in this study, this form will also be used to record your consent.

This purpose of this research project is to explore the effectiveness of two different forms of tactile, or touch-based, communication.

The current research project is to find out the efficiency of different types of vibrotactile signals. While vibrotactile signals are common in very simple applications, such as the vibration of a cell phone alarm, what we’re studying are more complex ways of sending signals. Signals can vary in perceived intensity through increases in force, frequency, and the location of vibration. The study today focuses on the difference between isolated single vibrations, or “dynamic” stimuli, time varied signals, “dynamic” stimuli, and signals that utilize an illusory phenomenon known as apparent motion.

If you choose to participate in this study, you will be asked to complete a short background questionnaire. Then you will be trained on our vibrotactile interface which consists of a series of small vibrating motors. You will be given a sample of both the minimum and maximum possible signals to determine if there is a possible comfort problem with the equipment.

All data you provide to us will be anonymized and no identifying information will be recorded to connect you to your data. All data collected will be registered under a subject number which you will receive upon your signing this consent form.

You are eligible to participate in this study if you are at least 18 years old and have normal or corrected-to-normal visual.

What will I be asked to do?

After a brief familiarization/training period with the equipment, you will complete the signal interpretation task, which will last approximately 1 hour. During the experimental scenario, the three signal categories (static, dynamic, and apparent motion) will be presented to you in a randomized order. You will attempt to draw the signals you are presented with as a fast as possible for each batch of stimuli. You may request the repeat of each signal, if you wish, to improve clarity, but this will be reflected in your completion time.

A number of parameters will be collected: accuracy of response, completion time, and the number of requested repeats. These data will be analyzed using your ratings of each attribute as between-subjects random independent variables.

After your participation in the study, you will fill out a questionnaire detailing your impressions of the study and suggestions to improve on the system itself.

What are the risks involved in this study?

Regarding the participants' safety, the risk is minimal: no more than the risk encountered in everyday life. In the unlikely case that you experience any discomfort, please keep in mind that you can leave the experiment at any point without consequence.

What are the possible benefits of this study?

There are no foreseeable direct benefits to the research participants; however, it may prove interesting to see demonstration of current multi-sensory interfaces. The benefits to society will be a greater understanding of the effect of different forms of touch in communication.

Hopefully, this may be later used to keep people safer in situations such as aviation, deep-sea diving, and even help those with reduced sensory capacity.

Do I have to participate?

No, you do not have to participate. Your participation is voluntary. Also, even if you consent to participate, if at any point you wish to leave the study you may do so without consequence.

Will I be compensated?

No compensation will be offered for this study.

Who will know about my participation in this research study?

Unless you inform others on your own, only the study team will know about your participation in this study. The signed consent forms will be kept in a locked cabinet in the TAMU Human Factors Laboratory. Data files will group data according to generic, unique subject labels (s1, s2, etc.), and will not be linked in any way to subject identifiers. The data files will be stored securely on password-protected computers and in locked cabinets in the Human Factors Lab, accessed only by the study team. All data will be kept until data analysis has been completed, or for at most three years, and then erased.

Whom do I contact with questions about the research?

If you have questions regarding this study, you may contact Dr. Thomas Ferris, (XXX) XXX-XXXX, tferris@tamu.edu; or Trey Roady, (XXX) XXX-XXXX, TreyRoady@neo.tamu.edu.

Whom do I contact about my rights as a research participant?

This research study has been reviewed by the Human Subjects' Protection Program and/or the Institutional Review Board at Texas A&M University. For research-related problems or questions regarding your rights as a research participant, you can contact these offices at (979)458-4067 or irb@tamu.edu.

Signature for consent form

Please be sure you have read the above information, asked questions and received answers to your satisfaction. You will be given a copy of the consent form for your records. By signing this document, you consent to participate in this study.

Signature of Participant: ________________

Date: _________________________________

Printed Name:__________________________

A.2 Background Questionnaire

- What is your age?
- What is your sex?
- How often do you play video games? (circle the closest answer)
    - a. never
    - b. 1 hour each week or less
    - c. 5 hours each week
    - d. 10 hours each week
    - e. 15 or more hours each week
- If you play videogames regularly, please describe the age at which you started playing them.
- What game genres do you prefer (action/first person shooter, strategy, puzzles, card games, etc.)?
- Have you played video games that utilize force-feedback or a similar vibrational feedback system? Did you find that these added to your experience? Did you find them distracting?

- Do you own a cell-phone? If so, have you ever experienced a “phantom vibration” from your cell phone when either there was no vibration or the phone wasn’t present? Please circle the closest answer and elaborate if necessary.

    a. never
    b. once or very few times
    c. sometimes
    d. frequently

A.3 Feedback Questionnaire

- How comfortable was the tactor shirt, on a scale from 1 to 10, with 1 being extremely uncomfortable and 10 being extremely comfortable?
- If this system was used to convey directions for a navigation task (e.g., telling you to “go straight”, “turn right”, or even “turn 45 degrees to your left and go forward quickly”), would you prefer: the static, dynamic, or apparent motion presentations? Why?
- On a scale of 1 to 10, please rate your confidence in your responses; 1 being a complete lack of confidence and 10 being complete confidence.
    - Static:
    - Dynamic:
    - Apparent Motion:
- Was there anything particularly unclear or difficult to understand in this study?
- Is there anything you would recommend that could improve the vibrotactile display system?
- Is there anything you would recommend that might improve this study?

APPENDIX B

SUPPORTING DOCUMENTS, SPEEDED COOPERATIVE NAVIGATION

B.1 Consent Form

Introduction

The purpose of this form is to provide you information that may affect your decision as to whether or not to participate in this research study. If you decide to participate in this study, this form will also be used to record your consent.

This purpose of this research project is to evaluate the effectiveness of the CHIAD (Creative Haptic Interaction At-a-Distance) system, as well as other forms of communication media for communicating a sequence of navigation instructions. The CHIAD system allows two people to interact via the sense of touch, such as tapping someone on the shoulder, patting their back, or lightly pushing them in a direction they should move; and supports these interactions even when the two people are not in the same location. It accomplishes this by allowing one person (the "director" role) to gesture using a Nintendo Wii© remote, and a pattern of vibrations mapped to that gesture are presented to the back of another person (the "actor" role). The actor can then react to the message sent by the director by moving in a direction specified.

