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Research paper

Guiding by touch: A vibrotactile navigation system for underwater situational awareness

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ABSTRACT

This study will test the usability of wearable, vibrotactile cues in providing intuitive orientation and communication cues to participants in visually challenging underwater navigation tasks. The device's signals were designed to communicate the three levels of situational 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 the vibrotactile display was compared against the Scubapro heads-up display, along with dive rescue team rope pulls based on performance measures (navigation, accuracy, and time). Subjective measures of mental workload, situational awareness, and usability were collected; as well as surveys designed to understand how participants classified tactor signals into SA levels. The results showed that the tactile design enhanced accuracy, but increased navigation time. This design was comparable to other standard methods across subjective mental workload, SA, and usability measures. The paper discusses the significance of these results for the navigation of both commercial and professional divers. It also explores the implications for navigation support in other visually challenging environments.

1. Introduction

Tactile cues have proven useful in providing intuitive orientation cues to individuals under significant cognitive workload. These cues have helped to improve situational awareness and allow for information to be relayed efficiently to the end user (Lawson et al., 2016a). Research in applying tactile cues has been conducted extensively in aircraft and medical research (Lawson et al., 2016b). The underwater applicability of this technology has received comparatively less attention. This is because older tactor technology could not overcome the harsh underwater environment (Rupert et al., 1999a). There has also historically been a risk of tactors accidentally setting off close-proximity, underwater mines, which could pose a serious hazard for military divers (Rupert et al., 1999a). However, tactor technology has advanced over the last three decades, and vibro-tactile cueing for orientation could prove particularly useful for dive operations. This is because diving is a complex, high-workload task. This is particularly true when there is an absence of visual cues, such as when diving in murky waters, in caves, at night, or during recovery operations. Tactor displays could enhance underwater navigation capabilities in these and low-visibility activities.

Disorientation is a known hazard in diving, particularly at depths of 60 ft or more. At these depths, visual degradation and reduced contrast sensitivity are more pronounced, and pressure changes can significantly affect the inner ear and equilibrium, increasing the risk of spatial disorientation (Clark, 2015). Divers frequently report episodes of benign paroxysmal positional vertigo, which causes a tumbling sensation and impairs orientation (ScubaBoard user, 2015). Inner ear damage from pressure, especially when diving with a partially blocked Eustachian tube (e.g., due to a cold), can also result in disorientation (as well as hearing loss) (U.S. Navy, 2018). Sudden temperature changes between the ears – such as from thermoclines (layers of water where the temperature changes rapidly) – can induce vertigo (Chang et al., 2023). In dark or low-visibility conditions, these effects may be intensified, further compromising a diver's ability to navigate safely. While there is minimal direct evidence of the impact visibility and associated disorientation play in diver mortality (Buzzacott and Denoble, 2018), ∼ 58% of dive fatalities occur in depths below 60 ft (Buzzacott and Denoble, 2018). Furthermore, visibility has been reported as an issue in ∼ 82% of reported unexpected incidents in the US and Canada (Buzzacott and Denoble, 2018). Clearly, effective navigation technology is essential for divers operating in low-visibility and demanding environments.

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Currently, a wrist-worn compass is the primary tool for diving navigation. The newest assisted orientation device is the Heads-Up Display (HUD; developed by Scubapro). The HUD positions a computer display in front of one eye of a specialized diving mask. This uses emissive electroluminescence circuitry to block a portion of the field of view in one eye while in use, and it can be manually moved out of the way. The navigation features of this mask display a compass, but this requires that grid coordinates be established prior to water entry. Typical diver activities can throw off the calibration of the compass. Both the compass and the HUD exclusively rely on vision and do not provide continuous information. Direction information must be found by navigating through the HUD's menu (via a trackball on the masking) or with the wrist-worn compass. This requires additional cognitive effort from divers and can distract them from the environment. Finally, the HUD is expensive, which limits its availability to many divers.

To mitigate these concerns, this work (which significantly extends preliminary findings from Camacho et al., 2025a) developed and evaluated a low-cost, vibro-tactile wearable device that provides continuous geomagnetic directions as needed. In what follows, we provide background on tactile displays, as well as situational awareness (SA) concepts that are critical to understanding our approach. This includes a description of our previous work on the vibrotactile display that we used in this study. We then describe the methods we used to evaluate the use of our system for accurate underwater navigation. We ultimately present our results, discuss their implications, and enumerate directions for future research.

2. Background

The following provides background on topics relevant to the research documented in this paper. This includes previous research focused on conveying navigation information via tactile displays, situational awareness concepts that are important to navigation, and our previous research integrating these concepts into navigation assistance for the blind.

2.1. Tactile communication for navigation

Use of tactile communication dates back to approximately 3200 BCE (Archeological Institute of America, 2016). However, the most topical work for this paper was pioneered by Weber and Fechner in the 19th century. These researchers defined and refined "Weber's law", which established the psychophysical thresholds of touch perception and other human sensory modalities (Fechner, 1948). Tactile displays have been built on this science (Bach-y Rita and Collins, 1973; Gault, 1927; Parisi, 2018; Li et al., 2015).

Examples of modern systems, which tend to use sparse signals to avoid overloading individuals (Chai et al., 2022; Samsel et al., 2025; Biondi et al., 2017), include the Tactile situational awareness System (TSAS) and the Tactile Orientation Garment (TOGA). In particular, six tactors were used in TOGA (Eguchi et al., 2022, 2023) because Van Erp (2005b, 2007, 2005a) identified it as ideal for avoiding overload and facilitating human discrimination between individual tactor signals. Furthermore, TOGA placed the tactors symmetrically around the torso (see Fig. 2) with a spacing of 3–4 cm starting at 1 cm from the sagittal midline and oriented vertically in line with the naval (Eguchi et al., 2022, 2023). This was also based on the empirically-derived recommendations of Van Erp (2005b, 2007, 2005a) and Bach-y Rita and Collins (1973).

The placement of the tactors in TSAS and TOGA was directly influenced by the results of Van Erp (2005b, 2007, 2005a), and Eguchi et al. (2022, 2023), who built on Collins' and Bach-Y-Rita (Bach-y Rita and Collins, 1973) identification that an acuity of 3–4 cm could be achieved when tactors were spaced apart on the torso starting at 1 cm from the sagittal midline.

TSAS specifically explored the use of tactors for navigation. Vibrations around the torso were designed to communicate three-dimensional navigation information to pilots (Raj et al., 1998). In tests with 60 U.S. Army UH-60 helicopter pilots, the pilots performed at a higher accuracy in hovering, takeoff, and landing exercises with visually degraded external views, but with 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. It lowered workload, reduced in-flight error, assisted in long-duration flights, helped sleep-deprived users stay focused, and improved hover target accuracy for helicopter pilots (Lawson et al., 2016a). The technology behind TOGA effectively duplicates the capabilities of TSAS, but in a consumer-friendly design, where tactors are integrated into garments. While the advances offered by TSAS and TOGA are impressive, they were not successfully integrated to assist the visually impaired or divers.

A notable limitation of these existing vibrotactile systems is that they focus on conveying information only pertinent to the current situation (Villalonga et al., 2021). They are thus only conveying a limited amount of information necessary for situational awareness. We cover this topic next.

2.2. Situational awareness and vibrotactile displays

SA is a concept related to what a person understands about their current situation. Its canonical definition was provided by Endsley (1995), who identified SA as having 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 levels of SA are important for navigation: this includes perception of what things are in your environment (level 1), comprehending where they currently are in relation to you (level 2), and projecting how their location will change as you move through the environment (level 3; Bolton et al., 2007; Wickens, 2002; Wei and Bolton, 2017; Bolton and Bass, 2008). However, tactile displays have largely focused on conveying the first two levels. That is, they allow for reactive human behavior, but do not establish temporal contexts to help people strategically navigate complex environments. This observation is reinforced by Villalonga et al. (2021), who stated that "surprisingly little is understood about the potential of the skin, our largest sensory organ, for communicating temporal information". Furthermore, most of these interventions constitute "unnatural codification", generic designs created without consideration of the appropriate use case (Andò et al., 2015; Wang et al., 2021). As a result, the usability and successful adoption of vibrotactile displays for navigation have been limited. The desire to fill this need motivated us to design an SA-compatible tactile system to enable navigation for the visually blind.

