EVALUATING TECHNOLOGY TO IMPROVE TACTILE NAVIGATION & COMMUNICATION IN PEOPLE WITH VISUAL DISABILITIES

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Abstract: This research designed a wearable vibrotactile prototype for providing intuitive orientation and communication cues to aid in navigation in visually challenging situations. The signals presented by this device were designed to communicate the three levels of situation awareness (SA; perceive, comprehend, and project) naturalistically as if one was being guided by a partner's hand. We evaluated the effectiveness of this device in a human subject experiment with visually impaired participants. Performance with the vibrotactile display was compared against participants' normal methods of navigation. Results showed that the tactile design enhanced accuracy, but increased navigation time. We expect reductions in navigation times will be achievable with the tactile device through training and enhancement of the design. Results of this preliminary study are informing designs and future experiments that will evaluate the ability of vibrotactile displays to convey SA in simulated space walks.

1 Introduction

There are many situations where individuals must learn to navigate their environments with degraded visibility. This includes people who must maintain orientation during spacewalks, avatar embodiment, scuba diving, aircraft piloting, military operations, or visually impaired navigation.

Vibrotactile displays, which use peoples' sense of touch to communicate information, can be a viable solution for assisting navigation. Torso mounted tactile navigation, where vibrations communicate spatial information, frequently requires minimal training, and can be utilized in many environments (Wenzel and Cooper, 2021). Most of the research and developments in this area have focused on tactor placement and the vibration intensities and patterns they use to communicate basic directional information (Wenzel & Cooper, 2021). However, to be useful for navigation, tactor displays would ideally help build SA. That is, they should help people (1) perceive elements in the environment, (2) comprehend their meaning in the current context, and (3) project this comprehension into the future (Endsley, 1995).

The research reported here is the first of a series of experiments that looks to support a new methodology for enhancing tactile display concepts in situations where visual navigation is challenging or impossible. Additionally, it explores opportunities when there could be clear benefits for freeing up the visual senses for other tasks. This methodology specifically seeks to communicate all three levels of SA to participants using tactile signals inspired by how human assistants help guide the visually impaired through touch. It is our intention to investigate how this can be used to help orient astronauts during space walks. However, because the visually impaired were the inspiration for the tactile communication patterns we employed, the presented study used this population to evaluate the effectiveness of our initial prototype. Results from this study will enhance the vibrotactile design and inform a simulated spacewalk experiment (using a scuba diving environment as a proxy) that is currently being developed.

2 Background

Haptic Tactile Displays for Navigation

The science of tactile sensation has a rich history that dates to the work of Weber and Fechner in the 19th century. These researchers defined and refined “weber’s law,” which established the psychophysical thresholds we associate with touch perception and other human sensory modalities (Fechner, 1860). Since this time, research has identified the sensory and neurological science of how the human body transforms touch stimuli into perception. Tactile displays have been built on this science, using touch to communicate information to people (Parisi, 2018).

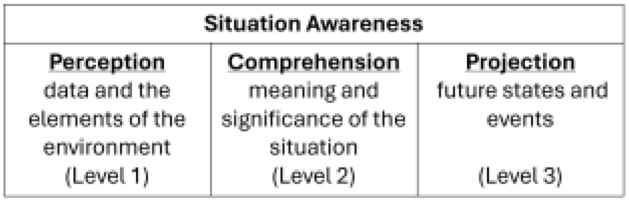
Vibrotactile haptic information has proven useful in providing intuitive orientation cues to individuals where conditions are visually degraded or overloaded. In particular, Collins and Bach-Y-Rita (1973) identified that the abdomen and back are not commonly used for communicating information. Thus, they are convenient locations for tactor displays. Ultimately, the work of Collins and Bach-Y-Rita was not successful, likely because they attempted to convey rich, image information through tactile displays. This likely overwhelmed many users, as it likely exceeded the processing capabilities typically available through touch. However, their findings did lead to the development of modern vibrotactile systems like the Tactile Situational Awareness System (TSAS), which used much sparser information.

