EVALUATING TECHNOLOGY TO IMPROVE TACTILE NAVIGATION & COMMUNICATION UNDERWATER

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Abstract

This study tests the effectiveness of wearable, vibrotactile cues to provide intuitive orientation and communication cues to participants in low-visibility for an underwater navigation task (an analog to space weightlessness). The device's signals were designed to communicate the three levels of situation awareness (SA; perceive, comprehend, and project) intuitively, as if one was being guided by a partner's hand. We evaluated the effectiveness of this device in a human subject experiment with divers wearing fully blacked-out dive masks. Performance with a vibrotactile display was compared with a heads-up display and rescue diver rope pulls based on navigation accuracy and time. The results showed that the tactile design improved accuracy compared to the other methods, but increased task completion time. This paper discusses results from this study to consider navigation aids for SA in a similar space environment.

Introduction

The weightless environment in space adds a level of complexity for astronaut navigation, especially given the six degrees of freedom of movement and the lack of obvious directional anchors. This is further exacerbated by weightlessness, where imbalances in the human vestibular system can lead to spatial disorientation[9] when faced with navigating and communicating effectively throughout operations. To facilitate navigation during spacewalks, NASA delineates a "critical need design of multi-modal interfaces to optimize performance for both training and actual operations"[13]. Tactile solutions, where navigation information is conveyed through vibrations on the human body, are underused in current spacewalk navigation systems. However, these have promise, as they can allow complex movement information to be communicated to different locations on the human body, while potentially freeing up valuable auditory and visual communication modalities and giving people grounded navigation aids.

Studying an alternative interface for conveying tactile navigation information to divers in a weightless environment similar to space allows for the development of a tactile solution to fulfill the critical need for an alternative sensory interface. It also investigates an alternative method of communication and allows for adaptation in this weightless environment.

This research sought to investigate a tactile navigation solution that could be used in spacewalk environments. The tactile cues used in our method were designed to mimic somebody directing a person by moving their hand over the person's body. They were also nested in Endsley's categories of situational awareness (SA) in that they seek to convey (1) perception of critical elements in the environment, (2) a comprehension of their relative spatial and temporal location, and (3) how these will change as the operator moves through the environment. To evaluate the effectiveness of this approach to assist navigation in a space-like environment, we evaluated divers navigating underwater in low visibility conditions. The performance of participants using this system were compared with conventional navigation methods. This included rope pulls (which are specific to diving) and an in-mask heads-up display (HUD; which is more comparable to displays astronauts might use).

In what follows, we provide a background to understand our approach. We then use this to provide a more concise definition of our objectives and formulate specific research hypotheses. We then describe our research methods and report our results. We ultimately discuss the implications of our results and explore directions for future research.

Background

This section provides background on topics relevant to this paper's research. First, we describe SA, a concept very topical to navigation. We then present a brief introduction to tactile displays and a tactile display we designed specifically to naturalistically convey SA navigation concepts.

Situation Awareness

SA is a psychological concept that encompasses what a person understands about their current environment. Its most popular definition was furnished by Endsley[6]. She claimed that SA has three levels (1) "the perception of the elements in the environment within a volume of time and space," (2) "the comprehension of their meaning," and (3) "the projection of their status in the near future."

All three SA levels are necessary for effective navigation. A navigator must perceive what relevant elements are in one's environment (level 1), comprehend where they currently are to the navigator (level 2), and project how the locations of these things will change as the navigator moves through the environment (level 3; Bolton et al.[1], Wickens[14]).

Tactile Displays

Tactile displays have proven their success in the aviation and medical industry, and show promise for space as well[8,9]. Underwater testing completed by McGrath et. al.[4], showed that tactile cueing was a viable option, where its use resulted in less navigation errors and lower workload compared to more conventional options. However, experimental testing called for a variety of improvements in tactile technology that needed to be addressed. Improvements for consideration were the choice of tactors, the electronic processor, sensors, and appropriate communication warnings coded in the tactors for various conditions within the underwater environment[12]. Advances in tactile technology have allowed for the reevaluation of these shortcomings.