2.3. Vibrotactile display design

Wenzel and Godfrey-Cooper (2021) identified factors that must be considered when designing tactor displays. The duration of tactor vibrations and the 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 (the 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 based on the placement of the tactors and the signals they convey.

The base prototype (Fig. 1) for our system was previously created and tested by Triton Systems to assure safety in end-user experiments (Eguchi et al., 2023). 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

Fig. 1. Triton Systems vibrotactile garment front and back, along with Arduino nano 33 IOT board.

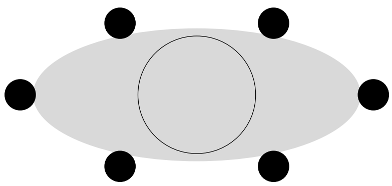


Fig. 2. Overhead silhouette showing the position of the six tactors on a participant's torso.

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. Our team extended this design with new software and hardware that enabled the tactile interface to match the needs of both the divers and the aquatic environment within this experiment.

The programming of the vibrations followed Weber's Law to ensure that end users would feel them (as per Lester and Thronson, 2011). A minimal temporal binding window of 100 ms was also used to ensure a temporal separation between sensory events and avoid shifts in perception thresholds over time and the development of change blindness (Wenzel and Godfrey-Cooper, 2021).

Vibrotactile cues for this experiment were specifically designed to convey Endsley's three levels of SA. All 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 via one tactor signal indicating a target's direction. It also provided some second-level (comprehension) SA by conveying the object's orientation 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 to turn and/or if they had reached the target (they needed to stop moving). The turning signal was designed to mimic a hand that guides the individual in a particular direction across their body. The stop signal (where all the tactors would vibrate) was designed to mimic someone holding an individual in an embrace in their current position. These second-level signals provide 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 they occurred temporally in sequences/pulses to convey the distance of the object. The number of pulses was designed to correspond to the number of fin kicks needed to reach the target or next navigation point. These are conceptually similar to a diving buddy tapping the person to convey spatio-temporal information.

Vibrotactile cues designed in such a manner are intended to be used in a variety of contexts with various end users. For example, we previously tested this design's ability to support navigation of the visually blind (Camacho et al., 2024, 2025b). In this experiment, participants were tested in an open 15 ft × 15 ft space with no objects for reference. Performance with the vibrotactile display was compared against participants' normal methods of navigation. The results showed that the tactile design enhanced navigation accuracy while maintaining comparable mental workload, situational awareness, and usability to participants' standard methods. This experiment indicated that our tactor display design was viable in low/zero visibility conditions and ready to be tested in an aquatic environment.

3. Objectives and hypotheses

This research sought to address the limitations of pre-existing vibrotactile navigation displays in two important ways. First, the design sought to convey all three levels of SA. Second, the design sought to find a natural codification: one that intuitively conveys navigation information. For the design, we took inspiration from tactile feedback of a person receiving navigation guidance from a human assistant guiding/navigating them by touching and moving their hand across their torso. This concept was used as the basis for constructing the prototype and evaluating its effectiveness in an experiment with visually disabled human subjects previously. The same codification was used with divers because they have a "battle buddy" that they communicate with while diving, with visual signaling and touch being the primary means of guidance communication.

In this experiment, participants were asked to perform a navigation task with their standard mode of rescue navigation of rope pulls, the HUD, and the TOGA tactile display. The success of the three navigation approaches was compared based on performance and subjective measures. We hypothesized that the use of our vibrotactile system would achieve all the following:

1. Enable a majority of participants to identify the meanings of tactors, categorize tactile sensations appropriately, and enhance usability, due to our intuitive design;
2. Reduce perceived workload by utilizing the underused tactile modality;
3. Enhance SA by providing information at all three levels;
4. Allow fully blind divers to navigate faster and more accurately compared to standard navigation methods, with these advantages.

The next section describes the experiment used to test these hypotheses.

4. Methods

This vibrotactile design was evaluated under the Institutional Review Board for Health Sciences Research (Protocol Number 230263) through the University of Virginia. Participants were asked to dive in a dry suit, with a blacked-out (zero-visibility) mask, while navigating a 15 × 15 sq. ft. area and moving 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 and subjective measures. To facilitate comparison, the design of this study was specifically designed to replicate our previous experiment that explored how our tactile design influenced blind navigation (Camacho et al., 2024).

4.1. Participants

Twelve participants were recruited to participate in the experiment. This allowed us to achieve greater than 80% statistical power for a repeated-measures ANOVA with the planned experimental design (see Section 4.7). Specifically, we computed our sample size with a power analysis in G*Power (Faul et al., 2009) for a repeated-measures design with 3 within-subject levels and a moderate effect size of $\eta_p^2 = 0.08$. The number of participants was then adjusted downwards (while retaining the same level of power) by using 9 replications per participant per level in accordance with the method described by Goulet and Cousineau (2019). This calculation assumed a correlation of $r = 0.14$ between replicated observations (a parameter used in the adjustment calculation). This particular value of r was adopted because it was recommended by Goulet and Cousineau (2019) as a conservative estimate for most human-subject studies, based on a meta-analysis of the psychological literature.

All the participants were recruited through the Monticello Dive Rescue Team, and one participant was a University of Virginia experienced recreational diver. Participants were selected based on their age (18 or older), willingness to volunteer (to include 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 (enables divers to not have buoyancy issues underwater and swim in a straight efficient manner), dive experience (for or more open-water dives with at least one in the past year), no illness, no sinus congestion, and no pregnancy. Their diving experience was defined by the highest level of scuba education they 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. All the participants had experience with rope pulls commensurate with their dive experience. None of them had experience with the HUD or the tactor display.

4.2. 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 inches. The shallower part of the pool allowed for experimental setup and participant acclimation before the experiment began.

4.3. Apparatus

The tactile display used was the prototype described in the second paragraph of Section 2.3 (and shown in Fig. 1), which used the TOGA system described in Fig. 1 and Section 2.1. This was fitted to participants by the experimenters so that the tactors were aligned with their naval and distributed around their torso consistently with the requirements discussed in Section 2.1 (see Fig. 3(a)). A fabric belt was placed around the tactors on participants' torsos to keep them in place. The TOGA system was connected to a 9-pin wire that exited the diver's dry suit. This wire was exposed to the water until it exited the pool and connected to the circuit board (Fig. 1). This circuit board had an additional wire that was hard wired directly to the lap-top controls where the experimenter sent commands to the diver acting a tender. An additional diver in the water shadowed participant movements to prevent injuries underwater, reset the participants during each trial, and help ensure there were no entanglement issues with any of the communication and tactor wires utilized. Radio communications were utilized with the participant divers during the entire course of an experimental run, allowing ongoing communication with the tender for safety.[1]

Participants navigated underwater within a 15 × 15 sq. ft. area that was flat and without obstacles. The blacked-out mask was warn for all three navigation methods (see Fig. 3(c)), which allowed participants zero visibility.

4.4. Independent variables

There was one independent, within-subject variable with three levels that represented the navigation methods used: Tactors, Pulls, and HUD, where participants only ever experienced one navigation method at any given time. A description of the signals used for communication with the tactors is shown in Table 1. The pulls methodology was consistent with the Monticello dive rescue team from the tender on the rope on the surface above the water translated to the diver holding the rope in the water where: four pulls indicates "proceed left", three pulls "proceed right", and one pull meant "stop". The HUD displayed a compass screen which directed individuals by the cardinal and number direction they needed to proceed (see Fig. 4).