The study today focuses on identifying the strengths and limitations of the CHIAD system for a fast-paced navigation task which will require communication between a director and an actor. You will play each role (director and actor) and complete the navigation task with a partner with each of three types of communication media: verbal communications, a laptop-based interface that the director interacts with to present vibrations on the actor, and the gesture-based CHIAD system.

You are eligible to participate in this study if you are at least 18 years old, have normal or corrected-to-normal visual and auditory acuity (glasses/contacts and hearing aids are ok), have no known injuries or conditions that would limit the tactile sensitivity of the back (must be able to reliably feel vibrations presented there), and are capable of light physical activity (walking quickly and bending over to touch traffic cone targets).

What will I be asked to do?

If you choose to participate in this study, you will be asked to complete a short background questionnaire. Then you will be familiarized with our vibrotactile interface which consists of a series of small vibrating devices affixed to the back of a compression shirt, which you will put on over a lightweight shirt. You will then experience a sample of all of the possible vibration patterns that can be presented to determine if there is a possible comfort problem with the equipment. You are encouraged to report any experienced discomfort.

After a brief familiarization/training period with the equipment and forms of communication (the CHIAD system, laptop-based interface, and verbal instructions), you and your partner will take turns attempting to guide each other through a safety cone course. The task will take place within a 2x25 grid of traffic cones. One partner, the director, will be placed at a higher vantage point and must attempt to communicate which cones the actor must move across. You will complete the task 3 times – once for each of the different forms of communication – in each role, and then 3 more times after switching the director-actor roles. Your performance will be scored according to the time it takes to complete each list of cones and the accuracy of cones touched.

After your participation in the study, you will fill out a questionnaire detailing your impressions of the study and suggestions to improve on the system itself. The entirety of the study is expected to last approximately 90 minutes.

What are the risks involved in this study?

Regarding the participants' safety, the risk is minimal: no more than the risk encountered in everyday life. With the tactor system some discomfort is possible but not common. You will be asked to walk quickly through the array of cones and bend over to touch them, and thus there is a slight risk of falling during this activity, but no more risk than you might experience walking quickly and occasionally bending over to pick something up in your everyday life. In the unlikely case that you experience any discomfort due to the vibrotactile devices or the required physical activity, please feel free to let the experimenters know and keep in mind that you can leave the experiment at any point without consequence.

What are the possible benefits of this study?

There are no foreseeable direct benefits to the research participants; however, it may prove interesting to explore a novel approach to interpersonal communication. The benefits to society will be a greater understanding of the effect of different forms of touch in communication. The continued development of the CHIAD system will make it more usable and useful in activities such as firefighting, search-and-rescue operations, and leisure activities such as deep-sea diving. Additionally, the CHIAD system may help those with reduced sensory capacity in navigation and other tasks.

Do I have to participate?

No, you do not have to participate. Your participation is voluntary. Also, even if you consent to participate, if at any point you wish to leave the study you may do so without consequence.

Will I be compensated?

Upon completing the 90-minute study, each participant will be compensated $10 for their time. Additionally, if either you or your partner are excused or choose to leave the study before it is completed, you will each be compensated at a rate of $1 per 10 minutes of participation, rounded up to the next 10-minute interval.

Who will know about my participation in this research study?

The records of this study will be kept private. No identifiers linking you to this study will be included in any sort of report that might be published.

People who have access to your information include the Principal Investigator and research study personnel. Representatives of regulatory agencies such as the Office of Human Research Protections (OHRP) and entities such as the Texas A&M University Human Subjects Protection Program may access your records to make sure the study is being run correctly and that information is collected properly. Information about you and related to this study will be kept confidential to the extent permitted or required by law.

Unless you inform others on your own, only the study team will know about your participation in this study. The signed consent forms will be kept in a locked cabinet in the TAMU Human Factors & Cognitive Systems (HF&CS) Laboratory. Data files will group data according to generic, unique subject labels (s1, s2, etc.), and will not be linked in any way to subject identifiers. The data files will be stored securely on password-protected computers and in locked cabinets in the HF&CS Lab, accessed only by the study team. In accordance with TAMU data retention policies, information will be kept for at least a minimum of 7 years.

Whom do I contact with questions about the research?

If you have questions regarding this study, you may contact Dr. Thomas Ferris, (XXX) XXX-XXXX, tferris@tamu.edu; or Trey Roady, (XXX) XXX-XXXX, TreyRoady@tamu.edu.

Whom do I contact about my rights as a research participant?

This research study has been reviewed by the Human Subjects' Protection Program and/or the Institutional Review Board at Texas A&M University. For research-related problems or questions regarding your rights as a research participant, you can contact these offices at (979)458-4067 or irb@tamu.edu.

Signature for consent form

Please be sure you have read the above information, asked questions and received answers to your satisfaction. You will be given a copy of the consent form for your records. By signing this document, you consent to participate in this study.

Signature of Participant: _______________

Date: **_________________________________**

Printed Name: _________________________

B.2 Background Questionnaire

- What is your age?
- What is your sex? M F (please circle one)
- Approximately how many hours a week do you participate in physical activities such as sports, exercise, or physical labor? (circle the closest answer)
  a) 1 hour each week or less
  b) 5 hours each week
  c) 10 hours each week
  d) 15 hours each week
  e) more than 15 hours each week
- In the space below, please list your most frequent physical activities.
- How often do you play action-based video games, such as first-person shooters or strategy/puzzle games that require hand-eye coordination? (circle the closest answer)
  a) never
  b) 1 hour each week or less

c) 5 hours each week

d) 10 hours each week

e) 15 or more hours each week

- In the space below, please list the types of games you like to play most frequently.

B.3 Feedback Questionnaire

Thank you very much for your participation in our study! Please answer the following.

- How comfortable was the tactor shirt, on a scale from 1 to 10, with 1 being extremely uncomfortable and 10 being extremely comfortable?

1 2 3 4 5 6 7 8 9 10

(uncomfortable) (comfortable)

- How would you rate the overall effectiveness of the verbal communication method in completing the navigation task quickly and accurately, on a scale from 1 to 10, with 1 being completely ineffective and 10 being extremely effective?

1 2 3 4 5 6 7 8 9 10

(ineffective) (effective)

- How would you rate the overall effectiveness of the button signal method?

1 2 3 4 5 6 7 8 9 10

- How would you rate the overall effectiveness of Wii Remote gesture system?

