AN ANALYSIS OF STATIC, DYNAMIC, AND APPARENT MOTION VIBROTACTILE STIMULI

A Senior Scholars Thesis

by

WILLIAM ARTHUR ROADY, III

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

May 2012

Major: Industrial and Systems Engineering

AN ANALYSIS OF STATIC, DYNAMIC, AND APPARENT MOTION VIBROTACTILE STIMULI

A Senior Scholars Thesis

by

WILLIAM ARTHUR ROADY, III

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

Approved by:

Research Advisor:	Thomas Ferris
Associate Director, Honors and Undergraduate Research:	Duncan MacKenzie

May 2012

Major: Industrial and Systems Engineering

ABSTRACT

An Analysis of Static, Dynamic, and Apparent Motion Vibrotactile Stimuli.
(May 2012)

William Arthur Roady, III
Department of Industrial and Systems Engineering
Texas A&M University

Research Advisor: Thomas Ferris
Department of Industrial and Systems Engineering

The sense of touch is uniquely suited for displaying certain types of information, such as navigation instructions and high-level messaging. As part of a line of research in developing a vibrotactile communication system to support person-to-person tactile messaging over a network, the present study examines the effectiveness and efficiency of three different vibrotactile signal presentation methods for communicating a spatial pattern. In an evaluation study, participants identified static (one or multiple locations vibrating at once), non-overlapping dynamic sequences of presentations, and saltatory presentations which induce the “apparent motion” tactile illusion; each at increasing levels of signal complexity and presentation duration.

The equipment used for the interface devices consists of two Engineering Acoustics, Inc. solenoid tactor systems and a computer interface developed in C++.

The results of the study suggest that both response time and accuracy are strongly dependent on the complexity of the signal and the presentation method utilized, with static and saltatory presentations outperforming dynamic presentations. With more complex signals, the relative benefit of saltatory presentations appears to increase. These results have implications for the design of tactile display signals of varying degrees of complexity, and will inform the continued development of the CHIAD (Creative Haptic Interaction At-a-Distance) system.

DEDICATION

To my wife, Erin, for all of her support

ACKNOWLEDGEMENTS

I would like to thank Dr. Ferris not only for his guidance and support, but also the opportunity and means to study and explore such intriguing topics. Also, I would like to thank Dr. Rodger Koppa for his early advice and guidance in human factors and ergonomics.

Thanks also to all of my friends in Texas A&M University Cepheid Variable for helping preserve my sanity and for never letting me forget what is important.

Finally, thanks to my wife for her patience and support. Without her, none of this would have happened.

NOMENCLATURE

EAI	Engineering Acoustics, Inc.
DOS	Duration of Stimulus
HCI	Human Computer Interaction
MRT	Multiple Resource Theory
SOA	Stimulus Onset Asynchrony

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

INTRODUCTION VIBROTACTILE COMMUNICATION

Human beings are complex, interoperating systems adapted for equally complex environments. However, the pace of life has increased along with the use of technology. Previous to the train or automobile, the suggestion that human beings would travel at speeds greater than twenty miles per hour seemed both reckless and preposterous. Now, such speeds generate the ire of motorists in school safety zones.

Simply, the world at its present state is much more complex than the world human beings are familiar with, and the rate of change is increasing. Modern life requires the management information in not only large volumes, but also from many different sources. As such, humans must advance beyond the original cognitive approaches if we are to continue to make sense of the world around us.

People are, primarily, vision-dependent. The sense of sight interacts strongly with the physical world to give meaning to shape, color, and texture. Current technological interfaces are strongly targeted towards vision and are supported by a large body of research and art expressing various ideals in visual form and function. Likewise, the sense of hearing is also largely understood and auditory communications are frequently

---

This thesis follows the style of *IEEE Transactions on Haptics.*

applied by themselves or as secondary reinforcement to visual communications.

Recently, in the field of human computer interaction (HCI), focus has shifted to the understanding of mechanisms for tactile sensation and control, or *haptics*. According to Jones and Sarter [5], the sense of touch has multiple interesting properties such as *proximity*, the immediate reliance on direct contact; spatial and temporal discrimination; and *omnidirectionality*, i.e., reception of a tactile signal does not depend on the spatial orientation of sensory receptors. These properties lend haptic feedback systems a unique level of immediacy, privacy, and spatial relevance. Touch also shows higher spatial resolution than audition and, in many cases, higher temporal resolution than vision [10]. Recent advances in tactile display technologies that can be found in widely available commercial solutions have led to greater numbers of dimensions that can be modulated in tactile display signals, and greater range in expressiveness for these signals [5], [7].