4.5. Dependent measures

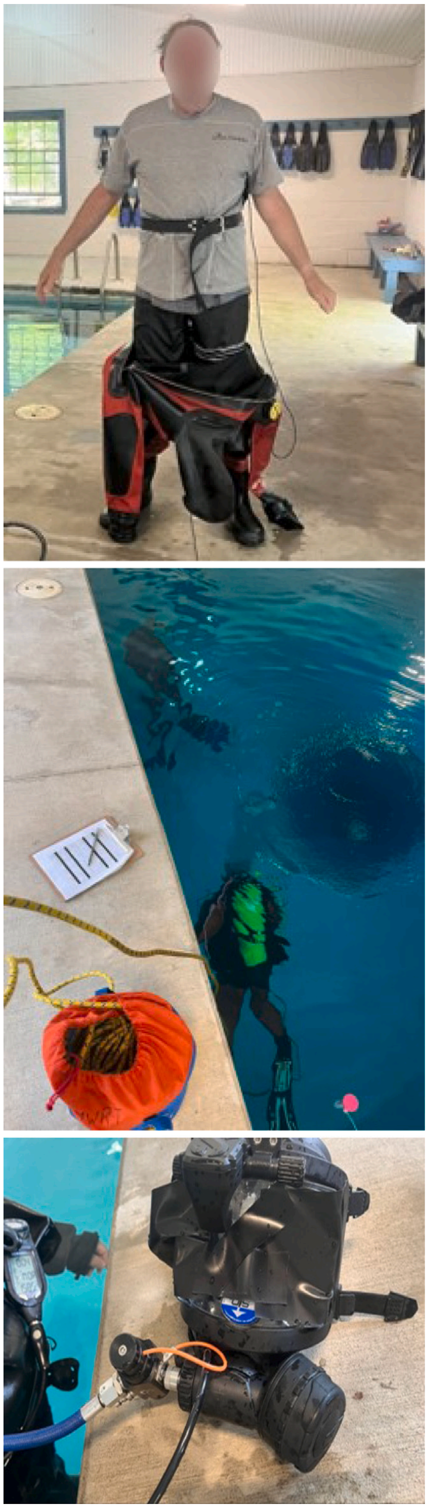
A survey designed to understand how participants thought about SA constructs was collected before any experimental trials were conducted. Within this, the participants described how they analyzed SA personally, described what they thought the tactors meant at first stimulation, and categorized the tactors according to Endsley's SA levels.[2] The experimenters manually processed these results and to determine whether participants understood the designed meaning or put the signal in the correct category. In each trial, two objective performance measures were used. Navigation time (in seconds) was measured with a stopwatch operated by an experimenter observing trials from out of the water. Timing began with the commencement of the trial and ended when the participant dropped the sandbag. Accuracy (inches) was measured as the distance of the final position of the placed sandbag from the target position using a tape measure. The test diver was instructed to start the participants' knees on an origin sandbag to enable a consistent start point.

Subjective measures collected after each trial evaluated the perceived workload, SA, and usability of each navigation method from the independent variable levels using verbal response protocols. That is, questions were read to participants by the experimenter, and participants verbally provided ratings within the standard ranges of the utilized scales.

Workload was measured using the NASA-TLX (Hart and Staveland, 1988), which has people rate dimensions of workload along six dimensions (all rated from 0 to 100): Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. From these dimensions, we used the "raw" method to calculate the overall workload (what we call the TLX Score) by averaging the six dimensions together (Byers et al., 1989). Note, there are contemporary criticisms surrounding the computation of this score due to multicollinearity and incompatible scales between dimensions (Bolton et al., 2023; Galy et al., 2018). Thus, we also collected an overall subjective workload score (which we call the Subjective Score) to both consider it in our analysis and facilitate comparison with the TLX score in the broader

[1] Participant 7 agreed to complete the experiment without a radio system when the center's system was not available.

[2] All the questionnaires used in this experiment can be found at https://drbolton.org/G/ExperimentalProceduresForDiveExperiment.pdf. This specific survey is available at https://drbolton.org/G/ExperimentalProceduresForDiveExperiment.pdf#page=12.



(a) (b) (c)

Fig. 3. a. Shows a participant demonstrating how tactors were worn underneath the dry suit. b. Shows how pulls were administered from the tender's perspective. c. Illustrates how the HUD was attached to a small corner of the blacked-out mask.

scientific literature. An additional open-ended question followed the administration of the NASA-TLX. This asked participants to explain why they gave the overall score that they did.

SA was assessed using the Situation Awareness Rating Technique (SART, Selcon and Taylor 1989). SART is a ten-factor index, where each

Fig. 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.

factor is rated from 1 (low) to 7 (high). These factors are categorized to allow participants to score the way a test condition placed Demand on attentional resources (based on the factors Instability of Situation, Complexity of Situation, and Variability of Situation), the Supply of attentional resources (based on Arousal, Concentration of Attention, Division of Attention, and Spare Mental Capacity) and Understanding of the situation (based on Information Quantity and Familiarity with Situation). These ratings are then combined into an overall score (the SART Score) as:

$$\begin{aligned}\text{SART Score} = &\sum(\text{Understanding Ratings}) \\ &- \left(\sum(\text{Demand Ratings}) - \sum(\text{Supply Ratings})\right)\end{aligned} \tag{1}$$

Similar to the methods for computing workload over the NASA-TLX dimensions, contemporary criticism suggests that this formula is incompatible with the dimensions of the scales that compose it (Bolton et al., 2021). Thus, we also collected an overall subjective SA score. As with the workload, participants were asked to explain the overall score they provided.

Usability was assessed using the System Usability Scale (SUS, Brooke, 1995). SUS is measured using a 10-item questionnaire, where participants rate each item on a 5-point scale. The items are arranged so that they alternate between having negative and positive connotations towards usability. When synthesizing the participants' ratings, odd-numbered items with positive usability statements are scored by subtracting 1 from the participant's rating (allowing a range of 1 to 5), and even-numbered items, which are negative usability statements, are scored by subtracting the participant's response from five (allowing a range between 0 and 4). The final SUS score is calculated by summing the scores for each rating and multiplying the total by 2.5. This produces a final score between 0 and 100 that is not an absolute percentage. Scores above 68 are considered above average with good usability, while scores below 68 suggest usability problems (Flowmapp, 2024). A subjective overall usability score of 0 to 100 was also collected as part of this experiment. The participants were once again asked to explain why they gave this overall score.

At the end of the experiment, participants completed a general survey regarding equipment and abilities. This allowed participants to give subjective ratings (from 0 to 100) on their overall experience with the tactors and their regular navigation method (e.g., a dive partner guiding them, compass, terrain association, following a dive master, counting fin kicks, using HUD, etc.) along 6 dimensions. This was followed by four open-ended questions that requested participants to share additional thoughts they had about the Tactor, Pull, and HUD navigation methods, and explain their regular navigation method.[3]

[3] See https://drbolton.org/G/ExperimentalProceduresForDiveExperiment.pdf#page=25.

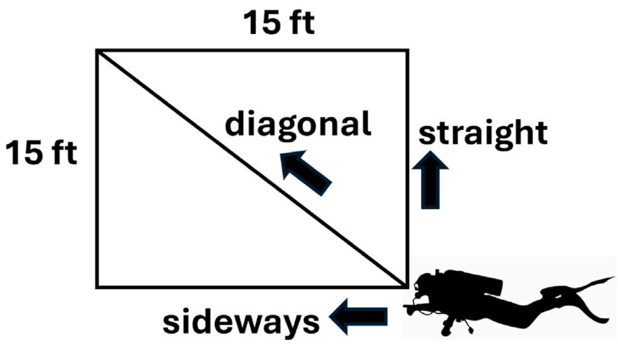


Fig. 5. Variations of diving directions for participants within 15 × 15 ft. square.

4.6. Procedure

Each experimental session lasted approximately 2 h. Participants were read 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.

Participants were next told what each signal meant and were physically placed at each start point underwater within the 15 × 15 ft. square in different directions (depending on the trial): sideways, diagonally, and straight (Fig. 5).

Before participants began trials with any given navigation system, they were trained in how to use it. For the tactors and pulls, participants ran through each sensation/pull and verified they understood the signal they received by stating the meaning out loud. For the HUD, the participant donned the mask prior to entering the water to confirm they had a visual. During this training, participants were connected to the experimenters via radio so they could receive answers to any questions they had throughout the experiment. This training established a baseline understanding of all navigation methods, especially the tactors and HUD, which were novel to all participants.

During the diving portion of the experiment, participants were told the specific distances they needed to dive over the radio, and they were oriented underwater by their dive guide to begin their dive: the start position of each trial, with an orientation such that the diver was flat against the ground so that they would crawl across it during the trials. Participants completed each trial dive three times for each direction: three times each for sideways (the horizontal side of the 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 a total of nine trial dives for each of the independent variable levels (tactors, pulls, and HUD navigation). During the tactor and pulls trials, the diver was monitored by an above-water tender who would manually communicate signals to the diver (see Fig. 3(b)). For tactor signals, this was accomplished through a computer interface that would send predefined tactile signals (Table 1) to the tactor display through the connected 9-pin cable. The pulls were relayed via the rope pulls defined in Section 4.4. Both of these activities were dictated by a strict experimental protocol.[4] The HUD provided continuous navigational guidance via a compass display (Fig. 4) that operated independently of the above-water tender. Open radio communication was maintained during all diving sections of the trials for safety purposes. After each nine-trial block for the three independent variable levels, the NASA-TLX, SART, and SUS measures were collected. At the end of the experiment, the questions regarding equipment and the abilities survey was conducted. This was followed by a debrief.