1 2 3 4 5 6 7 8 9 10

- Is there anything you would recommend that could improve the vibrotactile display system?
- Was there anything particularly unclear or difficult with the tasks required in this study? How might we improve the tasks or our instructions?

APPENDIX C

SUPPORTING DOCUMENTS, SPEEDED COOPERATIVE NAVIGATION UNDER INCREASED COMPLEXITY

C.1 Consent Form

Introduction

The purpose of this form is to provide you information that may affect your decision as to whether or not to participate in this research study. If you decide to participate in this study, this form will also be used to record your consent.

The purpose of this research project is to evaluate the effectiveness of the CHIAD (Creative Haptic Interaction At-a-Distance) system, as well as other forms of communication media for communicating a sequence of navigation instructions. The CHIAD system allows two people to interact via the sense of touch, such as tapping someone on the shoulder, patting their back, or lightly pushing them in a direction they should move; and supports these interactions even when the two people are not in the same location. It accomplishes this by allowing one person (the “director” role) to gesture using a Nintendo Wii© remote, and a pattern of vibrations mapped to that gesture are presented to the back of another person (the “actor” role). The actor can then react to the message sent by the director by moving in a direction specified.

The study today focuses on identifying the strengths and limitations of the CHIAD system for a fast-paced navigation task which will require communication between a director and an actor. You will play each role (director and actor) and complete the navigation task with the gesture based CHIAD system and three different feedback conditions: vibrational feedback through the Wii© Remote, mirrored vibrotactile signals (actor and director receiving exact same stimuli), and no feedback.

You are eligible to participate in this study if you are at least 18 years old, have normal or corrected-to-normal visual and auditory acuity (glasses/contacts and hearing aids are ok), have no known injuries or conditions that would limit the tactile sensitivity of the back (must be able to reliably feel vibrations presented there), and are capable of light physical activity (walking quickly and bending over to touch traffic cone targets).

What will I be asked to do?

If you choose to participate in this study, you will be asked to complete a short background questionnaire. Then you will be familiarized with our vibrotactile interface which consists of a series of small vibrating devices affixed to a neoprene belt, which you will put on over your shirt. You will then experience a sample of all of the possible vibration patterns that can be presented to determine if there is a possible comfort problem with the equipment. You are encouraged to report any experienced discomfort.

After a brief familiarization/training period with the equipment and forms of communication (the CHIAD system and its related gestures), you and your partner will take turns attempting to guide each other through a safety cone course. The task will take place within a grid of traffic cones. One partner, the director, will be placed at a higher vantage point and must attempt to communicate which cones the actor must move across. You will complete the task several times – once for each of the different forms of communication – in each role, and then several more times after switching the director-actor roles. Your performance will be scored according to the time it takes to complete each list of cones and the accuracy of cones touched.

After your participation in the study, you will fill out a questionnaire detailing your impressions of the study and suggestions to improve on the system itself. The entirety of the study is expected to last approximately 90 minutes.

What are the risks involved in this study?

Regarding the participants' safety, the risk is minimal: no more than the risk encountered in everyday life. With the tactor system some discomfort is possible but not common. You will be asked to walk quickly through the array of cones and bend over to touch them, and thus there is a slight risk of falling during this activity, but no more risk than you might experience walking quickly and occasionally bending over to pick something up in your everyday life. In the unlikely case that you experience any discomfort due to the vibrotactile devices or the required physical activity, please feel free to let the experimenters know and keep in mind that you can leave the experiment at any point without consequence.

What are the possible benefits of this study?

There are no foreseeable direct benefits to the research participants; however, it may prove interesting to explore a novel approach to interpersonal communication. The benefits to society will be a greater understanding of the effect of different forms of touch in communication. The continued development of the CHIAD system will make it more usable and useful in activities such as firefighting, search-and-rescue operations, and leisure activities such as deep-sea diving. Additionally, the CHIAD system may help those with reduced sensory capacity in navigation and other tasks.

Do I have to participate?

No, you do not have to participate. Your participation is voluntary. Also, even if you consent to participate, if at any point you wish to leave the study you may do so without consequence.

Will I be compensated?

Upon completing the 90-minute study, each participant will be compensated $10 for their time. Additionally, if either you or your partner are excused or choose to leave the study before it is completed, you will each be compensated at a rate of $1 per 10 minutes of participation, rounded up to the next 10-minute interval.

Who will know about my participation in this research study?

The records of this study will be kept private. No identifiers linking you to this study will be included in any sort of report that might be published. People who have access to your information include the Principal Investigator and research study personnel. Representatives of regulatory agencies such as the Office of Human Research Protections (OHRP) and entities such as the Texas A&M University Human Subjects Protection Program may access your records to make sure the study is being run correctly and that information is collected properly. Information about you and related to this study will be kept confidential to the extent permitted or required by law.

Unless you inform others on your own, only the study team will know about your participation in this study. The signed consent forms will be kept in a locked cabinet in the TAMU Human Factors & Cognitive Systems (HF&CS) Laboratory. Data files will group data according to generic, unique subject labels (s1, s2, etc.), and will not be linked in any way to subject identifiers. The data files will be stored securely on password-protected computers and in locked cabinets in the HF&CS Lab, accessed only by the study team. In accordance with TAMU data retention policies, information will be kept for at least a minimum of 7 years.

Whom do I contact with questions about the research?

If you have questions regarding this study, you may contact Dr. Thomas Ferris, (979)458-2340, tferris@tamu.edu; or Trey Roady, (325) 864-8216, TreyRoady@tamu.edu.

Whom do I contact about my rights as a research participant?

This research study has been reviewed by the Human Subjects' Protection Program and/or the Institutional Review Board at Texas A&M University. For research-related problems or questions regarding your rights as a research participant, you can contact these offices at (979)458-4067 or irb@tamu.edu.

Signature for consent form

Please be sure you have read the above information, asked questions and received answers to your satisfaction. You will be given a copy of the consent form for your records. By signing this document, you consent to participate in this study.