The most important tactile consideration for human interfacing is proper communication with the end user. Wenzel and Godfroy-Cooper[13] identified several factors that must be considered in tactor displays. The duration of tactor vibrations and 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 when placing tactors and designing their signals in a novel vibrotactile navigation display that we developed. Furthermore, our design filled a major gap in the vibrotactile displays by determining how to use them to convey all three levels of SA during navigation tasks.

Our Vibrotactile Design

Our design made use of a prototype (fig. 1) created and tested by Triton Systems[5]. This vibrotactile garment 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 garment. The tactors were positioned as shown in fig. 2.

We extended this design with new software that enables the tactors to convey custom signals. The programming of the vibrations followed Weber's Law to ensure that users would feel them[10]. A minimal temporal binding window of 100 ms was used to ensure temporal separation between sensory events[13].

Vibrotactile cues for this experiment were specifically designed to convey Endsley's three levels of SA[2,3]. These signals were designed to mimic how someone might receive navigation guidance from a human assistant by touching and moving their hand across the torso of the person being navigated.

First-level SA (perception) was communicated by a single tactor signal that indicated the target's direction. This 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. 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 mimicked a hand that guides the individual in a particular direction across their body. The stop signal (where all tactors would vibrate) mimicked someone holding the user in an embrace. These second-level signals provide more nuanced comprehension information than the level one signal because navigating to a target may not necessarily go in a straight line. The third level of SA (projection) used level one and two signals, where they occurred temporally in sequences/pulses to convey object distance. The number of pulses were designed to convey the number of motions needed to reach the target or next navigation point. Note that motions are a general concept that can be adapted to suit different environments: e.g., steps when walking, fin kicks when diving, or pushing force during spacewalks. These navigation cues themselves are conceptually similar to a person tapping the navigator to convey spatio-temporal information in terms of the motions.

We previously evaluated our navigation system in a human subjects study with blind participants[2,3]. The performance with the vibrotactile display was compared against participants' normal navigation methods. Our results showed that the tactile design enhanced accuracy, but increased navigation time. The design was also comparable to participants' standard methods based on subjective workload, SA, and usability measures.

Objectives and Hypotheses

Because of the success of our vibrotactile design in assisting the blind during navigation, we hypothesized that it would also be useful in a more space-like environment. Thus, in this experiment, we evaluated the ability of our device to support diver navigation under low visibility conditions. We hypothesized that our design would allow divers to navigate faster and more accurately than conventional approaches currently used by divers and rescue teams. This included a HUD (which conveyed navigation information in a participant's diving mask) and pull methods (which communicate navigation information via rope pulls from a tender above water).

Methods

This underwater vibrotactile design was evaluated under the University of Virginia's Institutional Review Board for Health Sciences Research (Protocol Number 230263). Participants were asked to dive in a dry suit with a blacked-out mask, navigate a 15x15 sq. ft. area, and move sandbags to designated locations. The performance of our vibrotactile design was compared with rope pulls (utilized in dive rescue scenarios) and a Scubapro Heads Up Display (HUD). These navigation methods were analyzed through performance. To facilitate comparison, this study replicated our previous experiment that explored how our tactile design influenced blind navigation[2,3].

Participants

Twelve participants were recruited through the Monticello Dive Rescue Team, and one partic-

Figure 1: Triton Systems vibrotactile garment front and Arduino nano 33 IOT board.