4.7. Experiment design and data analysis

This experiment used a within-subjects design. Trials for each independent variable level (that is, each navigation method) were grouped together in blocks. The order of block presentation was counterbalanced between participants. The block design allowed for 9 total replications for each diving navigation method (three for each of the three diving directions, the orders of which were also counterbalanced between participants; Fig. 5), in which each participant was given performance navigation tasks where they swam towards the target from their starting position. The counterbalancing of replications and navigation method blocks was used to counteract practice, fatigue, and other order effects.

Survey results from the experiment were processed using qualitative content analysis. Information received from participants was organized into summative themes of information to support or refute hypotheses, utilizing Braun and Clarke's reflexive thematic analysis described in Byrne (2021) and Maguire and Delahunt (2017). Conventional content analysis was observed through open-ended questions so that common keywords and content that were stated could be explored. The content was coded into initial themes derived from targeted questions in the data sets. These were analyzed at separate instances to ensure all content was appropriately summarized into this report.

Contingent on normality assumptions (evaluated using Bonferroni correction), the significance of the difference between the independent variable's levels for the performance measures and the subjective workload, SA, and usability measures were evaluated using repeated-measures ANOVAs. In the event that normality was violated, we used Bonferroni confidence interval adjustments for this purpose. Consistent with the recommendations from the literature (Bolton et al., 2021, 2023; Galy et al., 2018), NASA-TLX and SART dimensions were analyzed separately in addition to their respective overall measures.

5. Results

5.1. Situational awareness tactile survey data

The prototype tactors' vibration patterns conveyed distinct meanings. As shown in Table 1, between 3 (25%) and 12 (100%) of the participants were able to understand the designed meaning of each tactile signal. Eighteen of the nineteen signals had at least one participant correctly categorize them into their intended SA categories. Three participants categorized 100% of the signals.

5.2. Situational awareness construct survey

In the SA Construct Survey results, participants said they consider the following when thinking about SA: surroundings; familiarity with other people; hearing the environment; being aware of what is going on around them; experience; instructions; paying attention to the environment; knowing how surroundings impact you; no tunnel vision; using all senses to pay attention (which is easier said than done); and what you can see, hear, smell, and feel on your immediate person or within 30 ft around you.

Cues that participants identified as being useful to navigate in the water were "a husband" (meaning a dive partner), line of sight, sunlight, bottom topology, landmarks, verbal cues from the dive tender

[4] See https://drbolton.org/G/ExperimentalProceduresForDiveExperiment.pdf#page=14.

Table 1
List of the tactile sensations, their designed meaning and SA Level, and the number of participants that understood each signal and their designed levels.

Order	Tactile signal	Designed meaning	Number that understood	Designed level	Number that categorized to each level			
					None	Perceive	Comprehend	Project
1	Single	Turn right	12	Perceive	9	2	1	
2	Single	Front right	12	Perceive	9	2	1	
3	Single	Back right	12	Perceive	8	1	2[j]	
4	Single	Left	12	Perceive	7	2	3[k]	
5	Single	Front left	12	Perceive	7	3	2	
6	Single	Back left	10[a]	Perceive	8	2	2[l]	
7	Multiple	Full turn left	12	Comprehend	2	5	5	
8	Multiple	Half turn left	12	Comprehend	2	8	2	
9	Multiple	Full turn right	11[b]	Comprehend	4	4	4[m]	
10	Multiple	Half turn right	12	Comprehend	2	7	3	
11	Double	Move forward	7[c]	Perceive	3	4	5[n]	
12	Double	Move backward	7[d]	Perceive	3	3	6[o]	
13	Double	Move left	12	Perceive	6	3	3[p]	
14	Double	Move right	12	Perceive	6	3	3[p]	
15	All	Stop	5[e]	Comprehend	2	5	5	
16	Combination (two front, then all vibrate)	Go forward three times, then stop	3[f]	Project	2	2	8	
17	Combination (two back, then all vibrate)	Go back three times, then stop	7[g]	Project	1	1	10	
18	One, then all vibrate	Go left three times, then stop	8[h]	Project	0	2	10	
19	One, then all vibrate	Go right three times, then stop	7[i]	Project	1	1	10[q]	

Explanation of designed meaning misunderstandings:
[a] 2 people thought more shallow or stop.
[b] 1 person said tiny turn right.
[c] 5 people thought: same, confused, go down, stop, forward left.
[d] 5 people thought: stop, left back come up go to left, up and left, surface, or stop.
[e] 7 people thought: come up, danger, come on up, come up surface, or stop, watch out caution you are going to die, surface there is a problem, come up, shark and get out of water a danger emergency signal of some kind, everyone laughed at this particular vibration.
[f] 9 people thought: turn 45 degrees then stop, got trouble come on up, search area, go forward and surface, surface there is a problem, stay still, turn left stop face me, come up.
[g] 5 people thought: back up quickly and come up, search area to left, stop and surface, surface problem, go, twirl around.
[h] 4 people thought: move then come up, search area left hard side, surface to the left, something there in area.
[i] 5 people thought: sharp turn and come up, search on right side, stop, surface to the right, surface problem, come up to surface.
Explanation of designed level miscategorization:
[j] Very light.
[k] Loud and longer more intense.
[l] Long buzz, seems more powerful.
[m] Felt short bursts.
[n] Longer duration.
[o] Long duration; intensity greater.
[p] Felt longer.
[q] Overall felt like a lot of something, likely indicating a serious situation.

(assistants to divers that are above the water), compass, ropes, sight, feeling, touch, pressure, objects, communication devices such as radios, landmarks, rope pull line when blinded, and hand cues.

Changes in the water that participants said generally caused them to navigate differently were blackout, lack of visibility, point of reference, particulates in the water, current, depth, structure of the river bed lake bed, usability of setup of communication devices (Bluetooth without wire or by hard line), rope and search patterns, arch searches, debris and foreign objects to navigate around, other moving objects, and communication from others.

Divers specified that to plan the route they needed to know visual cues, depth changes when closer to shore, bottom structures, entanglement hazards, visibility, which way is current going, obstacles, obstructions overhead or a tree stump, expected conditions of current rate and clarity, lay of the land before starting, weather, inherent dangers, what to wear to accommodate to the environment, other moving objects, and communication from others with further information about the route.

Regular methods of navigation divers identified included a diving partner to help them, pulls method, hardwired/Bluetooth radio communications, compass, watch, hand signals, and underwater landmarks.

When asked about their overall thoughts on SA, the participants said that knowing the hazards, knowing your limits, and diving within your experience level can help keep them safe.

5.3. Performance measures

A repeated measures ANOVA utilizing a Bonferroni correction determined that mean navigation times did significantly differ across the three methods of navigation ($F(2,34) = 3.75, p = .034, \eta_p^2 = 0.18$). Pairwise comparisons showed that participants navigated significantly faster with Pulls than with the Tactors. No significant differences between the HUD and the other two methods were observed; see Fig. 6(a).

A repeated-measures ANOVA utilizing a Bonferroni correction determined that mean Accuracy scores differed significantly among the 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).