Signature of Participant: _______________

Date: _________________________________

Printed Name: ________________________

C.2 Background Questionnaire

- What is your age?
- What is your sex? M F (please circle one)

- Approximately how many hours a week do you participate in physical activities such as sports, exercise, or physical labor? (circle the closest answer)
    - f) 1 hour each week or less
    - g) 5 hours each week
    - h) 10 hours each week
    - i) 15 hours each week
    - j) more than 15 hours each week
- In the space below, please list your most frequent physical activities.
- How often do you play action-based video games, such as first-person shooters or strategy/puzzle games that require hand-eye coordination? (circle the closest answer)
    - f) never
    - g) 1 hour each week or less
    - h) 5 hours each week
    - i) 10 hours each week
    - j) 15 or more hours each week
- In the space below, please list the types of games you like to play most frequently.

C.3 Feedback Questionnaire

Thank you very much for your participation in our study! Please answer the following.

- How comfortable was the tactor shirt, on a scale from 1 to 10, with 1 being extremely uncomfortable and 10 being extremely comfortable?

1 2 3 4 5 6 7 8 9 10

(uncomfortable) (comfortable)

- How would you rate the overall effectiveness of the verbal communication method in completing the navigation task quickly and accurately, on a scale from 1 to 10, with 1 being completely ineffective and 10 being extremely effective?

1 2 3 4 5 6 7 8 9 10

(ineffective) (effective)

- How would you rate the overall effectiveness of Wii Remote gesture system?

1 2 3 4 5 6 7 8 9 10

- Is there anything you would recommend that could improve the vibrotactile display system?
- Was there anything particularly unclear or difficult with the tasks required in this study? How might we improve the tasks or our instructions?

APPENDIX D

SUPPORTING DOCUMENTS, VERIFICATION STUDY

D.1 Consent Form

Introduction

The purpose of this form is to provide you information that may affect your decision to participate in this research study. If you decide to participate, this form will also be used to record your consent. The current research project is studying the how people understand signals that are communicated through vibration (vibrotactile signals). Vibrotactile signals are mild vibrations, much like those you experience with common cellphone alerts. We will be using the data from this study to help design more effective weather information systems for pilots to help prevent crashes. You are eligible to participate in this study if you are at least 18 years old, have corrected to normal vision, and have no peripheral nerve damage in your hands and wrists that might make it hard to feel vibration.

What will I be asked to do?

After you fill out the consent form, you will be asked to complete a short background questionnaire. Then you will be introduced to the equipment for the experiment. A brief training session will show you what to expect from the equipment and what kinds of signals are possible. During the experiment, compare a series of signals to establish which ones feel like they're more intense. Additionally, you will be asked to identify different snippets of vibrotactile music to see if you recognize familiar songs. The entire duration of participation, including training and filling out the questionnaires is expected to take approximately half an hour.

What are the risks involved in this study?

With regard to your safety, the risk is minimal: no more risk exists than in everyday life. If you experience discomfort, frustration, or undue stress during the experiment, please keep in mind that you can leave the experiment at any time without consequence by informing the experimenter that you wish to stop the study. If you are experiencing distress, you should stop the study. What are the possible benefits of this study? Direct, personal benefits from this study are small. Some personal understanding may be gained about current vibrotactile technology.

The benefits to society will be a greater understanding of how we can design vibrotactile signals to help people understand information in mentally demanding environments.

Do I have to participate?

No, you do not have to participate. Your part in this study is voluntary. Even if you consent to participate, you may leave at any point without consequence by telling us that you wish to stop.

Will I be compensated? Yes. You will be compensated $10 for your participation in this study, regardless of completion. You will be compensated even if you decide to withdraw consent.

Who will know about my participation in this research study? Whom do I contact with questions about the research?

If you have questions regarding this study, you may contact Dr. Thomas Ferris, (XXX) XXX-XXXX, tferris@tamu.edu; or Trey Roady, (XXX) XXX-XXXX, TreyRoady@tamu.edu.

Who will have access to my study information?

Information about you will be kept confidential to the extent permitted or required by law. People who have access to your information include the Principal Investigator and research study personnel. Representatives of regulatory agencies such as the Office of Human Research Protections (OHRP) and entities such as the Texas A&M University Human Research Protection Program may access your records to make sure the study is being run correctly and that information is collected properly. Whom do I contact about my rights as a research participant? This research study has been reviewed by the Human Subjects' Protection Program and/or the Institutional Review Board at Texas A&M University. For research-related problems or questions regarding your rights as a research participant, you can contact these offices at (979)458-4067 or irb@tamu.edu. Signature for consent form Please be sure you have read the above information, asked questions and received answers to your satisfaction. You will be given a copy of the consent form for your records. By signing this document, you consent to participate in this study.

Signature of Participant: _______________

Date: ________________________________

Printed Name: ________________________

D.2 Feedback Questionnaire

- Age:
- Sex: Male / Female (Please Circle)
- Are you an international student? If so, where are you from?
- What electronic devices do you use that have vibrational feedback? (i.e.: cell phone, gaming
- controllers, etc.)
- Do you have any experience tuning these vibrations for your needs?
- Do you have any feedback or observations over the study?

D.3 Signal Set Analysis

This section covers the R code used to develop the signal sets for the Verification Study detailed in Chapter VIII.

Analysis code for tests is formatted in `Courier New`, with blue text identifying user-supplied commands and black text indicating system responses.

D.3.1 “SetAnalysis.r”

```
#Takes argument 'k', the signal set to be tested (3, 4, or 5)
#returns a .csv with the top 10 signal sets and their score
#Run in folder with 'mel_total_mat.csv' & 'sync_total_mat.csv'
#the matrix containing average subject strength scores for
#Signal 1 – 10 on [-1 to 1].

#Load participant ratings
#Rows and columns are index matched on Signal 1- Signal 10
#Negative score favors X
#Positive score favors y
mel_rating <- read.csv('mel_total_mat.csv', header = FALSE)
sync_rating <- read.csv('sync_total_mat.csv', header = FALSE)

require('gtools') #For permutations()
```

```
      #Create R scoring function
      #Takes array of signals and returns the score
      score <- function(arg1, arg2){
        #arg1: 10x10 array of participant ratings
        #arg2: 1xn array of signals, least to greatest
        sum <- 0
        #i for each entry in arg2, except the last
        for(i in 1:(length(arg2)-1)){
          #j for each entry, after i, in arg2, loop through
          for(j in (i+1):(length(arg2))){
            sum <- sum + arg1[arg2[i],arg2[j]]
          }
        }
        return(sum)
      }


      perms <- permutations(10,5) #load all permutations for 3 conditions

      #for each perm, calculate a score
      sync_scores<-NULL
      mel_scores <-NULL

      for(i in 1:nrow(perms)){ #for each row in perms, calculate a score
        sync_scores[i] <- score(sync_rating, perms[i,])
        mel_scores[i] <- score(mel_rating, perms[i,])
      }

      #Sort scores and return the indices of the new ordering
      mel <- list(Perm=perms[tail(sort(mel_scores,index.return=TRUE)$ix,
10),], Scores=tail(sort(mel_scores), 10))
      sync <-
list(Perm=perms[tail(sort(sync_scores,index.return=TRUE)$ix,
10),],Scores= tail(sort(sync_scores), 10))

      write.table(mel, "mel5.txt", col.names = TRUE, row.names=FALSE,
sep="\t")
      write.table(sync, "sync5.txt", col.names = TRUE, row.names=FALSE,
sep="\t")
```