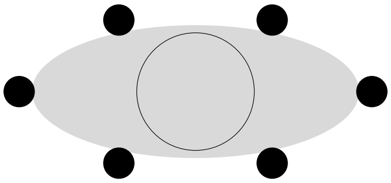

Figure 2: Overhead silhouette showing the position of the tactors on a participant's torso.

ipant was a University of Virginia experienced recreational diver. Participants were selected based on their age (18 or older), willingness to volunteer (including having a blacked-out mask underwater), certification for open-water and dry suit training from an appropriate diver organization (NAUI, PADI, SDI, etc.), streamlined buoyancy, dive experience (four or more open-water dives with at least one in the past year), and lack of illness, sinus congestion, and pregnancy. Their experience in diving was marked with their highest scuba education achieved. This resulted in a range of beginner, intermediate, and advanced divers: 1 open water diver, 3 master divers, 1 divemaster, 2 rescue divers, 4 public safety divers, and 1 underwater criminal investigation diver.

Facilities

This field experiment was completed at the Fluvanna Dive Center in Louisa County, Virginia. Experimentation at this indoor pool was completed at a depth of 14 ft 2 in. The shallower walking portion of the pool enabled experimental setup and acclimation for the participants prior to beginning the experiment.

Apparatus

The base prototype (described above) was connected to a 9-pin cable that exited the diver's dry suit. This cable was exposed to the water until it exited the pool and connected to the circuit board (fig. 1). This circuit board had an additional cable that was hard cabled directly to the laptop controls. This laptop was used by the experimenter (acting as a tender) to send commands to the diver. An additional diver in the water shadowed participants' movements to prevent injuries underwater, reset the participants during each trial, and helped to ensure there were no entanglement issues with any of the communication and tactor cables. Radio communications were utilized with the participant divers during the entire course of an experimental run. This allowed ongoing communication with the tender for safety.[1]

Participants navigated underwater within a 15×15 sq. ft., flat, obstacle-free area. The blacked-out mask was utilized in all navigation methods of tactors, pulls, and the HUD (see examples in fig. 3).

Independent Variables

There was one independent, within-subject variable with three levels. This represented the navigation methods used: Tactors, Pulls, and HUD. The pulls method was consistent with one used by the Monticello dive rescue team, where the tender on the rope on the surface

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[1] Participant 7 agreed to complete the experiment without a radio system when it was not available