In TSAS, vibrations around the torso were designed to communicate three-dimensional navigation information to pilots (Raj, et al., 1998). In tests with U.S. Army UH- 60 helicopter pilots, the pilots performed at a higher accuracy in hovering, take off, and landing exercises with visually degraded external views, but access to instrument displays and the TSAS. This experiment showed that improvements to tactile display could significantly assist in SA (Raj, et al., 1998). Subsequent research studies confirmed TSAS’s effectiveness in lowering workload, reducing in-flight error, useful in long duration flights, helpful with sleep deprived users, and improved hover target accuracy for helicopter pilots (Lawson, et al., 2016).

Despite these successes, TSAS-like technology has struggled to transition into real world flight operations (Lawson, et al., 2016). A notable limitation of existing vibrotactile systems is that they largely focus on conveying information only pertinent to the current situation. That is, they allow for reactive human behavior, but do not establish temporal contexts that would help people strategically navigate through a complex environment. Thus, there is clearly a need to design tactile display technology that supports all levels of SA.

Situation Awareness

SA is a concept related to what a person understands about their current situation. It was more precisely defined by Endsley (1995) as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.” Thus, SA is commonly thought to have three levels as shown in Figure 1.



Situation Awareness		
Perception data and the elements of the environment (Level 1)	**Comprehension** meaning and significance of the situation (Level 2)	**Projection** future states and events (Level 3)

Figure 1. Endsley’s (1995) three levels of SA.

Clearly, all three levels of SA are important for navigation: knowing what things are in your environment, understanding where they are in relation to you, and understanding how their location will change as you move through the environment (Bolton, Bass, & Comstock, 2007). For example, astronauts are faced with navigating in six degrees of freedom while completing assigned tasks on their missions (Wenzel & Cooper, 2021). Due to a lack of gravity, these astronauts need to comprehend their location in space, additional equipment they will be utilizing, as well as varying changes within the environment they are exploring. Their SA is challenged regularly as they need a timely cognizant awareness of their environment (National Academies of Sciences, 1998).

As described above, tactile devices have historically targeted the perception and comprehension levels of Endsley’s SA, but they have not categorized tactile vibrations as such. Vibrations have also not been utilized for the projection level. Thus, the full potential for vibrotactile displays used in navigation has yet to be realized.

3 Objectives & Hypotheses

This research sought to both design a vibrotactile system to convey all three levels of SA in conditions where visual navigation is difficult and evaluate how individuals with visual disabilities interacted with this vibrotactile system. We hypothesized that the use of our vibrotactile system, will enhance SA, thereby, allowing blind individuals to navigate faster and more accurately than they could using their standard navigation methods. In achieving these research objectives and testing this hypothesis, this research will ultimately provide preliminary data for improving the system and the experiment for exploring space-relevant application areas.

4 Methods

Vibrotactile Display Design

Wenzel and Cooper (2021) identified factors that must be considered when designing tactor displays. The duration of tactor vibrations and locations of their placement on the body hold the most influence on the perception of encoded information. Signals should be simple. Masking effects (stimuli not recognized when another stimulus is presented before or after), change blindness (inability to detect a change in a tactile pattern placed between other signals), limited perceptual resolution, and bandwidth can cause vibrotactile signaling to be ineffective. These factors were accounted for in our novel design.

The base prototype for our system was previously created and tested by Triton to assure safety in end user experiments (Eguchi et al., 2022; Eguchi et al., 2023; Figure 2). For this experiment, our team designed new software that enables the tactile interface to match the needs of the visually disabled users within this experiment. It also enabled the use of Bluetooth by the device to allow participants the ability to walk independently.

Figure 2. Triton vibrotactile t-shirt front and back along with Arduino nano 33 IOT board.

This vibrotactile t-shirt consisted of 6 eccentric rotating mass motors (vz7al2b1692082, Vibronics) operated by a lithium polymer battery with all signals conveyed via a driver in a microcontroller (an Arduino nano 33 IOT). The electrical circuitry was screen printed directly onto the t-shirt. The tactors were positioned as shown in Figure 3.

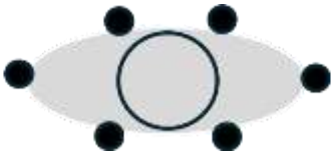


Figure 3. Overhead silhouette showing the position of the six tactors on a participant’s torso.

Programming of the vibrations followed Weber’s Law to ensure that end users would feel them (as per Lester & Thronson, 2011). A minimal temporal binding window of 100 ms was also used to ensure a temporal separation between two sensory events (Wenzel and Cooper, 2021).

