Tactile Distance Feedback for Firefighters: Design and Preliminary Evaluation of a Sensory Augmentation Glove

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ABSTRACT
In this paper, we describe the design and preliminary evaluation of a vibrotactile glove for distance display in low vision search contexts. Specifically, this glove was developed for firefighting applications in which users experience compromised vision due to a combination of smoke and low ambient light levels. The glove maps an ultrasonic rangefinder to a pair of vibrating motors on the dorsal surface of the hand. Initial perceptibility testing with 15 participants showed participants were consistently able to detect the presence and absence of obstacles in a gap-detection task (93% correct detection) and to detect relative changes in the proximity of an obstacle (74% correct identification of relative position). Mapping tactile stimuli to absolute position was more challenging, with an accuracy rate of 57% (adjusted to 89% within one unit of actual position). Challenges to implementation of the concept include response time-lag, challenges of absolute judgment, and width of the sensor signal cone.

Categories and Subject Descriptors
H.5.2 [**User Interfaces**]: Haptic I/O; I.3.6 [**Methodology and Techniques**]: Interaction Techniques

General Terms
Design, Human Factors.

Keywords
Wearable technology, sensory augmentation, smart clothing, vibrotactile display, distance sensing, glove.

1. INTRODUCTION
Visibility and navigation are major challenges in structural firefighting. Smoke and darkness that can make it difficult to construct a mental model of the fire scene and compromise spatial awareness of rescuers [20]. Specific data about injuries and deaths related to obscured vision are not readily available, but in 2008 deaths due to impact or contact with an object, being caught or trapped, or falling (all of which may be influenced by poor visibility) made up 44% of career firefighter deaths, and 48% of volunteer firefighter deaths [1]. While the visual modality may be compromised in certain contexts, the tactile modality offers a promising substitute. The application context imposes further challenges to the design of a tactile sensory augmentation device, including needs for mobility, dexterity, quick donning/doffing (firefighters are required to be able to don full safety gear within 1 minute [22]), and high levels of stress and cognitive load [21]. However, the surface area, structure, and volume of firefighters' turnout gear offer a convenient space in which to integrate wearable technologies.

The research presented here is motivated by the potential for wearable technology to augment the sensory perception of the firefighter. Because sensory augmentation is currently in limited use in this domain (limited to things like night-vision displays) and sensory substitution is very seldom used as an augmentation method, the approach we have taken is to develop a prototype in the lab, informed only by the first author's experiences as a volunteer firefighter (which serves here as participant observation or our means of meeting the unique adequacy requirement for this domain). In the larger project, this prototype can be considered as a design probe intended to elicit feedback and open discussion about the potential for directed tactile feedback and selective sensory augmentation through wearable technology in the firefighting domain. Because unfamiliar or hypothetical design directions are difficult to discuss with users, this prototype is intended to open discussion both in terms of assessing the viability of this particular application and in terms of exploring alternative approaches to sensory augmentation for first responders. Specifically, we believe a tool that uses a targeted/selective approach, controlled by the user, rather than an ambient approach (continuous, omnidirectional feedback) maximizes the sensory-substitution potential while minimizing distraction, habituation, and unnecessary cognitive load. This paper will focus on the experimental validation of the ability of the test prototype glove to communicate specific aspects of distance perception related to navigating obstacles and detecting openings (which in practice could be ingress/egress openings or potential hazards) through an alternate modality.

2. BACKGROUND
2.1 Firefighting
Primary search is the firefighter's first search of a building, occurring concurrently or even before fire control operations have begun. Primary search is often characterized by low vision conditions due to smoke and darkness, often requiring rescuers to identify victims by touch alone [20]. Protective headgear such as a breathing apparatus can further obscure vision [2][3]. During primary search, firefighters first search the perimeter of the room before searching the center of the room if necessary. One of the

aims of our glove design is to better inform rescuers of the size and location of objects in the center of the room that may not be visible. Firefighters are also trained to search under objects and inside of tight spaces where children may hide during an emergency. As a result, a firefighter may often undertake less than ideal body positions, with significant weight of protective equipment due to search demands or excessive heat. Though firefighters possess a generalized knowledge of building types and familiarity with floor plans and layouts typical to their jurisdiction, the firefighter will ultimately navigate an unfamiliar structure during a primary search, finding doors and other openings to pass through.