In his Multiple Resource Theory (MRT), Wickens [17] argues that the human mind has a limited capacity for concurrent processing of data. These processes, however, do not always require the exact same resources. This explains how many individuals can talk on the telephone and cook a meal at the same time. MRT suggests that this effect is due to division of processes between information processing stages (perceptual/cognitive vs. response), codes (verbal/symbolic vs. spatial/analog), and sensory modality (auditory vs. visual vs. tactile, etc.). The less that two activities compete for the same types of cognitive resources, the more likely that they will be able to be effectively timeshared.

In light of MRT, tactile systems provide expanded communication and decreased workload. This is valuable in high information saturation areas such as aviation where one individual must manage large amounts of incoming visual and auditory data to determine pertinent details or in wildfire response where the availability of the visual and auditory sensory channels can be unpredictable but receiving critical messages can be the difference between life and death. Tactile communications systems are also helpful for situations in which large demands exist on visual and auditory channels to the point that these modalities are either inconvenient or otherwise unavailable, such as when used to present GPS navigation cues for cyclists or information systems for the blind [12]. Greater understanding of tactile communication not only allows us to understand how to get a message across but also how much engaging this underutilized sensory channel can improve overall human information processing performance.

Previous haptic applications have focused on simple notification systems [3], directional navigation [14], [16], physical activity instruction [13], and even to alleviate spatial distortion experienced by pilots in the cockpit [15]. However, most applications focus on the use of previously defined symbols. These symbols must have a unique learned association, which requires a higher learning curve. This also breeds in inflexibility for the system because each symbol must be assigned to a set response prior to actual use and any system redesign requires the reprogramming of all stimuli and the retraining of users. As MacLean [6.] argues, these systems are insufficient for greater application due to a lack of “transparency” and must instead push for greater abstraction capability with intuitive design protocols.

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. This creativity should be harnessed for person-to-person tactile communications, by designing tactile displays that support open-ended and expressive patterns to be composed by a communicator and presented to a receiver.

The goal of this analysis is to establish a more versatile approach to haptic feedback systems by exploring the application of several types of presentation patterns, including those that induce the “apparent motion” illusion (e.g., [8], [9]) to generate general, recognizable icons that can be easily identified by users with minimal training and re-associated with event context as needed so as to establish intuitive, immediately responsive signals. Very few studies have looked at comparing signals for these applications, and to our knowledge, none have directly addressed the complexity of the signal patterns. Therefore, this study sought to fill this gap. This new analysis should be informative to the design of next-generation tactile displays, supporting a range of practical vibrotactile solutions in a wider range of contexts by decreasing overall training time and system reliability.

“Static” signaling is the most researched of the three methods analyzed in this study. It consists of the activation of one or more tactors for a set duration, with no temporal variation. 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.). This is the simplest of the methods to design, but the range of expression is extremely limited as directionality is only established in relation to physical location.

The second method, dynamic signaling, consists of temporally spaced tactor activations. These allow both the physical communication of the static method and an additional component of perceived direction of motion. The potential range of expression is much larger than that of static signaling, but may be slightly more time consuming to present and also to interpret the signal.

The third method, apparent motion, can aid in the recognition of tactile icons, or *tactons* [2], of various complexities. To elicit the apparent motion illusion, saltation, or the “cutaneous rabbit phenomenon”, is created by the overlap of stimuli. Instead of sensing two independent points, a series of “hops” are felt between the initial and final points [9]. Later studies have determined parameters that, when properly accounted for, present a saltatory patterns that allow a user to perceive clear direction and relative force for linear signals [8]. This supports transparent interaction with limited display space and reduces workload with greater signal redundancy.

CHAPTER II

METHODS

Overview

Six study participants were recruited from the student body of Texas A&M University (TAMU) via mass email. After consenting to participate, participants experienced examples of, and practiced identifying, each type of presentation. This approximately 15-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 (see Fig. 1). 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 30 trials and C2 blocks consisted of 60 trials (30 single direction presentations and 30 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.