Vibrotactile cues for this experiment were specifically designed to convey Endsley's' three levels of SA. All of these signals were designed to mimic how somebody might receive navigation guidance from a human assistant touching and moving their hand across the torso of the person being navigated.

First level SA (perception) was communicated via one tactor signal that indicated the direction of a target. It also conveys some second level (comprehension) SA by indicating the orientation of the object to the user. This signal mimicked the navigator being tapped in a given direction.

Additional second level SA (comprehension) was conveyed using multi-tactor vibration to tell the user how they needed to turn and/or if they had reached the target (they needed to stop moving). The turning signal was designed to mimic a hand guiding the individual in a particular direction across their body. The stop signal (where all the tactors would vibrate) was designed to mimic someone holding you in an embrace in your current position. "Note," that this provides more nuanced comprehension information than the perception signal because navigating to a target may not necessarily go in a straight line.

The third level of SA (projection) made use of level one and two signals, where these occurred temporally in sequences/pulses to convey the object's distance. The number of pulses were designed to convey the number of steps needed to reach the target or next navigation point. These are conceptually similar to a navigator tapping the person to convey spatiotemporal information.

Human Subjects Study

We evaluated the effectiveness of our vibrotactile design with a Social Research and Ethics Committed application Log 2023-223 through the University of College Cork, Ireland, Research Ethics Support Council. This study had participants navigate a 15x15 sq ft area using different navigation to reach a specific target position. Performance achieved using our vibrotactile systems were compared based on multiple performance and subjective measures.

Participants

Participants were recruited through Vision Ireland, Cork Audible Book Club, and Cork Community Art Link. Garda vetting was procured to work with visually disabled individuals. Participants were selected based on their age (18 or older), willingness to volunteer, lack of mental impairments, and physical capabilities compatible with the demands of the study.

There were 17 visually disabled participants in total: 5 females and 12 males aged from 29-91. Individuals varied in occupations and across all levels of education with all utilizing technology daily. In the results presented here, we focus on analyzing the results of the 11 who were completely blind, this included 3 females and 8 males. The focus was on these 11 participants, as they were fully blind. The other participants were still capable of seeing their environment with their disabilities.

Facilities

The locations where the experiment occurred varied across Ireland at individuals' homes and backyards (Ballincollig, Wicklow, Galway, Kinsale, Sligo, Dublin, and Cork) along with the University of College Cork Western Gateway, and at Vision Ireland both in Cork and Dublin. The researcher coordinated and traveled to various locations to provide full accessibility for those who wished to participate.

Apparatus

To enable proof of concept for this prototype and ensure safety, all signals were directed through the experimenter to the wearable device directly influencing all movements of the end user. The experimenter also shadowed the users while they walked to make sure they could intervene should the user need assistance.

Participants navigated within a 15x15 sq ft area, that was flat without obstacles. The environment varied to accommodate the locations of the participants (see examples in Figure 4).

Figure 4. Representative examples of indoor and outdoor testing environments.

Independent Variables

There was one independent, within–subject variable with two levels: regular use and tactor use. In the regular use case, participants navigated with the method they normally used. This included the use of pace counts, echolocation, and walking sticks. In the tactor use condition, participants navigated with the new tactor navigation system only.

Dependent Measures

Two objective measures of navigation task performance were collected: navigation time and accuracy. Navigation time indicated how long it took participants to reach a navigation target. This was recorded using a stopwatch during trials. Accuracy indicated the distance that a participant was from the target at the end of the trial. Accuracy was measured with a tape measure as the distance of the participant's final position of the heel of their closest foot to the target destination.

Subjective measures (where participants provided ratings about their experiences during trials on scales) were also collected for each level of the independent variable. This included standard subjective ratings for mental workload with the NASA Task Load Index (NASA-TLX; Hart & Staveland 1988), SA with the Situational Awareness Rating Technique (SART, Selcon et al., 1989), and usability with the System Usability Scale (SUS, Brooke, 1995).

Additional surveys were also collected in the experiment. A survey designed to understand how participants thought about SA constructs was collected before experimental trials. Within this, participants described how they analyzed situational awareness personally, described what they thought the tactors meant at first stimulation, and categorized the tactors by Endsley's SA levels. At the end of the experiment, participants were asked to complete a general survey regarding equipment and abilities. This allowed participants to give subjective feedback about their overall experience with the tactors. Within the scope of this manuscript, our discussion will focus on the results of time and accuracy due to page limitations.