5.4. Workload

An examination of the workload results showed that participants tended to rate the HUD higher (indicating more workload) across all of the subjective workload results except Physical Demand (see Fig. 7). The rope pulls generally received higher workload ratings than the tactor display except for Frustration. This results in a computed TLX rating with tactors as producing the least workload, followed by pulls,

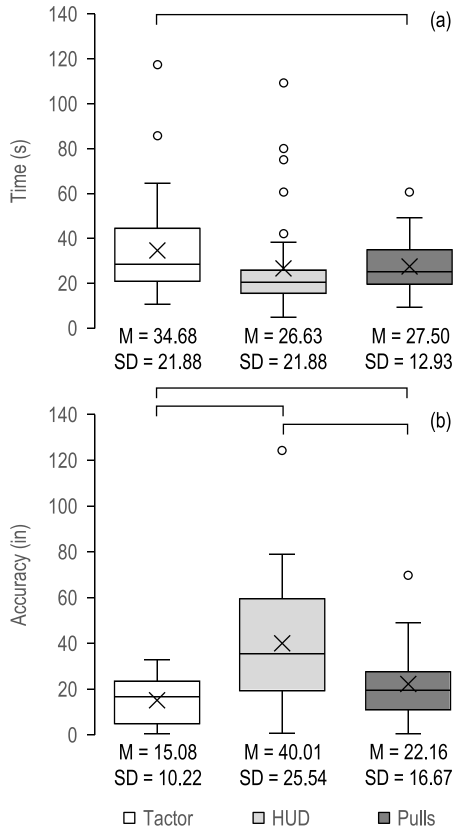


Fig. 6. Box plots (with descriptive statistics) showing significant difference observed between (a) navigation times and (b) accuracy when participants used tactor, HUD, and pull navigation methods. In (b), the closer to 0, the higher the accuracy. In both plots, the horizontal line indicates the median. A × shows the mean. The box shows the interquartile range (IQR), with the lower and upper edges representing the first (Q1) and third quartiles (Q3). Whiskers extend to the smallest and largest data points within 1.5 times the IQR from both Q1 and Q3. Points beyond these are outliers. Brackets above plots indicate significant differences between pairs.

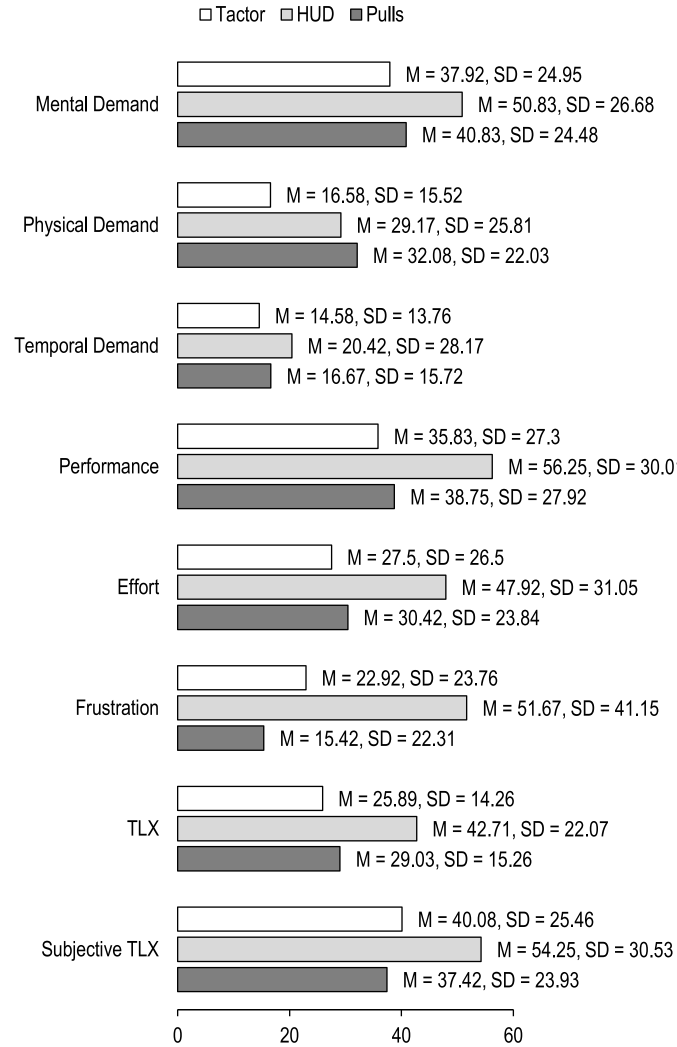


Fig. 7. Average workload measures from participants measured when using the tactors, HUD, and pull navigation methods. Note that TLX is the computed workload score created by averaging each participant's ratings on the preceding NASA-TLX dimensions. Subjective TLX is the subjective overall workload rating collected from participants.

followed by the HUD. However, for the subjective TLX rating (where participants directly rated their overall workload), the pulls were rated as producing the lowest workload, followed by the tactor display, and then the HUD. Despite these results, the repeated measures ANOVAs showed no significant differences between the navigation types, except for the Physical Demand sub-scale ($F(2,10) = 6.13, p = .018, \eta_p^2 = 0.55$). Pairwise comparisons showed significant differences between the Pulls and Tactor Navigation methods.

The explanations participants gave for providing their overall workload ratings described the pull task as being "straight forward", requiring less responsibility for the diver (since they followed instructions given by the tender), being more familiar and comfortable, not physically demanding, easier to "just follow training", and affording them the ability to just sit and wait for one clear signal. One participant stated that they could not focus due to suit discomfort. Two other participants described the experience of pulls involving task saturation. This is because they had to concentrate and think about what the tender wanted them to do, and then execute that. They also preferred to work with a select tender. Another participant said they paid attention to their breathing and concentrated so hard that they accidentally navigated directly into a wall, even with the tender above directing them.

The participants described their overall workload rating for the HUD as resulting from it being frustrating or hard to get it to work correctly, hard to concentrate on (especially the compass readings), or hard to see. They also said that it displayed too much information, depicted information that was irrelevant to the current task, and that the compass was poorly calibrated, which made it hard to keep track of fin kicks. One participant said that they found the HUD easy and straightforward when just looking at the compass.

The explanations for the overall workload ratings for the Tactor task included descriptors such as "more straightforward", "easy", and "fun" compared to normal rope pulls. The tactors were also described as being the least stressful in sorting where to go, not physically demanding, easy to feel, and very similar to rope pulls (thus participants knew what to do). Participants also positively noted that no extra equipment or memorization was required with the tactor display. The participants did describe difficulty in trying to understand the signals due to the low vibrations of one of the tactors (the one placed on the right-hand side of the torso). They said they had to concentrate to make sure the vibrations were felt and stated it was hard to always make sure they were doing the right thing due to small amounts of latency. Participants also said that using a different sense (touch) added another level of concentration to the task.

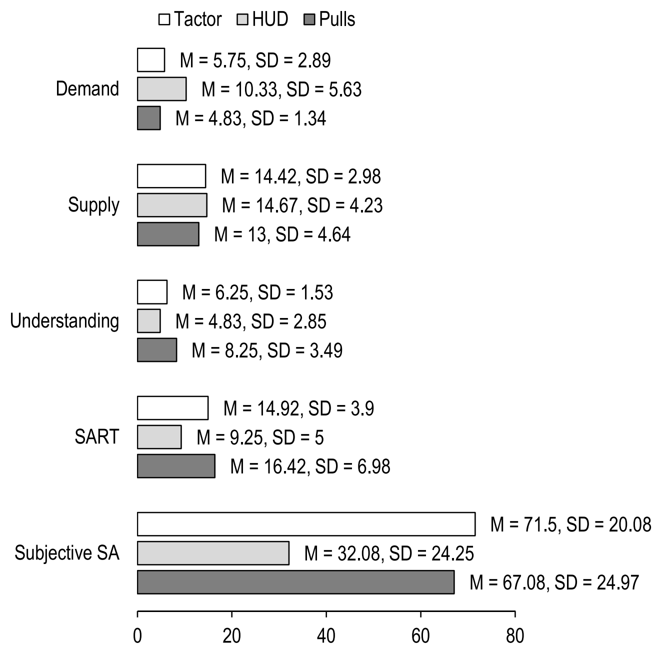


Fig. 8. Average SART-based SA measures. SART for each participant was computed using the Demand, Supply, and Understanding scores (Taylor, 1990). Subjective SA asked participants to rate their overall SA subjectively from 0 to 100.

Overall, the explanations participants provided for their workload ratings suggest that they felt that they experienced comparable workload for the Pull and Tactor navigation methods, and higher workload with the HUD.

5.5. Situational awareness

The SART's dimensions showed Pulls rated with a higher Understanding rating, with the Tactors not far behind. The HUD and Tactors ratings were higher than the Pulls for Demand and Supply. The repeated-measures ANOVA determined that mean SART Demand scores did significantly differ between the navigation methods ($F(2, 10)$ = 4.507, p = .040, η_p^2 = .474). Pairwise comparisons showed significant differences between HUD and Pulls.