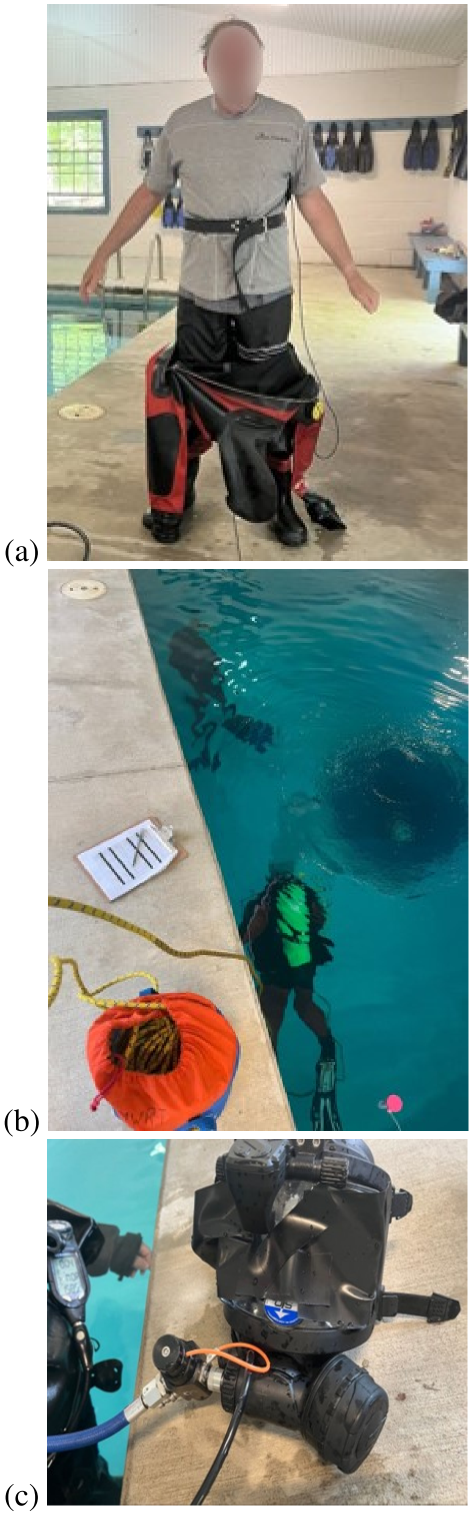

Figure 3: (a) Is a participant showing how tactors were worn underneath a dry suit. (b) Shows pulls being administered from the tender's perspective. (c) Illustrates the HUD attached to the corner of the blacked-out mask.

Figure 4: Participants were instructed to maintain a steady buoyancy to follow the number and cardinal direction that would direct them to their intended target to drop the sandbag.

above the water translated to the diver holding the rope in the water. Four pulls indicate "proceed left," three pulls "proceed right," and one pull means "stop." The HUD displayed a compass screen which directed individuals by the cardinal and number direction they needed to proceed (see fig. 4).

Dependent Measures

In each trial, two objective performance measures were used. Navigation time (in seconds) was measured using a timer. Accuracy (inches) was measured as the distance of the final position of the placed sandbag from the target position using a tape measure.

Procedure

Each experimental session lasted approximately 2 hours. Participants listened to and verbally agreed to their informed consent form. They also indicated whether they allowed pictures and video recordings to be used for academic purposes. Participants were then interviewed to complete a demographic survey and the SA construct survey. In the SA construct survey, participants wore the tactile display garment and ran through two series of the display's nineteen different vibrations. In the first series, participants explained what they thought each vibration signal was communicating to them about navigation. In the second series, participants were asked to categorize vibrations into Endsley's SA categories of perceive, comprehend, and project.

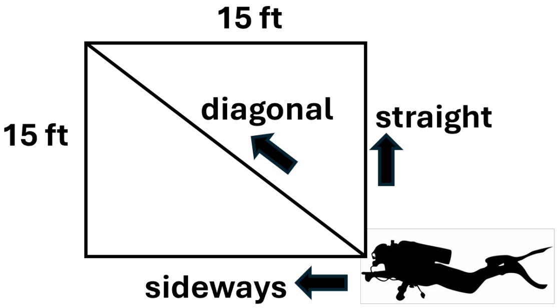

Figure 5: Variations of diving directions for participants within 15 × 15 ft. square.

The participants were then told what each vibration meant and were physically guided to each start point underwater within the square in different directions (depending on the trial): sideways, diagonally, and straight (see fig. 5).

During the experiment, participants were told the distances they needed to dive over the radio. They were oriented underwater by their dive guide. Participants completed each trial dive three times for each direction: three times each for sideways (the horizontal side of square facing the participant), diagonal (diagonally towards the opposite corner of the square), and straight (either of the vertical sides of the square facing the participant). This resulted in blocks of nine trial dives, one for each of the independent variable levels: tactors, pulls, and HUD navigation. Additional subjective measures and survey questions were asked of participants before the experiment, between blocks, and after all trials. These will be reported in latter publications.

Experiment Design and Data Analysis

This experiment used a within-subjects design. Trials (for each separate navigation task) for each independent variable level (navigation method) were grouped into blocks. Block presentation order was counterbalanced between participants. Block design allowed for nine replications, three for each navigation method.These replications were presented in unique random orders for each participant in each trial block.