Depending on the stage of the fire, the firefighter may also need to stay vigilant about potential unexpected openings. Structural damage to floors and stairs during searches of multistory buildings is also a concern for firefighters. When visibility is limited due to smoke or darkness, searchers must continually feel the floor ahead of them with either hands or tools to ensure it is still intact [20]. A selectively-activated tactile distance feedback can be seen to augment this tactile navigation modality to enable safer detection from a distance rather than weight-bearing direct manual manipulation.

Solutions to this context of impaired vision have been proposed and tested, particularly in the audio domain [4][5][6]. Similarly, tactile display has been used for other purposes targeted to the needs of firefighters, such as communicating temperature [7]. Riener and Hartl recently presented results from a prototype ultrasonic belt-based obstacle-avoidance system [8], which shares characteristics with the system presented here. However, a torso-mounted system such as this limits the user's ability to selectively "scan" the immediate surroundings or intended path (which can lead to irrelevant and possibly distracting information being presented). The system we present parallels the paradigm of "feeling" one's way in the dark, which relies on using the hand to *selectively* navigate. Further, a glove-based system eliminates the need to don an additional base-layer garment (close enough to the skin to be perceived). Given the dressing time constraints for emergency responders, this is a non-trivial implementation variable.

Firefighters involved in primary search, and entering a fire scene in general, are required to carry a forcible entry tool (such as an ax) at all times. Being without a tool is unacceptable for two reasons: first, the time required to return to the apparatus to procure a tool is considered to be time wasted, and second, firefighters may need to use any available tools to force their way out of a building in the event they are trapped [20]. This tool-carrying requirement has several effects on a hand-mounted system design. First, it limits the ability to place technology on the palmar surface of the hand (which would limit dexterity and effective tool use); second, it affects the position of the tool-carrying hand; and third, it limits the feasibility of implementing a hand-carried device for navigation or other purposes. Tactile display

Tactile display is often an underused modality in wearable systems, but offers significant potential for communicating sensory information. Most tactile or haptic systems focus on replicating or communicating tactile sensations (e.g. force or pressure in simulation environments), but have also been used in sensory substitution applications to replace or augment a missing or impaired sense [9]. Haptic feedback systems often use input from the virtual environment to generate tactile output, but sensory substitution devices must also include a sensing component that is also body-mounted or co-located with the output device. For example, the Tactaid [10] is a wearable device that maps audio input via a wearable microphone to vibrotactile feedback via an array of vibrating motors which can be positioned in many locations on the body (e.g. arm, chest). Vision-substitution devices have also been evaluated, most often for blind users, and most often for display of graphics (typically through a grid- or line-shaped array of actuators) [11], [12]. The most common locations for tactile feedback are the sensitive areas of the body (tongue [12], fingertips [13][14]) and areas with large surface area (e.g. the back [15]). For the purposes of firefighting, a tongue-mounted system would be difficult to implement and could interfere with speech-based communications. The genitals would also be difficult to use for tactile display. The hand, therefore, is the most sensitive body area feasible for garment-integrated tactile display in the firefighting context.

Tactile feedback for navigation purposes has also been investigated in a number of prototypes and studies. These can be classified by body location of feedback, and by the sensing mechanism used to detect information about the environment. Camera-based systems can collect a great deal of detail about the environment, but correspondingly often require a complex array of actuators to communicate this level of detail. For example, Zelek et al. investigated mapping a camera image to a 2D array of vibrating motors attached to a glove [16]. GPS data has also been used in a glove-based system [17] and a belt-based system [18], but is difficult to implement without a predetermined route or while indoors. Sonar or ultra-sonic sensing is more direct to implement, and has been used in a variety of applications: as a stand-alone hand-held device [19], [20], as a belt [21], and as a headband [22]. Most of these applications use stand-alone ultrasonic rangefinders, but Straub et al. have also explored belt-based vibrotactile navigation feedback using an indoor, infrastructure-mounted ultrasonic tracking system [23].