Participants generally rated pulls displays as providing better SA than the other navigation methods via Subjective SA. However, tactors were rated as providing better SA in their Subjective Scores (see Fig. 8). A repeated-measures ANOVA determined that mean SART scores differed significantly among the navigation methods used, ($F(2, 10)$ = 7.921, p = .009, η_p^2 = .613). Pairwise comparisons showed significant differences between Tactors and HUD and between HUD and Pulls.

When explaining their overall SA ratings, participants said that they had extensive practice and familiarity with Pulls. They felt like they did not navigate towards walls as often, knew what they were trying to find, and trusted the person at the surface. However, they also described having guidance but not knowing where other things were. Beginner dive rescue team divers stated that they had not practiced enough to remember all the rope pull commands naturally. One participant stated that you could “crawl into a whale’s mouth or be chased by a boat and not know, since you are just crawling along”.

Participants described their SA ratings for the HUD as stemming from unfamiliarity working with a device that required streamlined buoyancy, the instability of the compass isthmus, and difficulty in reading the numbers. They also said that they felt like they could not get the information they needed, and that what was there was too specific for underwater divers. The same participant from above also

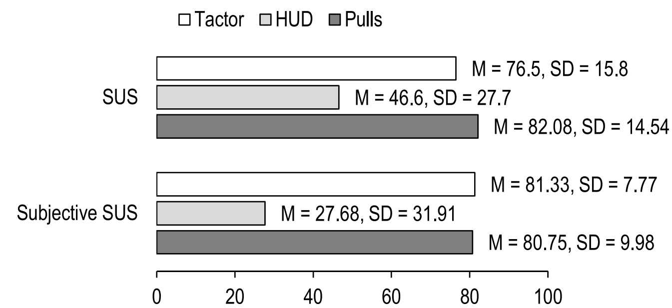


Fig. 9. The system usability survey and corresponding average subjective scores of participants when utilizing Tactors, HUD and Pulls (SUS, Brooke 1995).

claimed that this display would also allow them to “crawl into the mouth of a whale and not know”. One participant said that the compass heading made it easier to have a sense of where they were in the pool.

The participants described their SA ratings of the tactors as being more straightforward, relaxed, and less stressful. They also claimed that they felt more aware of where they were and that they were able to anticipate their surroundings. Some also described the Tactors as the easiest navigation method, providing good direction, giving them confidence about their location in the pool. One participant stated that they put too much focus on the tactors, which distracted them from monitoring their fin kicks for distance. Two participants did not know exactly where they were. Scarring on the abdomen of a participant prevented that individual from feeling the two tactors on the front of their abdomen. Additionally, another participant reported not feeling feedback from any of the tactors very well.

Overall, participants’ explanations of their SA ratings suggest that they felt that SA was lowest with the HUD and similar for the Pulls and Tactor navigation methods.

5.6. Usability

The System Usability Survey scores were 82.08% with the Pulls, 76.45% with the tactors, and 45.21% with the HUD. Subjectively asking participants for usability scores without taking the survey, the participants rated the Pulls 80.75%, Tactors 81.33%, and the HUD 27.68% (see Fig. 9).

The repeated-measures ANOVA of SUS scores showed a significant difference between the navigation methods ($F(2, 10)$ = 7.799, p = .009, η_p^2 = .609). Pairwise comparisons showed significant differences between the Tactors and HUD and between the HUD and Pulls.

When explaining their overall usability ratings, participants stated that they found the pulls to be easy to learn, straightforward, easy, and direct. They also claimed that pulls required “a lot to think about”, but were easy when they were using them to map out a large surface area. However, participants did say that it was “cumbersome to hold a rope the entire time while focusing to find something”. They also claimed that it could be, “confusing to comprehend the large number of tugs”, and that it was a “limiting system because there was one less limb available for underwater tasks”.

Only one participant considered the HUD to be straightforward. The rest considered the compass hard to understand and thought the information given in the HUD was unstable, inconsistent, irrelevant, and difficult to see. They also described difficulties operating the HUD, particularly for locating smaller objects, and mentioned potentially needing more practical experience with it before it could be useful.

The participants described the Tactors as being straightforward and simple, making it easy to understand where they were supposed to go. They were described as being similar to rope pulls, but easier because they knew for certain it was a buzz instead of an accidental pull. The

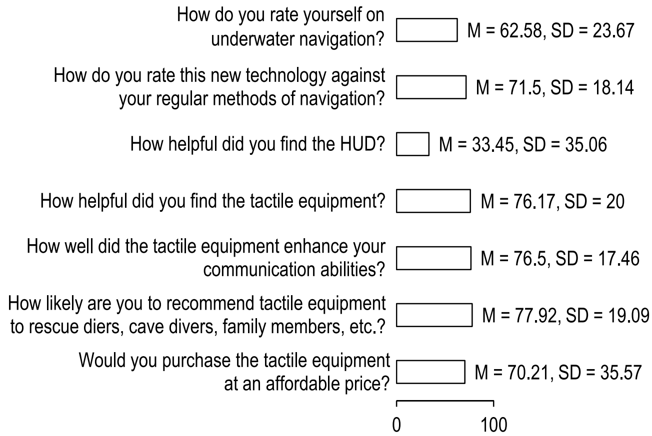


Fig. 10. The average participant ratings on their abilities and usability of the tactors.

tactors were also described as being well integrated, having lots of applications, and that they would be great for situations where you cannot use the rope (like when searching far away from a tender). However, participants expressed concerns about the dry suit interfering with tactor connectivity, as well as the need to recognize a few commands that they were not accustomed to receiving through pulls.

Overall, participants' explanations of their usability ratings were consistent with them feeling like the tactors were comparable to the pulls, with the HUD being less usable.

5.7. Equipment and abilities survey and general comments

The results of the overall equipment and ability subjective ratings are shown in Fig. 10. Participants, on average, rated the tactile display to be helpful at 76.16 on a scale of 1 to 100.

Comments collected during the survey echoed themes found in the workload, situational awareness, and usability results, but also highlighted additional considerations. The following summarizes the feedback we received from each participant for each navigation method. This includes what they liked, what they disliked, and recommendations they made for improvement.

5.7.1. Pulls

General commentary on pulls emphasized their simplicity and reliability. Participants noted that the system required no electronics and was easy to use. Pulls were seen as straightforward, clear, direct, intuitive, and consistent once a system was established. Many described it as fail-proof and so familiar that using it became muscle memory. Some remarked that they grew up with the system and could build a rapport with the tender, even inventing a shared language. Overall, the method required little conscious thought. However, some concerns were raised about occasional ambiguity on the tender's side.

For improvements on pulls, participants stated they would prefer no cable to avoid any potential of getting held up. Alternatively, some said that a more taught cord and/or a more refined set of commands could facilitate clearer communication. Five participants stated there is no way to make it better, and that it is imperative to work with the tender and know their pull styles.

5.7.2. HUD

Overall, most participants described the HUD navigation method as straightforward and "dummy-proof", with high potential if technical issues could be resolved. The HUD was largely seen as being extremely intuitive. No participants reported physical discomfort from wearing it. Some openly expressed appreciation for its compact design, which was tucked away on the mask, and its bright, easy-to-read display. Some noted that it was convenient to have the information directly in their line of sight, allowing them to access it when needed. However, three participants stated that they found nothing to like about the HUD.

Dislikes for the HUD centered on the instability of the compass and the complexity and confusion caused by the displayed information. Some found the screen difficult to read due to its small size and noted that the HUD had to be positioned at a very specific angle on the mask to avoid blurriness. Some participants felt the system was unintuitive and, in some cases, made navigation more difficult by interfering with their own navigation process.

To improve the HUD, participants recommended simplifying the display by removing degree-based indicators and, generally, reducing the complexity of the information display. They also called for a larger, more legible screen, improved consistency in system calibration and loading, and a universal mounting system to fit different mask types. One participant equated this to creating an "Iron Man"-like mask to enhance readability. Additionally, participants suggested that the HUD should better account for the diver's body position to avoid divers making overly dramatic or misleading adjustments.

5.7.3. Tactor

Participants described the tactors as being easy to feel, clear, and intuitive to understand and use for navigation (even with only a short training period). They also appreciated that they did not need a hand on the line (as was required by pulls), thereby making navigation more straightforward and hands-free. Many appreciated the tactile sensation more than getting pulled around. They also thought that it was "pretty cool" to have different sensory input, because people learn differently, and any additional input is good underwater.