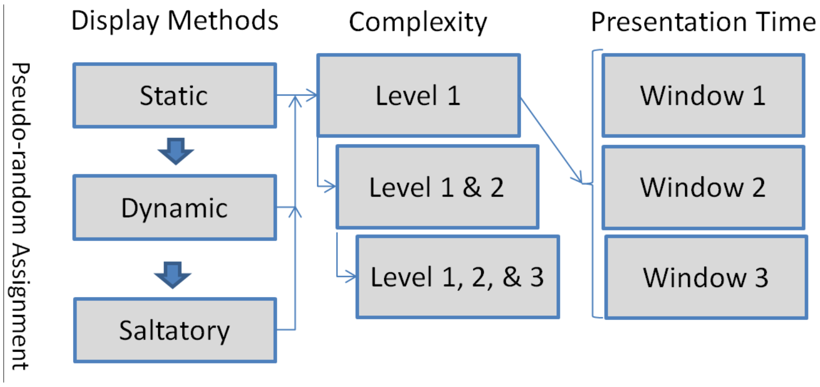

Fig. 1. Study Design

Signal generation and data collection were carried out via a simple console application developed for this study. Each individual trial was presented by a simple interface. After the presentation, participants responded by drawing the pattern they felt with a pen on their printed paper response forms. At this point, 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 fairly certain of the accuracy of their response, since both accuracy and the time to complete each experimental block were performance measures of interest. After the end of each block a short break could be taken before starting the next block, until all 18 were completed. A new response sheet was used for each block.

Display design

Signals were administered to participants by way of two EAI© C2 systems (http://www.eaiinfo.com/Tactor%20Products.htm) and 16 solenoid-based "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 10 cm (see Figure 2). This system allowed a lightweight arrangement of equipment to be worn over a thin undershirt while ensuring adequate contact pressure so that each tactor activation was clearly perceptible. The positions of the tactors were arranged to accommodate participants of various sizes, such that the 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 (see Fig. 2) to provide greater signal redundancy for cardinal and ordinal directions, and also greater expressiveness for complex patterns. Static signals could therefore be communicated with multiple tactors as if radiating from the center, and the sequences of vibrations for dynamic and saltatory presentations could follow many different expressive paths.

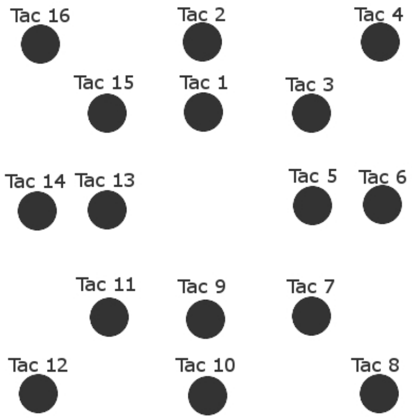

Fig. 2. Tactor Array Layout

Signal design

All vibrotactile stimuli in this study are displayed with a frequency of 250 hertz at the maximum hardware-supported gain (1 mm displacement of the actuator against the skin), which supported the best vibrotactile sensitivity [11]. Static presentations simply involved simultaneous activation of all tactors involved in the pattern 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. 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 Fig. 3). In order to best evoke the apparent motion illusion, the DOS was twice that of the SOA [8].