APPENDIX E

SUPPORTING DOCUMENTS, COGNITIVE WORKLOAD STUDY

E.1 Consent Form

Introduction

You are invited to take part in a research study being conducted by Tom Ferris, a researcher from Texas A&M University and funded by the Federal Aviation Administration. The information in this form is provided to help you decide whether or not to take part. If you decide to take part in the study, you will be asked to sign this consent form. If you decide you do not want to participate, there will be no penalty to you, and you will not lose any benefits you normally would have. You may choose to withdraw from the study at any time without penalty. NOTE: If you are employed then it is your responsibility to work with your employer regarding work leave for participation in this study if during work hours.

If there are any concerns, please contact Tom Ferris: tferris@tamu.edu

Why Is This Study Being Done?

The FAA is concerned with General Aviation (GA) pilot fatal accidents due to pilots flying into weather conditions they aren't trained for. To provide recommendations for weather information device manufacturers, the FAA wants to identify the number of vibrotactile signals that participants can identify while flying.

How Many People Will Be Asked to Be in This Study?

65,000 people (participants) will be invited to participate in this study, locally.

What Are the Alternatives to Being in This Study?

The alternative to being in the study is not to participate.

What Will I Be Asked to Do?

After you fill out the consent form, you will be asked to complete a short background questionnaire. Then you will be introduced to the flight software and other equipment for the experiment. You will also be shown tasks you will be asked to complete in the software. A brief training session will introduce you to the protocol and actions in the flight simulator. During the experiment, you will complete a series of flight simulator scenarios, each of which will take between three and five minutes. Simulated scenarios are intended to reflect the cognitive workload of flying in different conditions. During the flights, you will be asked to identify the levels of vibrotactile signals you receive on your hands or arms. Vibrotactile signals are mild vibrations, much like those you experience with common cellphone alerts.

Following the study, you will be asked to complete a final questionnaire about your experiences and the effect on your mental workload.

The entire duration of participation, including training, scenarios, and filling out the questionnaires is expected to take approximately 2-2.5 hours.

Are There Any Risks to Me?

With regard to your safety, the risk is minimal: no more risk exists than in everyday life. You may experience some minor physical fatigue, dizziness/mild nausea, or stress when you are performing in the software. Because of this, you will not begin the next task in the session until you are ready. The scenarios vary in level of challenge to provide a range of conditions and may be difficult. If you experience discomfort, frustration, or undue stress from these occurrences or otherwise, please keep in mind that you can leave the experiment at any time without consequence by informing the experimenter that you wish to stop the study. If you are experiencing distress, you should stop the study.

What are the possible benefits of this study?

Direct, personal benefits from this study are small. Some personal understanding may be gained about personal cognitive workload. The benefits to society will be a greater understanding of pilot decision and may help design pilot information systems to reduce chances of crashes.

Do I have to participate?

No, you do not have to participate. Your participation in this study is voluntary. Even if you consent to participate, you may leave at any point without consequence by telling experimenters that you wish to stop.

Will There Be Any Costs to Me?

Aside from your time, there are no costs for taking part in the study.

Will I Be Paid to Be in This Study?

Yes. Compensation for this study is $20. If you must leave the study before it is complete, your compensation will be pro-rated to match the amount of the study you have completed so far.

Who will know about my participation in this research study? Whom do I contact with questions about the research?

If you have questions regarding this study, you may contact Dr. Thomas Ferris, (XXX) XXX-XXXX, tferris@tamu.edu; or Trey Roady, (XXX) XXX-XXXX, TreyRoady@tamu.edu.

Will Information from This Study Be Kept Private?

Information about you will be kept confidential to the extent permitted or required by law. People who have access to your information include the Principal Investigator and research study personnel. Representatives of regulatory agencies such as the Office of Human Research Protections (OHRP) and entities such as the Texas A&M University Human Research Protection Program may access your records to make sure the study is being run correctly and that information is collected properly.

Your information will be stored in locked file cabinet and computer files will be password-protected. This consent form will be filed securely in an official area.

Whom do I contact about my rights as a research participant?

This research study has been reviewed by the Human Subjects' Protection Program and/or the Institutional Review Board at Texas A&M University. For research-related problems or questions regarding your rights as a research participant, you can contact these offices at (979)458-4067 or irb@tamu.edu.

What if I Change My Mind About Participating?

Your participation in this research is voluntary, and you have the choice whether or not to be in this research study. You may decide to not begin or to stop participating at any time. If you choose not to be in this study or stop being in the study, there will be no negative effect on your academic standing with Texas A&M University. Any new information discovered about the research will be provided to you. This information could affect your willingness to continue your participation.

STATEMENT OF CONSENT

I agree to be in this study and know that I am not giving up any legal rights by signing this form. The procedures, risks, and benefits have been explained to me, and my questions have been answered. I know that new information about this research study will be provided to me as it becomes available and that the researcher will tell me if I must be removed from the study. I can ask more questions if I want. A copy of this entire consent form will be given to me.

Participant Signature ________________ Date ______________

Printed Name ______________________ Date ______________

INVESTIGATOR'S AFFIDAVIT:

Either I have or my agent has carefully explained to the participant the nature of the above project. I hereby certify that to the best of my knowledge the person who signed this consent form was informed of the nature, demands, benefits, and risks involved in his/her participation.

Signature of Presenter _______________ Date ________________

Printed Name ______________________ Date_________________

E.2 Questionnaire

- Age:
- Sex: Male / Female (Please Circle)
- Are you an international student? If so, where are you from?
- What electronic devices do you use that have vibrational feedback? (i.e.: cell phone, gaming
- controllers, etc.)
- Do you have any experience tuning these vibrations for your needs?
- Do you have any feedback or observations over the study?