A common concern with the tactor display was the need to be trained in and remember specific signal codes. There was particular concern for this if additional signals were added because they may not be as intuitive as the signals currently used. Some felt that the vibration signal was too light, especially on the right-hand side or when tactors got wet, which reportedly reduced their sensitivity. Some participants also desired patterns that more closely aligned with standard rope pull commands. Some felt the signals were delayed and suggested a consistent initial buzz that would intensify as the diver approached the target. There were also concerns about communication if the tender was unable to track the diver in black water (an issue that also occurs with pulls). One participant noted that due to scarring on their abdomen, they could not feel all the individual tactors. They suggested customization in tactor placement. Finally, it was recommended that a built-in delay could help ensure signals are received and acknowledged.

Suggestions for improving the tactors included placing them higher on the chest for better sensation. Some participants also suggested considering alternative stimulation points such as the sternum, limbs, legs, or hands. Some participants recommended that a reference card could help divers remember signal meanings when underwater. Other suggestions expressed the need for stronger, more consistent vibration patterns, the ability to secure the tactors more tightly, and increasing the number of tactors. Additional feedback included reducing cable entrapment hazards (from the cable relaying signals from the surface) and improving the durability and fit of the system.

6. Discussion

In this work, we designed a tactor display to convey spatial navigation information in situations where underwater visibility is difficult. We then evaluated this design with Monticello's dive rescue team.

Below, we consider each of our hypotheses and discuss whether and how they were supported by our results. We then discuss the broader implications of our findings and explore future research directions.

6.1. Hypothesis 1: The tactile display will be the most intuitive and usable method of navigation

Overall, the results showed that the tactor navigation option was more intuitive than the HUD and comparable to the rope pulls.

The SUS score results indicated that the HUD was not user-friendly compared to the other options. There was no statistical difference between pulls and the tactor display for any of the usability measures. The commentary of participants had many statements reinforcing the idea that rope pulls were the, "bread and butter" of their experiences with dive navigation. Given that the tactors were viewed as comparably useful to such a long-established and practiced approach speaks to their potential. Indeed, many participants indicated that, with more training, they saw a lot of application for the use of the tactors.

Furthermore, many participants were able to intuitively understand what the tactors were communicating. The results of the SA Tactile Survey (reported in Table 1 and Section 5.1) supported the hypothesis that individuals would have an innate understanding of touch cues. This survey also supported our hypothesis that vibrations could be categorized in accordance with Endsley's SA model. These results correspond with our findings obtained when the tactile design was evaluated with blind participants (Camacho et al., 2025b). However, there was confusion about vibrations that signaled participants to stop. Participants interpreted this signaling as an alert telling them they were in imminent danger and needed to surface. There was also some confusion mapping some pull commands to vibrations. Some participants assumed that directional vibrations were telling them to search an area in the indicated direction, instead of swimming in that direction. The intensity, frequency, and duration of the alerts also led some participants to believe certain alerts were telling them to dive shallower or decrease depth. Participant 6, who did not have dive rescue training, was the only participant who did not confuse the intended meaning of the stop with a trained reaction to swim to the surface.

6.2. Hypothesis 2: The tactile display will reduce workload

The results generally support the conclusion that the tactile display produced low physical demand, and generally supported workload comparably to the other methods.

The computed TLX workload measure had the tactor display perform approximately three points better (lower workload) than the pulls, and more than 16 points better than the HUD. However, the subjectively measured overall TLX workload showed the pulls being slightly better (3 points less workload). In the statistical analyses, the only significant difference was observed between tactors and pulls under the Physical Demand sub-scale: with the tactor display producing the lower average physical demand.

In describing their ratings, participants described how they felt like a "dope on a rope" with pulls as the brain power was left to the tender: they just followed where the tender guided them to go. For the tactor displays, participants also said that they assigned the subjective workload scores they did due to the tactors providing an enjoyable, fun, straightforward (similar to rope pulls), hands-free way to navigate. However, the participants also stated they had difficulty comprehending the tactor signals due to low vibrations felt on their right side. Some said that they had to concentrate to feel the vibrations and were uncertain whether they were headed in the right direction due to small delays. Participants further stated that using a different sense forced them to concentrate more, as they were not as extensively trained in the new navigation technique. Thus, the performance of the tactile display for reducing workload could be further improved if these issues could be overcome.

6.3. Hypothesis 3: The tactile display will enhance SA

The results suggest that the tactor display supports SA better than the HUD and at least as well as rope pulls.

Participants (on average) rated the tactors better by 4 points than Pulls, with the HUD rated lower than both. However, the overall SART score favored Pulls by 2 points. Pulls were statistically significant overall, with the specific factor of Demand 1 point lower than Tactors and 6 points lower than the HUD. The tactor display was close, but was bested by the pull methodology.

The majority of participants' comments supported the idea that the tactor display facilitated SA, since they were able to utilize both hands. However, the tactor signals were not the same as acquiring guidance from a tender that they could rely on. This is because a familiar tender could incorporate special messages into their pulls. Overall, participants stated they had a better sense of what was around them and they were confident about where they were in the pool when using the tactors.

However, increasing the vibration strength and decreasing the delay on the tactor signal would help close the gap between the ratings of the tactors compared to the pulls. Additional training would also help provide divers with familiarity with the tactors. The delays in the tactors hindered the continuous orientation cues meant to be interpreted by the participants (Rupert et al., 1999b). Furthermore, additional training with tactors could help to recalibrate the demands placed on divers' perceptual systems. This would allow them to acclimate to and accommodate the tactor cueing information in their assigned tasks (Gibson, 1966).

6.4. Hypothesis 4: The tactile display will enable faster and more accurate navigation

Our performance metric results were consistent with our hypothesis that participant navigation accuracy would improve with our vibrotactile system, but not faster than the other methods.

Median participants' navigation accuracy increased by an order of magnitude (24.92 inches closer to the target than the HUD, and 7.08 inches closer to the target than the pulls; see Fig. 6(b)). 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 an order of magnitude (an approximate 8.05 s slower than the HUD, although with no significant difference, and an approximate (significant) 7.18 s slower from pulls; see Fig. 6(a)).

The observed increase in navigation time seen for the tactor display was likely caused by the novelty of the stimuli and the few technical issues we experienced during trials: with participants taking more time to concentrate on and think about the coded tactor signals. This observation is consistent with participants' subjective feedback.

Note that we observed a confound in navigation time. Most of the participants explained that they had not previously been exposed to complete darkness underwater and needed time to acclimate. As a result, they expressed that they became more comfortable as the trials progressed and thus felt like they could spend more time thinking about the signals they received. This phenomenon can be seen in Fig. 11(a), (c), and (e), which show how navigation time tended to skew upward in the third trials for each navigation method. Future work may need to conduct a longer-term study to understand how timing is affected without novelty factors influencing the results.

Accuracy was more consistent with the tactors Fig. 11(b) compared to the HUD (d) & Pulls (f). The participants had not used the tactors before, so they also discussed how, with more training, they believed they could learn the signals just as well as pulls. One participant reiterated this sentiment, stating, "With more training, the cumbersome would go away; rope pulls are my bread and butter". All but one participant relayed dissatisfaction with the HUD, even if they received