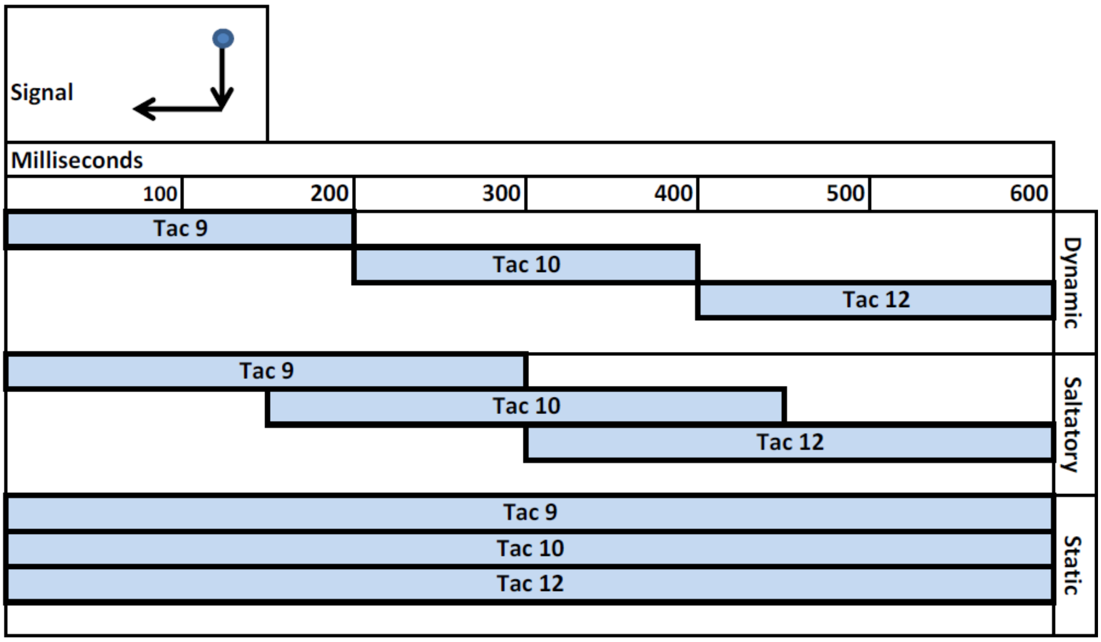

Fig. 3. Signal Method Comparison

The independent variables used within this study were display method (static, dynamic, saltatory), signal complexity (C1, C2), and presentation duration (500, 750, 1000 ms). Of particular interest was the possibility of a two-way interaction between display method and complexity. The metrics utilized as dependent variables in analysis were response accuracy, response time per trial, and the number of requested repeats for trial presentations. Each dependent measure was analyzed individually using repeated-measures ANOVAs with Tukey tests for post-hoc comparison of means.

CHAPTER III

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.

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. Fig. 4 shows the mean accuracy for each presentation method and complexity.

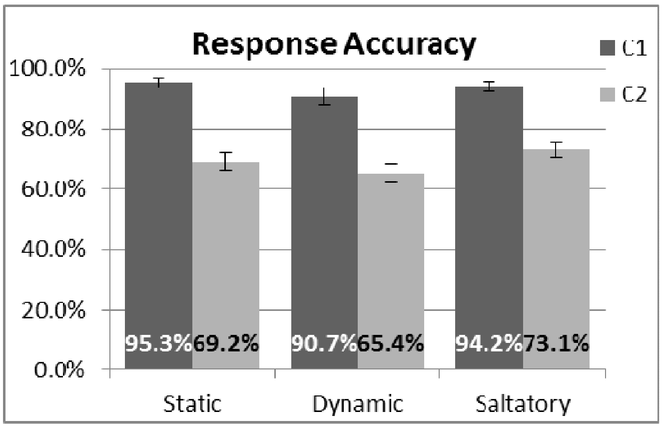

Fig. 4. Response accuracy versus complexity level and signal method. Error bars represent standard error.

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.

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). Fig. 5 shows the relationship between response times for blocks with each presentation method and level of signal complexity. No significant interaction effects were found.

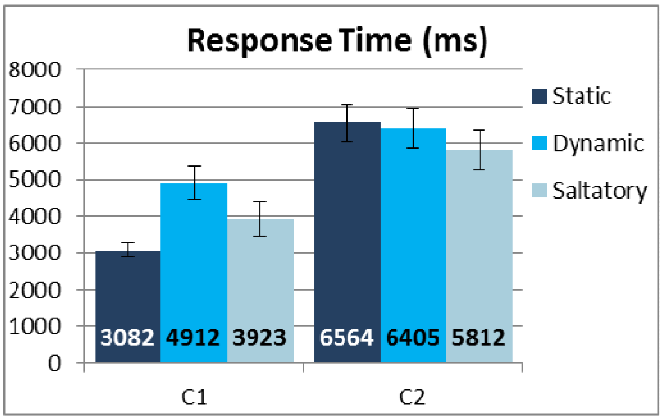

Fig. 5. Average signal response time versus complexity level and presentation method. Error bars represent standard error.

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 (see Fig. 6).