E.3 Cognitive Workload Study Analysis

This section covers the R output for statistical analysis of the Cognitive Workload Study. Each sub-header covers a particular test, with follow-up tests as sub-headers, as appropriate.

Analysis code for tests is formatted in `Courier New`, with blue text identifying user-supplied commands and black text indicating system responses.

E.3.1 Hypothesis Testing: Non-Parametric

E.3.1.1 Aligned-Rank Test

```
#Load longform data and aggregate data by average within subject.
#Treat independent variables as factors
>agg_WinSub <-
aggregate(data$Correct,by=list(data$Method,data$MATB,data$Levels,da
ta$Subject),FUN=mean,na.rm=TRUE)
>agg_WinSub$Method <- factor(agg_WinSub$Method,
levels=c(0,1,2),labels= c('Sync','Mel','Count'))
>agg_WinSub$MATB <- factor(agg_WinSub$MATB, levels=c(0,1),
labels=c('Mod','High'))
>agg_WinSub$Levels <- factor(agg_WinSub$Levels)
#Begin ART Analysis
> require(ARTool)
> fit.art <- art(Mean_Correct ~ MATB * Method * Levels +
(1|SubjectID),data=agg_WinSub)
> anova(fit.art)
Analysis of Variance of Aligned Rank Transformed Data


Table Type: Analysis of Deviance Table (Type III Wald F tests with
Kenward-Roger df)
Model: Mixed Effects (lmer)
Response: art(Mean_Correct)




                             F Df Df.res     Pr(>F)
1 MATB                0.659646  1 283.03 0.41736751
```

```
2 Method             54.321999  2 283.03 < 2.22e-16 ***
3 Levels             35.213477  2 283.05 2.2036e-14 ***
4 MATB:Method         0.062375  2 283.05 0.93954377
5 MATB:Levels         1.214958  2 283.03 0.29826519
6 Method:Levels       5.131411  4 283.03 0.00052619 ***
7 MATB:Method:Levels  0.267085  4 283.04 0.89898846
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

E.3.1.2 Wilcoxon Signed-Rank Post-Hoc Tests

```
> Sync_v_Count_in3 <-wilcox.test(agg_WinSub[agg_WinSub$Method ==
"Sync" & agg_WinSub$Levels == "3",]$Mean_Correct,
agg_WinSub[agg_WinSub$Method == "Count" & agg_WinSub$Levels ==
"3",]$Mean_Correct, paired=TRUE)

> Sync_v_Mel_in3 <-wilcox.test(agg_WinSub[agg_WinSub$Method ==
"Sync" & agg_WinSub$Levels == "3",]$Mean_Correct,
agg_WinSub[agg_WinSub$Method == "Mel" & agg_WinSub$Levels ==
"3",]$Mean_Correct, paired=TRUE)

> Mel_v_Count_in3 <-wilcox.test(agg_WinSub[agg_WinSub$Method ==
"Mel" & agg_WinSub$Levels == "3",]$Mean_Correct,
agg_WinSub[agg_WinSub$Method == "Count" & agg_WinSub$Levels ==
"3",]$Mean_Correct, paired=TRUE)

> Sync_v_Mel_in4 <-wilcox.test(agg_WinSub[agg_WinSub$Method ==
"Sync" & agg_WinSub$Levels == "4",]$Mean_Correct,
agg_WinSub[agg_WinSub$Method == "Mel" & agg_WinSub$Levels ==
"4",]$Mean_Correct, paired=TRUE)

> Sync_v_Count_in4 <-wilcox.test(agg_WinSub[agg_WinSub$Method ==
"Sync" & agg_WinSub$Levels == "4",]$Mean_Correct,
agg_WinSub[agg_WinSub$Method == "Count" & agg_WinSub$Levels ==
"4",]$Mean_Correct, paired=TRUE)

> Mel_v_Count_in4 <-wilcox.test(agg_WinSub[agg_WinSub$Method ==
"Mel" & agg_WinSub$Levels == "4",]$Mean_Correct,
agg_WinSub[agg_WinSub$Method == "Count" & agg_WinSub$Levels ==
"4",]$Mean_Correct, paired=TRUE)

> Sync_v_Count_in5 <-wilcox.test(agg_WinSub[agg_WinSub$Method ==
"Sync" & agg_WinSub$Levels == "5",]$Mean_Correct,
agg_WinSub[agg_WinSub$Method == "Count" & agg_WinSub$Levels ==
"5",]$Mean_Correct, paired=TRUE)

> Sync_v_Mel_in5 <-wilcox.test(agg_WinSub[agg_WinSub$Method ==
"Sync" & agg_WinSub$Levels == "5",]$Mean_Correct,
agg_WinSub[agg_WinSub$Method == "Mel" & agg_WinSub$Levels ==
"5",]$Mean_Correct, paired=TRUE)

> Mel_v_Count_in5 <-wilcox.test(agg_WinSub[agg_WinSub$Method ==
"Mel" & agg_WinSub$Levels == "5",]$Mean_Correct,
agg_WinSub[agg_WinSub$Method == "Count" & agg_WinSub$Levels ==
"5",]$Mean_Correct, paired=TRUE)
```

```
> L3_v_4_inSync <- wilcox.test(agg_WinSub[agg_WinSub$Levels == "3"
& agg_WinSub$Method == "Sync",]$Mean_Correct,
agg_WinSub[agg_WinSub$Levels == "4" & agg_WinSub$Method ==
"Sync",]$Mean_Correct, paired=TRUE)

> L4_v_5_inSync <- wilcox.test(agg_WinSub[agg_WinSub$Levels == "4"
& agg_WinSub$Method == "Sync",]$Mean_Correct,
agg_WinSub[agg_WinSub$Levels == "5" & agg_WinSub$Method ==
"Sync",]$Mean_Correct, paired=TRUE)

> L3_v_5_inSync <- wilcox.test(agg_WinSub[agg_WinSub$Levels == "3"
& agg_WinSub$Method == "Sync",]$Mean_Correct,
agg_WinSub[agg_WinSub$Levels == "5" & agg_WinSub$Method ==
"Sync",]$Mean_Correct, paired=TRUE)