Procedure

Each experimental session lasted approximately 1.5 hours. Participants were read and verbally agreed to their consent form and indicated whether they allowed pictures or video footage to be used for academic purposes. Participants were then interviewed to fill out a demographics survey and the SA construct survey. Participants were then shown how to walk within the 15 x 15 square in different directions (depending on the trial): sideways, diagonally, and straight (see Figure 5).

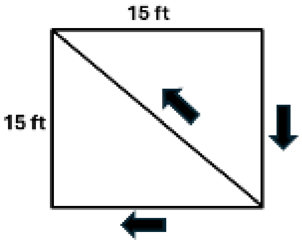


Figure 5. Variations of walking directions for participants within 15 x 15 square.

During the experiment, participants were told specific distances they needed to walk and oriented in the direction they would start their walk for the experiment. Participants completed each trial walk three times in each direction. Nine trial walks with the tactors and nine trial walks with the participants using their regular navigation method were completed. Participants were given instructions on what the tactors were programmed for before the block of trials. After each nine-trial block for the two independent variable levels, the NASA-TLX, SART and SUS measures were collected. At the end of the experiment, the general question regarding equipment and abilities survey was conducted. This was followed by a debrief.

Experiment Design & Data Analysis

This experiment used a within-subjects design, where the trials for each independent variable level were grouped together in blocks. The order of block presentation among participants was counterbalanced between participants. The block design allowed for 9 replications, three each, in which each participant was given performance navigation tasks where they walked towards the target sideways, diagonally, and straight from their starting position. Participants experienced these replications in a unique random order in each trial block. This experimental design was used because it achieved greater than 80% power with 11 participants when accounting for replications using the method described by Goulet (2019).

Contingent on the normality of the difference between the independent variable levels, we planned to evaluate our results using two-tailed, paired t-tests to determine if there were significant differences in navigation time and accuracy between the regular use and tactor use conditions. In the event that normality was violated, we planned to use Wilcoxon signed-rank tests.

5 Results

Shapiro-Wilk tests of normality revealed that the difference between the independent variable levels for both navigation time and accuracy were not normally distributed ($W = 28.22$, $p < 0.01$ and $W = 21.22$, $p < 0.01$ respectively). Thus, Wilcoxon signed-rank tests were used for comparisons.

The Wilcoxon signed-rank test comparing navigation times between the independent variables' levels revealed a significant difference ($W = 0$, $p < 0.01$, $r = -1$), with participants taking significantly longer (*Mdn* = 15.47 s) with tactor use than regular use (*Mdn* = 6.85 s), see Figure 6.

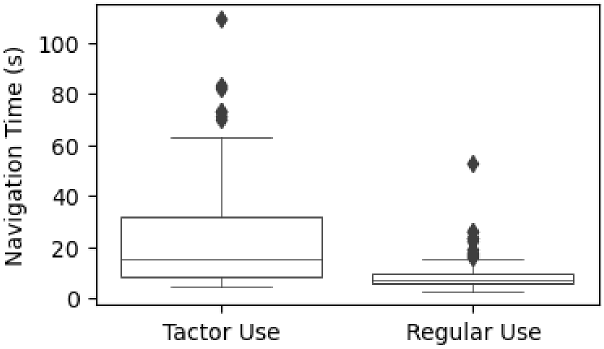


Figure 6. Box plot showing the significant difference observed between navigation times when participants used the tactor navigation systems compared to when the participants used their regular method. In each plot, the line indicates the median. The box shows the inter quartile range. Whiskers show data upper and lower values, excluding outliers. Outliers are single points.

The Wilcoxon signed-rank test comparing accuracy between the independent variables levels also showed significant difference ($W = 936$, $p < .001$, $r = 0.89$). In this case, participants were more accurate (*Mdn* = 4.0 in) when using the tactor system than when using their regular method (*Mdn* = 18 in); see Figure 7.