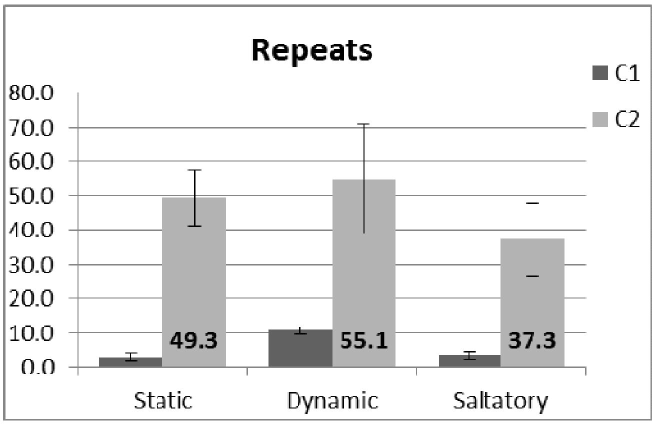

Fig. 6. Average number of repeats versus presentation method and signal complexity. Error bars represent standard error.

CHAPTER IV

SUMMARY AND CONCLUSIONS

The sense of touch is uniquely suited for communicating immediately relevant spatial information, such as navigation instructions [1], [4], [14], [16]. 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 – the Creative Haptic Interaction At-a-Distance (CHAID) – 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 development process for the CHAID 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 (which concerns both accuracy and time) that relate to signal duration. Of particular interest was the possible interaction effect between signal complexity and presentation method.

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 (note the accuracy scores between 90 and 95%), but 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 in the future 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 shape of the pattern. The reasoning for this solution comes from the fact that for C1, two tactors provided sufficient stimuli for highly accurate responses, but when C2 is used, only three tactors were activated (rather than 2 for each direction in the sequence). In comparison with previous studies of tactile identification, the CHAID system's concentric square design applied a larger set of redundant tactors for simple signals, and significant gains may yet be realized by providing more stimuli to aid in signal perception.

The results also show differences in performance due to presentation method among static, dynamic, and saltatory signals. Generally, and especially with more complex signals, the saltatory presentations showed the greatest accuracy. Saltatory presentations also showed faster response times than dynamic displays and trended toward the fastest responses among all presentation methods for more complex signals (C2). 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.

One interesting piece of anecdotal evidence was that participants generally felt that the main problem in signal recognition was not sensing the signal or determining whether it was a single direction or sequenced combination of directions, but rather, in determining the precise location and/or order of locations presented. 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 [9]. Also, it is worth noting that in order to assure reliable perception, the range of presentation duration windows used in this study (500 ms – 1000 ms) were longer than those used in the literature to induce the apparent motion illusion, which were within the order of 100 ms [9], [8]. It is possible that a shorter (or longer) duration could improve the results as well.

The C1 and C2 blocks provide another aspect for consideration. The study necessitated the combination of simple and complex level signals to provide a clearer reference for signal location. It is important to note that the signal blocks for C2 are composed of half simple and half complex signals. In later studies these data should be analyzed based on only the complex signals themselves to allow for clearer signal complexity performance criteria.

A clear limitation of this study was that only 6 (or 5, after data removal) participants' worth of data were able to be analyzed in this initial study. Though a large number of trials were used, the low participant sample size may have led to the lack of some differences reaching significance. It also potentially limited the observation of a more representative range of interindividual differences that may be present in a larger sample of the population.

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 favor the directionality provided by saltatory vibrational signals, in terms of both accuracy and response time. This efficient means of presenting complex patterns is likely the best alternative for representation in the CHAID system, and will be used in future studies investigating the benefits and communication strategies developed by pairs of communicators interacting with each other through this system. Finally, the results provide evidence to inform the design of "transparent" tactile communications (e.g., [6]), which are critical to consider in designing haptic/tactile displays to support the attention and task management of human operators in many complex environments.

REFERENCES

[1] L. Elliott, J. van Erp, E. Redden, and M Duistermaat, “Field-based Validation of a Tactile Navigation Device,” *IEEE Trans. On Haptics*, vol 3, no. 2, pp. 78-87, 2010.

[2] T. Ferris and N. Sarter, “Evaluation of Multiparameter Vibrotactile Display Designs to Support Physiological Monitoring Performance in Anesthesiology.,” *Proc. of the Human Factors and Ergon. Soc. Annual Meeting*, vol. 55, no. 1, pp. 515-519, 2011.