> L3_v_4_inMel <- wilcox.test(agg_WinSub[agg_WinSub$Levels == "3" &
agg_WinSub$Method == "Mel",]$Mean_Correct,
agg_WinSub[agg_WinSub$Levels == "4" & agg_WinSub$Method ==
"Mel",]$Mean_Correct, paired=TRUE)

> L4_v_5_inMel <- wilcox.test(agg_WinSub[agg_WinSub$Levels == "4" &
agg_WinSub$Method == "Mel",]$Mean_Correct,
agg_WinSub[agg_WinSub$Levels == "5" & agg_WinSub$Method ==
"Mel",]$Mean_Correct, paired=TRUE)

> L3_v_5_inMel <- wilcox.test(agg_WinSub[agg_WinSub$Levels == "3" &
agg_WinSub$Method == "Mel",]$Mean_Correct,
agg_WinSub[agg_WinSub$Levels == "5" & agg_WinSub$Method ==
"Mel",]$Mean_Correct, paired=TRUE)

> L3_v_4_inCount <- wilcox.test(agg_WinSub[agg_WinSub$Levels == "3"
& agg_WinSub$Method == "Count",]$Mean_Correct,
agg_WinSub[agg_WinSub$Levels == "4" & agg_WinSub$Method ==
"Count",]$Mean_Correct, paired=TRUE)

> L4_v_5_inCount <- wilcox.test(agg_WinSub[agg_WinSub$Levels == "4"
& agg_WinSub$Method == "Count",]$Mean_Correct,
agg_WinSub[agg_WinSub$Levels == "5" & agg_WinSub$Method ==
"Count",]$Mean_Correct, paired=TRUE)

> L3_v_5_inCount <- wilcox.test(agg_WinSub[agg_WinSub$Levels == "3"
& agg_WinSub$Method == "Count",]$Mean_Correct,
agg_WinSub[agg_WinSub$Levels == "5" & agg_WinSub$Method ==
"Count",]$Mean_Correct, paired=TRUE)
```

E.3.2 Hypothesis Testing: Parametric

E.3.2.1 Maximal Logistic Mixed-Model

```
#data2 is the long-form data for the study, with NAs removed and
independent variables treated as factors.

> mixed_maximal <- mixed(Correct ~ MATB * Levels * Method + (MATB *
Levels * Method | Subject), family = binomial, control =
glmerControl(optCtrl=list(maxfun=1e6)),method="LRT",data=data2)

Contrasts set to contr.sum for the following variables: MATB,
Levels, Method

Fitting 8 (g)lmer() models:

[........]

There were 14 warnings (use warnings() to see them)


> mixed_maximal

Mixed Model Anova Table (Type 3 tests, LRT-method)


Model: Correct ~ MATB * Levels * Method + (MATB * Levels * Method |

Model:     Subject)

Data: data2

Df full model: 189

              Effect df     Chisq p.value

1               MATB  1      2.09     .15

2             Levels  2 28.93 ***   <.0001

3             Method  2 20.14 ***   <.0001

4        MATB:Levels  2      1.56     .46

5        MATB:Method  2      1.87     .39

6      Levels:Method  4   10.19 *     .04

7 MATB:Levels:Method  4      3.02     .56

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘+’ 0.1 ‘ ’ 1

Warning messages:

1: lme4 reported (at least) the following warnings for 'full':

  * Model failed to converge with max|grad| = 0.0845584 (tol =
0.001, component 1)

2: lme4 reported (at least) the following warnings for 'MATB':

  * unable to evaluate scaled gradient

  * Model failed to converge: degenerate  Hessian with 5 negative
eigenvalues
```

```
3: lme4 reported (at least) the following warnings for 'Levels':

  * Model failed to converge with max|grad| = 0.0403631 (tol =
0.001, component 1)

4: lme4 reported (at least) the following warnings for 'Method':

  * unable to evaluate scaled gradient

  * Model failed to converge: degenerate  Hessian with 4 negative
eigenvalues

5: lme4 reported (at least) the following warnings for
'MATB:Levels':

  * unable to evaluate scaled gradient

  * Model failed to converge: degenerate  Hessian with 1 negative
eigenvalues

6: lme4 reported (at least) the following warnings for
'MATB:Method':

  * unable to evaluate scaled gradient

  * Model failed to converge: degenerate  Hessian with 3 negative
eigenvalues

7: lme4 reported (at least) the following warnings for
'Levels:Method':

  * unable to evaluate scaled gradient

  * Model failed to converge: degenerate  Hessian with 1 negative
eigenvalues

8: lme4 reported (at least) the following warnings for
'MATB:Levels:Method':

  * unable to evaluate scaled gradient

  * Model failed to converge: degenerate  Hessian with 4 negative
eigenvalues
```

E.3.2.2 Estimated Marginal Means, Maximal Mixed-Model

These data represent the logistic transformed GLMM.

```
> emmeans(mixed_maximal, c('Method','Levels'))

NOTE: Results may be misleading due to involvement in interactions



 Method Levels    emmean        SE  df   asymp.LCL asymp.UCL

 Sync   3      1.7448750 0.4009352 Inf  0.95905656 2.5306935

 Mel    3      1.9829097 0.3853483 Inf  1.22764102 2.7381784

 Count  3      3.1368755 0.5354903 Inf  2.08733384 4.1864172

 Sync   4      0.9854558 0.2843840 Inf  0.42807332 1.5428382
```

```
 Mel    4      0.3316514 0.2258197 Inf -0.11094696 0.7742498
 Count  4      2.5259970 0.5041663 Inf  1.53784923 3.5141448
 Sync   5      0.3362397 0.2923769 Inf -0.23680855 0.9092879
 Mel    5      0.5144394 0.2563733 Inf  0.01195703 1.0169218
 Count  5      1.7621837 0.3687892 Inf  1.03937009 2.4849973

Results are averaged over the levels of: MATB
Results are given on the logit (not the response) scale.
Confidence level used: 0.95
```

These data represent the data back-transformed from the logistic GLMM.