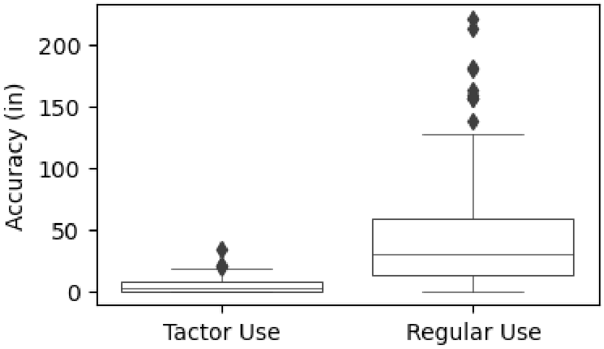


Figure 7. Box plot (see Figure 6) showing the significant difference observed in accuracy between when participants used the tactor navigation systems compared to when they used their regular method. Closer to zero is closer to the destination.

6 Discussion

In this work, we designed a novel tactor display to convey three levels of SA in situations where visual navigation is difficult. We evaluated this system with blind participants who performed a simple navigation task. Our results were consistent with our hypothesis that participant navigation accuracy would improve when our vibrotactile system was used. In fact, median participants' navigation accuracy increased by an order of magnitude (an approximate 14 in. improvement; see Figure 7). However, our results contradicted our hypothesis for navigation time, with median tactor navigation taking about 10s longer than when participants used their standard method. These results suggest that tactor based navigation had potential, especially when accuracy is critical.

Many of the experiment's participants had additional disabilities. These included partial deafness, full deafness, chronic back pain, arthritis, diabetes, no light awareness, no leg awareness, vertigo, lymphoma, Hutchinsons, gout, and a hand amputation. Participants consistently navigated accurately with the vibrotactile display with these disabilities. Their ability to do so suggests that the design and technology were universally useful.

The observed increase in navigation time seen for the tactor display will require some additional examination. However, it is likely that unfamiliarity with this tactile technology played a significant role in the result. Many participants tended to move slower in early tactor display trials. However, by the final trial, they were moving at a pace like what was seen without the tactors. This is seen in the skew of the tactor use plot in Figure 6, where there were clearly more lower observations, but a long tail for higher values. Obviously, participants were more familiar with their traditional forms of navigation. Thus, we expect additional experience and training with the vibrotactile system will significantly reduce navigation times. This possibility will be investigated further in future research.

Another potential source of slowdown is latency in the tactor system. There are two potential sources of such latency. First, the experimenter handling navigation had to dynamically react to participants sudden movements and manually send commands. Thus, the experimenter's reaction time was a source of delay. Second, the screen-printed circuit used by the prototype has long trace lengths and routing that can affect the signal's propagation time (Muth et al., 2002). We are currently investigating technological improvements to address both problems.

Wenzel and Cooper (2021) identified several unknowns in modern tactile display technology. Our results appear to provide answers to several of these unknowns. First, it was unclear how placement of the tactors on the torso should consider spatial influence dependency (i.e., how the location influences the perception of spatial information). Our approach was coded such that vibrations on an individual's back conveyed that there was important information behind them. Because our accuracy results were so compelling, this suggests that our design accounted for spatial influence dependency in an intuitive way. Similarly, our approach adopted a very egocentric design. That is, vibrations were designed to convey spatial information relative to the orientation of the person. The accuracy findings we obtained thus suggest that navigation is well suited to such an egocentric perspective as opposed to an external one. Analysis of the survey results should provide additional insights into how intuitive participants found our presentation of these concepts.

Visually impaired individuals have a higher acuity in tactile senses than those who are not visually impaired due to their increased reliance on alternative nonvisual senses (Goldreich & Kanics, 2003). Thus, there is some risk that the results we obtained here may not generalize to other populations. However, preliminary work we have been doing in preparation for a simulated spacewalk experiment suggests that our tactor signal designs are just as perceivable for those without visual impairment as they are for those with it.

One potential advantage of tactile displays is that, because they convey information over an underused sensory modality, they can free up resources on alternative modalities (Lawson, et al., 2016). This has the potential to improve multitasking and/or reduce user mental workload. Future work will assess how mental workload was impacted based on the collected NASA-TLX measures. Future work will also explore the impact of tactor navigation on the other collected subjective measures of SA and usability. Additionally, survey results collected from tactor use will contribute to refinement of the tactor display signals to better communicate navigational concepts. These contributions will ultimately inform subsequent experiments that will test the updated navigation systems in a simulated spacewalk environment. The first of these experiments will involve scuba diving.

Acknowledgements

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