[3] I. Hwang, K. MacLean, M. Behmer, J. Hendy, A. Sotirakopoulos, et al., “The Haptic Crayola Effect: Exploring the Role of Naming in Learning Haptic Stimuli,” *IEEE World Haptics Conf.*, Istanbul, Turkey, 2011, pp. 385-390.

[4] L. Jones, B. Lockyer, and E. Piateski, “Tactile Display and Vibrotactile Pattern Recognition on the Torso,” *Adv. Rob.*, vol. 20, no. 12, pp. 1359-1374, 2006.

[5] L. Jones, and N. Sarter, “Tactile Displays: Guidance for their Design and Application,” *Human Factors: the Journ. of the Human Factors and Ergon. Soc.*, vol. 50, no. 1, pp. 90-111, 2008.

[6] K. MacLean, “Foundations of Transparency in Tactile Information Design,” *IEEE Trans. On Haptics*, vol. 1, no. 2, pp. 84-95, 2008.

[7] K. MacLean, “Haptic Interaction Design for Everyday Interfaces,” *Rev. of Human Factors and Ergon.*, vol. 4, no. 1, pp. 147-194, 2008.

[8] M. Niwa, R. Lindeman, Y. Itoh, and F. Kishino, “Determining Appropriate Parameters to Elicit Linear and Circular Apparent Motion Using Vibrotactile Cues,” *Eurohaptics Conf. and Symp. On Haptic Interfaces for Virtual Environment and Teleoperator Syst., 3rd Int.*, Salt Lake City, UT, USA, 2009, pp. 75-78.

[9] C. Sherrick, “Bilateral apparent haptic movement,” *Perception and Psychophysics*, vol. 4, no. 3, pp.159-160, 1968.

[10] C. Sherrick and R. Cholewiak, “Cutaneous Sensitivity,” *Handbook of Perception and Human Performance, Vol. 1: Sensory Processes and Perception*, K. Boff and L. Kaufman, eds., John Wiley & Sons, pp. 1-58, 1986.

[11] K. Shimoga, “Finger Force and Touch Feedback Issues in Dexterous Telemanipulation,” *Virtual Reality Annual Int. Symp.*,Seattle, WA, USA, 1993, pp. 271-279.

[12] A. Sklar and N. Sarter, “Good Vibrations: Tactile Feedback in Support of Attention Allocation and Human-Automation Coordination in Event Driven Domains,” *Human Factors: the Journ. of the Human Factors and Ergon. Soc.*, vol. 41, no. 4, pp. 543-552, 1999.

[13] D. Spelmezan, M. Jacobs, A. Hilgers, and J. Borchers, “Tactile Motion Instructions for Physical Activities,” *Proc. of the 17th Conf. on Human Factors in Comp. Syst., CHI ’09*, pp. 2243-2252, 2009.

[14] K. Tsukada and M. Yasumura, “ActiveBelt: Belt-Type Wearable Tactile Display for Directional Navigation,” *UbiComp 2004,* Springer-Verlag, Heidelberg, Germany, pp. 384-399, 2004.

[15] J. van Erp, E. Groen, J. Bos, and H. van Veen, “A Tactile Cockpit Instrument Supports the Control of Self-Motion During Spatial Disorientation”, *Human Factors*, vol. 48, no. 2, pp. 219-228, 2006.

[16] J. van Erp, H. van Veen, C. Jansen, and T. Dobbins, “Waypoint Navigation with a Vibrotactile Waist Belt,” *ACM Trans. On Applied Perception*, vol. 2, no. 2, pp. 106-117, 2004.

[17] C. Wickens, “Multiple Resources and Performance Prediction,” *Theor. Issues in Ergon. Sci.*, 2002, vol.3, no. 2, pp. 159-177, 2002.

CONTACT INFORMATION

Name: William Arthur Roady, III

Professional Address: c/o Dr. Tom Ferris
Department of Industrial and Systems Engineering
3131 TAMU
College Station, TX 77843

Email Address: TreyRoady@tamu.edu

Education: B.S., Industrial and Systems Engineering,
Texas A&M University, May 2012
Undergraduate Research Scholar