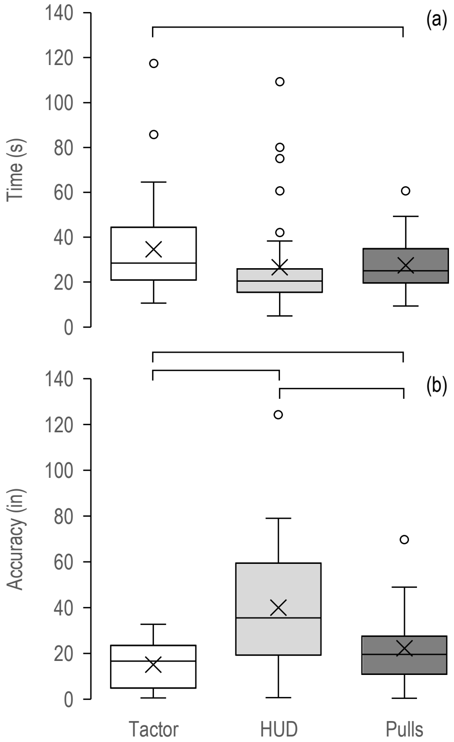

Figure 6: Box plots showing the difference observed between (a) navigation times and (b) accuracy (the lower, the more accurate) when participants used tactor, HUD, and pull navigation. Horizontal lines indicate medians and × show means. Boxes show interquartile range (IQR). Whiskers extend to the extreme data points within 1.5 times the IQR. Points beyond the whiskers are outliers. Brackets above plots indicate significant differences.

Contingent on normality assumptions (based on Shapiro-Wilks tests), the significance of differences of performance measures between the independent variable levels were evaluated using repeated-measures analyses of variance (ANOVAs). Bonferoni corrections were used to adjust alpha levels ($\alpha = 0.05$) to account for multiple comparisons across ANOVAs and associated post-hoc analyses.

Results

A repeated–measures ANOVA with a Bonferroni correction determined that mean times did significantly differ across the navigation methods $(F(2,34) = 3.75, p = .034, \eta_p^2 = 0.18)$. Pairwise comparisons showed differences between all methods, with pulls being the fastest and tactors the slowest; see fig. 6(a).

Another repeated-measures ANOVA with the Bonferroni correction determined that mean Accuracy scores did significantly differ amongst navigation methods utilized $(F(2,34) = 20.73, p < .001, \eta_p^2 = 0.55)$. Pairwise comparisons showed differences between all navigation methods, with tactors being the most accurate and the HUD the least accurate in navigation trials; see fig. 6(b).

Discussion

In this work, we evaluated a tactor display for conveying spatial navigation information in a weightless (underwater) environment under low visibility conditions. Overall, our results are consistent with our previous study that tested our design with a visually disabled population: the tactor display improved navigation accuracy while being intuitive and usable^2. Participants also took longer to complete their navigation tasks with the tactors.

Our performance metric results were consistent with our hypothesis that participant navigation accuracy would improve with our vibrotactile system. In fact, median participants' navigation accuracy improved by 24.92 in with the tactors than with the HUD (fig. 7(d)) and 7.08 in than with the pulls (fig. 7(f)). Thus, the tactor display does appear to significantly improve accuracy. However, our results contradicted our hypothesis for navigation time: median participants' navigation accuracy increased by 8.05 s with the tactor display than with the HUD (fig. 7(c)) and 7.18 s compared to pulls (fig. 7(e)).

Accuracy was more consistent with the tactors than the other options (fig. 6(a) and fig. 7(b) vs (d) and (f)). This speaks to the capabilities of the tactor display given that participants had never used the tactors before.