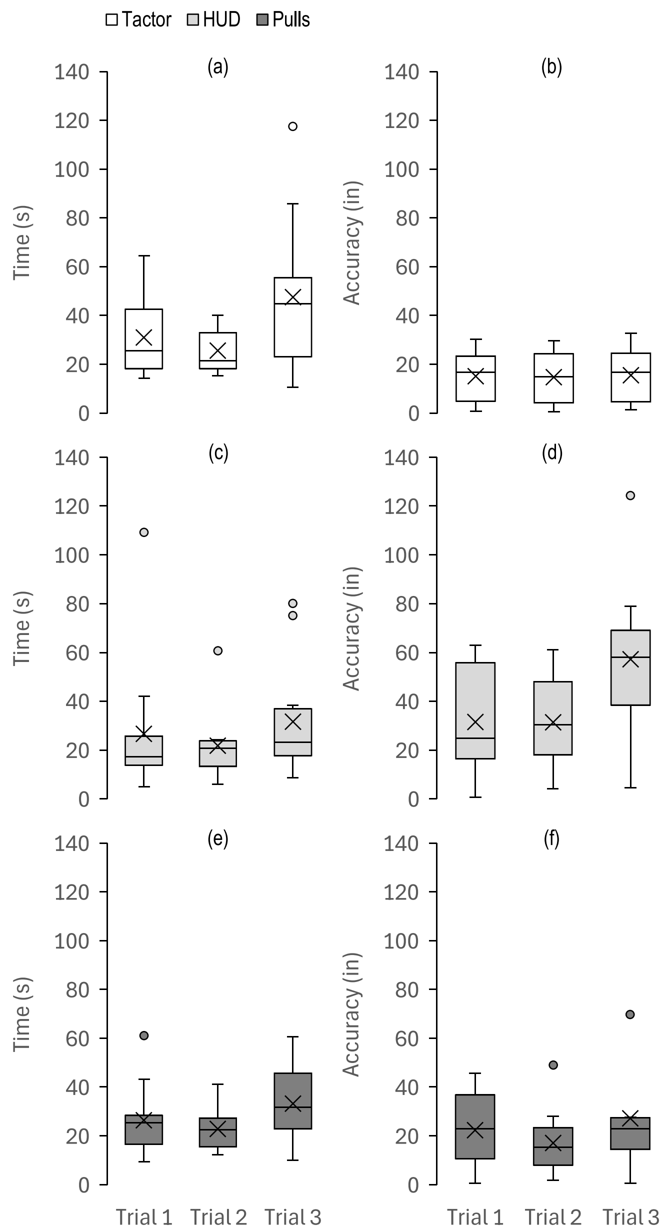


Fig. 11. Box plots showing how participants' navigation time and accuracy changed over time. Plots ((a) and (b)) are with the use of the tactor display, plots ((c) and (d)) are with the HUD, and plots ((e) and (f)) are utilizing the pull methodology. In (b), (d), and (f) the closer to 0, the higher the accuracy.

further training. The chief complaint was the inability to consistently see the displayed information due to: mask fog, a need for visual correction of their eyesight, and the changing direction on the display.

Participants discussed difficulty in comprehending tactor signals, as there was latency in vibrations and low vibrations on their right side. There were three sources for these latency issues. The first source was the experimenter manually sending commands for navigation, where they 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 design has long trace lengths and routing that can affect the signal's propagation time (Muth et al., 2002). The third source of delay occurred when some participants had seals that were broken within their dry suits, which unexpectedly exposed the tactors to full submersion. This led to delays with continued water exposure, with tactors completely flooded, destroying the integrity of their vibrations. This caused participants to be unable to understand the navigation signals confidently. Upgrades to both the design and the tactors are being addressed to resolve these flaws in the system.

6.5. Comparison with previous results

Overall, the results of the study reported in this paper are consistent with our previous testing with the visually blind (Camacho et al., 2025b), despite differences in context and participant characteristics. Both groups showed improved navigational accuracy when using the tactile display compared to other options, though at the cost of slower movement and some latency-related usability concerns. Participants in both studies expressed strong subjective preferences for the tactile system over their respective baseline methods. Both groups also found that the majority of the designed cues were natural and intuitive.

However, there were important differences. Visually disabled participants reported lower workload and slightly higher situational awareness when using the tactor display, whereas divers experienced a slight increase in workload and reduced situational awareness, particularly in their understanding of the environment. However, differences in these subjective measures were not statistically significant. Initial confusion about the meaning of tactile cues was observed mostly in the blind group. This is likely due to the participant's prior associations with obstacle alerting systems (like those discussed by Chun et al. (2012)). In contrast, diver participants benefited from refined training protocols. Thus, they appear to have adapted to the cues more readily. These findings suggest our navigation system design is broadly effective. However, context-specific design refinement and training may be required to support user understanding and reduce frustration in different environments.

6.6. General discussion

Overall, the findings of this study suggest that our new tactor-based navigation system offers a promising alternative to traditional dive navigation methods. While rope pulls remain a highly familiar and effective technique for trained participants, the tactor display significantly improved navigation accuracy. It also demonstrated comparable usability, subjective workload, and SA. The HUD, by contrast, consistently underperformed across all measures, most likely a result of reported difficulties reading the HUD form mask fogging, poor visual acuity, and distractions from shifting visual cues. These findings underscore the limitations of visual displays in underwater contexts and point to the advantages of tactile systems, particularly when the visual channel is unreliable. Thus, despite longer navigation times and some confusion with signal interpretation, we feel like our novel tactor display was successful and well-received. When these results are considered with our previous findings (Camacho et al., 2024, 2025a,b), they reinforce the theoretical perspective that the three levels of SA (Endsley, 1995; Bolton et al., 2007; Wickens, 2002) can be effectively supported through non-visual sensory channels.

This paper extends a long tradition of tactile communication research by moving beyond early approaches (particularly that of Gault, 1927 and Geldard, 1957) that relied on rote memorization of vibration codes. Gault (1927) showed that, with extensive training, students could significantly improve speech comprehension through tactile vibration using the Teletactor. Geldard (1957) expanded the potential of tactile signaling to communicate spatial and temporal information. However, both pioneers used symbolic coding systems that required memorization and multiple hours of training. This limited the practical usability and adaptability of tactile communication. Thus, this work makes a significant contribution by departing from the memorization-based paradigm by implementing an intuitive, semantically meaningful vibrotactile signaling system.

The limitations of our tactor display were largely due to minor hardware issues and limited participant training. These shortcomings will be mitigated in future iterations.

6.7. Future research

6.7.1. Study improvements and extensions

There were several limitations of our study that could be improved with future research. First, the number of participants we were able to recruit for this study was sufficient to show significant differences between multiple measures. However, the small sample size may have resulted in subtle differences in some subjective measures (such as the subscales that compose the NASA-TLX and SART) being undetected. Future research should attempt to larger study, possibly with the design improvements noted below, incorporated into the tactor display.

Second, the experimental task was admittedly simplistic due to IRB constraints for the first underwater experimental test of this prototype. Future research should attempt to evaluate the tactor display in realistic diving scenarios (such as search and rescue) with limited visibility.

Third, the nature of the experimental environment resulted in a situation where verbal administration and response to questions, which was administered by the researchers and/or third-party volunteers, was expedient for data collection. It is possible that this approach introduced experimenter expectation or social desirability biases. We attempted to avoid this by explicitly instructing participants to provide their honest, unbiased perspectives on questions. Future work could potentially avoid this potential confound by employing a consistent neutral third party to administer the experiment, or by having computer software administer the verbal data collection.

6.7.2. Design improvements

In this study, and in our previous work (Camacho et al., 2024, 2025a,b), inconsistencies were observed in the execution of tactile commands. All the tactors were programmed to give the same responses, but exhibited variation in force and speed. This partially impacted the SA results. When the tactors were more forceful, participants categorized them at the comprehend SA level (level 2), and if the tactors felt longer, they categorized them at the project SA level (level 3). Furthermore, when participants were presented with multiple signals at the beginning of the experiment, some found the projection tactor signal overwhelming and did not want to guess at the meaning. For example, five of the twelve divers understood multiple buzzes to mean stop, but the other seven took the urgent buzzing to mean that they needed to surface immediately. Future work will seek to refine this signal and/or improve training with the tactile device to avoid this confusion. Finally, the back tactors were harder on individuals who had scoliosis, nerve impingement, or surgery around their waistline. Placement of the tactors should allow some personalization to the end user to avoid shortcomings. Future iterations of our design will explore this feature.

6.7.3. Other application domains

Our tactile display offers potential benefits by freeing up visual or auditory perceptual modalities for other tasks (Lawson et al., 2016b). For the visually disabled, this would mean freeing up auditory senses or touch in other critical parts of the body (such as the hands or the feet). For divers, this would allow complete use of their hands during rescue operations and other diving tasks, allowing for a safer, more-focused dive. Future research should explore if our design has utility in other application areas where navigation is important (e.g., military ground and air operations, avatar embodiment, health impairments, ground transportation, space walking, etc.) to see if our design can be effective while freeing up perceptual modalities for other operations, both with and without limited visibility.

CRediT authorship contribution statement

Giovanna Camacho: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Matthew L. Bolton:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Amanda Watson:** Writing – review & editing, Supervision, Software, Resources. **Henry Bearden:** Investigation. **Sharon Lu:** Investigation.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used chatGPT and Grammarly to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of competing interest

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Data availability

Data will be made available on request.

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