```
> emmeans(mixed_maximal, c('Method','Levels'),type="response")
NOTE: Results may be misleading due to involvement in interactions
 Method Levels      prob         SE  df asymp.LCL asymp.UCL
 Sync   3      0.8513052 0.05075223 Inf 0.7229329 0.9262657
 Mel    3      0.8789910 0.04098788 Inf 0.7734054 0.9392422
 Count  3      0.9583885 0.02135537 Inf 0.8896660 0.9850270
 Sync   4      0.7281894 0.05628801 Inf 0.6054135 0.8238769
 Mel    4      0.5821611 0.05493053 Inf 0.4722917 0.6844395
 Count  4      0.9259443 0.03457140 Inf 0.8231518 0.9710876
 Sync   5      0.5832768 0.07106659 Inf 0.4410730 0.7128544
 Mel    5      0.6258466 0.06003304 Inf 0.5029892 0.7343726
 Count  5      0.8534829 0.04611702 Inf 0.7387284 0.9230834

Results are averaged over the levels of: MATB
Confidence level used: 0.95
Intervals are back-transformed from the logit scale
```

```
> emmeans(mixed_maximal, 'Method',type="response")
NOTE: Results may be misleading due to involvement in interactions
 Method      prob         SE  df asymp.LCL asymp.UCL
 Sync   0.7353990 0.05643486 Inf 0.6115316 0.8307041
 Mel    0.7197053 0.05171000 Inf 0.6084011 0.8092901
 Count  0.9223719 0.02875561 Inf 0.8439465 0.9631072
```

```
Results are averaged over the levels of: MATB, Levels
Confidence level used: 0.95
Intervals are back-transformed from the logit scale

> emmeans(mixed_maximal, 'Levels',type="response")
NOTE: Results may be misleading due to involvement in interactions
 Levels      prob         SE  df asymp.LCL asymp.UCL
 3      0.9078967 0.02969525 Inf 0.8309250 0.9518572
 4      0.7826259 0.04631935 Inf 0.6786107 0.8599259
 5      0.7049442 0.05122410 Inf 0.5958661 0.7947239

Results are averaged over the levels of: MATB, Method
Confidence level used: 0.95
Intervals are back-transformed from the logit scale
```

E.3.2.3 Random Intercepts Logistic Mixed-Model

Using Random Effect: Subject

```
> require(afex)
> partial_mixed = mixed(Correct ~ Method * Levels * MATB + (1 |
SubjectID),family = binomial, data= data2clean)
Mixed Model Anova Table (Type 3 tests, LRT-method)
Model: Correct ~ Method * Levels * MATB + (1 | Subject)
Data: data2clean
Df full model: 19
              Effect df      Chisq p.value
1             Method  2 174.54 ***  <.0001
2             Levels  2 135.95 ***  <.0001
3               MATB  1       0.01     .94
4      Method:Levels  4  21.05 ***   .0003
5        Method:MATB  2       0.77     .68
6        Levels:MATB  2     4.67 +     .10
7 Method:Levels:MATB  4       1.69     .79
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘+’ 0.1 ‘ ’ 1
```

```
> summary(partial_mixed)
Generalized linear mixed model fit by maximum likelihood (Laplace
Approximation) ['glmerMod']
 Family: binomial  ( logit )
Formula: Correct ~ Method * Levels * MATB + (1 | Subject)
   Data: data2clean

     AIC      BIC   logLik deviance df.resid
  4603.3   4725.2  -2282.6   4565.3     4511

Scaled residuals:
    Min      1Q  Median      3Q     Max
-4.9059 -0.6839  0.3544  0.5920  1.8263

Random effects:
 Groups  Name        Variance Std.Dev.
 Subject (Intercept) 0.756    0.8695
Number of obs: 4530, groups:  Subject, 18

Fixed effects:
                       Estimate Std. Error z value Pr(>|z|)
(Intercept)            1.181444   0.208896   5.656 1.55e-08 ***
Method1               -0.329280   0.051814  -6.355 2.08e-10 ***
Method2               -0.396058   0.051918  -7.629 2.37e-14 ***
Levels1                0.608708   0.057102  10.660  < 2e-16 ***
Levels2               -0.161221   0.052849  -3.051  0.00228 **
MATB1                  0.002876   0.037927   0.076  0.93955
Method1:Levels1       -0.068669   0.076390  -0.899  0.36869
Method2:Levels1        0.183151   0.077251   2.371  0.01775 *
Method1:Levels2        0.182732   0.072137   2.533  0.01131 *
Method2:Levels2       -0.317815   0.071332  -4.455 8.37e-06 ***
Method1:MATB1          0.012756   0.051708   0.247  0.80515
Method2:MATB1          0.035272   0.051646   0.683  0.49464
Levels1:MATB1         -0.121100   0.056619  -2.139  0.03245 *
Levels2:MATB1          0.050910   0.052799   0.964  0.33493
Method1:Levels1:MATB1  0.042346   0.076382   0.554  0.57930
```

```
Method2:Levels1:MATB1 -0.012933   0.077183  -0.168  0.86693
Method1:Levels2:MATB1 -0.033750   0.072194  -0.467  0.64015
Method2:Levels2:MATB1  0.073972   0.071349   1.037  0.29985
---()
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Method: 0 – Sync, 1 – Mel, 2 – Count
Levels: 1 – 3 Levels, 2 – 4 Levels, 3 – 5 Levels
MATB: 0 – Moderate, 1 – High
```

E.1.2.4 Estimated Marginal Means, Random Intercepts Logistic Mixed-Model

```
> emmeans(partial_mixed,c("Method","Levels"),type="response")
Note: D.f. calculations have been disabled because the number of
observations exceeds 3000.
To enable adjustments, set emm_options(pbkrtest.limit = 4530) or
larger,but be warned that this may result in large computation time
and memory use.
NOTE: Results may be misleading due to involvement in interactions
 Method Levels    emmean         SE  df asymp.LCL asymp.UCL
 Sync   3      0.7678571 0.04094680 Inf 0.6876029 0.8481114
 Mel    3      0.7956349 0.04094680 Inf 0.7153807 0.8758892
 Count  3      0.8932817 0.04085326 Inf 0.8132108 0.9733526
 Sync   4      0.6785558 0.04097156 Inf 0.5982530 0.7588586
 Mel    4      0.5654762 0.04094680 Inf 0.4852219 0.6457305
 Count  4      0.8364691 0.04097159 Inf 0.7561663 0.9167720
 Sync   5      0.5608131 0.04113583 Inf 0.4801883 0.6414378
 Mel    5      0.6019505 0.04097157 Inf 0.5216477 0.6822533
 Count  5      0.7755883 0.04097161 Inf 0.6952854 0.8558911

Results are averaged over the levels of: MATB
Degrees-of-freedom method: asymptotic
Confidence level used: 0.95
```