Figure 7(a), (c), and (e) report how navi-

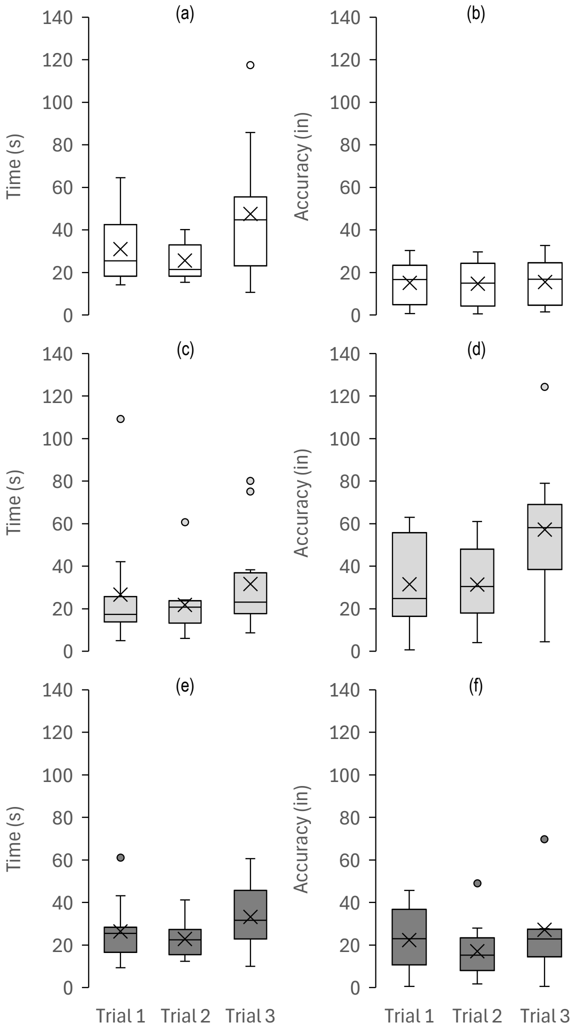

Figure 7: Box plots showing how participants' time and accuracy measures changed over time. Plots (a) and (b) are results for the tactor display, plots (c) and (d) are for the HUD, and plots (e) and (f) are for pulls. In (b), (d), and (f) smaller values indicate higher accuracy.

gation time performance changed over time for the three navigation technologies. This shows that results skewed more in the third trial across the methods. We believe this occurred because participants became more comfortable being blindfolded underwater over time. Overall, there appeared to be more variance in time (compared to the other alternatives) when the tactor display was used (this is also present in fig. 7). With additional training and experience, we would expect navigation times with the tactor display to both improve and become more consistent. This should be the subject of future study.

Outside of training, there were other factors that contributed to participants taking longer to navigate with the tactor display. There was a latency in vibrations and low vibrations on participants' right sides. This resulted in delayed responses and the need for repetitions of navigation commands. The tender above the water could see that messages were sent and the divers would begin movement a few seconds after the signal was given. Furthermore, additional signals were sent to participants' right sides multiple times when the tender observed a participant not moving the first time. We expect that this occurs due to long trace lengths and routing, which can impact propagation time[11]. Additionally, there were participants with broken seals in their dry suits. This exposed the tactors to unanticipated full submersion in water. This reduced the ability of the tactors to vibrate against the divers' bodies. Future work is currently underway to address these design issues.

This experiment placed the tactors in varied conditions for evaluation. There were five dive participants that experienced variance in tactor performance. These variations impacted the ability of the tactors to convey information. However, these participants' accuracy was still enhanced in comparison with the HUD or pulls navigation methods. The following trials help to draw attention to improvements needed on the tactor prototype while still showing their potential.

Participant 4 had to complete the final tactor dive separately due to increased ear pressure from the first two diving rounds. This participant returned to complete the final dive with a different, less-experienced tender. This participant was not an outlier in their performance (24.27 in and 22.19 s vs 15.08 in and 34.67 s on average). These results suggest consistency of tactor performance.

Participant 7 opted to perform the entire experiment without the underwater radio communication system since the system was not working that day. This participant showed that all navigation techniques could be completed without verbal communication and solely tactile cueing. This participant's average time was 73.87 s (more than double the participant average of 34.67 s) as they moved cautiously. However, their accuracy was 20 in (only 5 inches off the overall average of 15.08 in).

Participant 9 did not seem to feel any of the tactors for the initial orientation, even though they were vibrating. Their performance indicated otherwise in the water, as they completed their trials with an average time of 46.09 s and accuracy of 25.56 in. Both scores were greater than the overall average. However, the initial test outside the water seemed to show no validity on the performance of the participant. This did raise considerations that some users may not have the same sensory abilities with touch as others.

Participant 10 had their entire dry suit flood. However, the consistency provided by the tactile cueing enabled completion of the experiment even with faint vibrations. This participant's time across three trials averaged 35.83 s, 1 second slower than the overall average. Their accuracy was 19.45 in, 5 in off the overall participant average. This provided insight to the necessity for redundancy amongst future prototypes with the tactors.

Upon experiment completion, Participant 12 followed up stating that they had limited feeling of the tactors and believed it could have been due to scarring they had on their torso. This participant's average time was 26.37 s with an average accuracy of 13.99 in, both better than the respective overall averages. Understanding this could be a concern for other users was important to truly consider placement of the tactors in future experiments.

These experiences with the tactors reinforce the need for modifications. Design changes and a more durable tactor choice could make the system more rugged. Furthermore, understanding how to adapt the system to overcome injuries across populations could help the approach be beneficial to a larger population of users. Ultimately, the design tested here and in[2,3] showed that both the visually disabled and rescue divers benefited from the precision enabled by the tactor navigation system.

Some of these technical challenges underwater will not be present in space. However, creating a robust system to overcome them will ensure viability in challenging space environments. Future and current space operations are similar to diving. Furthermore, innovations in propulsion systems should make space navigation even more similar to diving. Astronauts similar to divers will overcome gravitational pull and resistance similar to buoyancy of divers depth control. Calculated adjustments in navigation will need to be made to ensure accurate travel with precision in orientation. Targeted movements will help to ensure energy efficiency of astronauts similar to that of divers with extended mission durations.

Future Research

Our tactor display has been tested on special populations, such as the visually disabled and rescue divers. It has yet to be tested on the general populace. Expanding to this population would allow for more trials and more data about how different participants respond to tactor signals. Such experiments could allow for a more complete understanding of how the system could be improved. They could also enable longer experimental sessions that could explore how performance changes once participants are more experienced with the signals.

We plan to modify our prototype to enhance its performance. This includes increasing the contact surface area on participants' skin, preventing discrepancies in latency and tactor response by redesigning the electrical system, and enhancing the ability to regulate tactor pulse-width modulation. These corrections should enable consistent cueing that will overcome the attenuation of tactile signals with diverse end users in varying environments.

Beyond the improvement listed above, there are at least three research extensions that could make our developments more relevant to spacewalk navigation. First, the experiment presented ultimately only considered two-dimensional navigation, where there is a maximum of three degrees of freedom. Future research should determine how to extend our design to accommodate the three-dimensional navigation and six degrees of freedom of spacewalks. Second, tactor displays make use of electricity to convey information. This could present a problem during spacewalks, where electricity could be a limited and valuable resource. Thus, future research should investigate methods for making tactors as energy efficient as possible. Third, a major promise of tactor display technology is that it will free up attentional resources[7], allowing visual and auditory modalities to be used for other information, and potentially improving human workload. Future work should investigate whether this is indeed a benefit of tactor navigation and what types of concurrent tasks can be effectively displayed on visual and auditory channels.

Acknowledgements

This work was supported by the Virginia Space Grant Consortium (GR103780), Women Diver's Hall of Fame (Award Recipient 2023), and the National Science Foundation Research Traineeship (NRT) program under Grant No.1829004. Thank you Triton for the material transfer agreement for the TOGA prototype originating SBIR contract (W81XWH-21-C-0051).

The authors would like to thank Cole Godzinski and Triton Systems for the material transfer agreement of the base prototype that was used in our experiment. The authors also would like to thank Marshall Clyburn for assisting with coding of the prototype; Larry

Antonacci for his full-fledged support helping recruit participants and allowing use of gear and facilities at the Fluvanna Dive Center; and all dive participants for their cooperation with this experiment.

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