While no previous studies have addressed the specific challenge of navigation and rangefinding in a glove-based tool for firefighters, elements of the previous literature on vibrotactile display are relevant for this application. Firefighters must wear heavy, stiff, bulky turnout gear, which has been found in previous studies to interfere with localization and separation of individual tactors, especially in applications where the device is fitted to a complex 3D body shape [24]. However, tactile display has also been shown to be particularly effective in situations with high stress and/or high cognitive load [25][26], where the tactile modality appears to be effective at providing intuitive communication and reducing the load required to process information [27]. Further, in some domains (such as [26]), tactile display has proven to be more intuitive and faster to process than complex visual display which requires simultaneous processing of the visual display and the visual stimulus. Implementing a second modality allows more effective parallel processing [28].

2.2 Distance perception

Methods for encoding distance have been explored by many investigators. The most common encoding patterns implemented in evaluation systems have been differences in perceived magnitude (generally achieved through pulse-width modulation) and use of temporal patterns of pulses. However, Van Erp found no difference in intelligibility of these two encoding schemes on navigation speed [29]. Here, we elected to use perceived

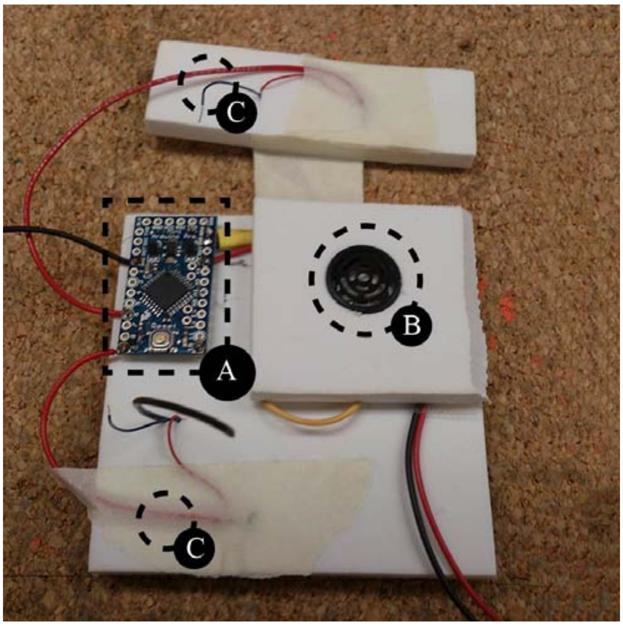

Figure 1. System hardware.

magnitude of the tactile response, mainly because pilot testing illuminated the potential additional time requirements for processing temporal patterns, particularly at the slower end of the scale (individual must wait to see how close the following pulse is to the detected pulse), which would limit the feasible range of the vibrotactile stimulus.

This limitation could influence the accuracy of judging distance, if the stimulus range were shortened. Absolute judgment of an analog stimulus is difficult in most modalities, and accurate discrimination is generally restricted to about 5 levels of the stimulus [28]. For vibrotactile stimuli, these levels should be at least 20% different [30].

3. SYSTEM DESIGN

The glove was designed to operate primarily through the dorsal surface of the hand. This position was selected for several reasons: first, due to the mobility and dexterity requirements of the application, which restrict the possibility of locating bulky and/or rigid components on the palmar surface of the hand or near joints. Second, task-related tool use always accompanies indoor navigation during primary search, blocking the palmar surface and exposing the dorsum [20]. Lastly, navigation is often performed in a low crawl or crouched position, bringing the back of the hand in front of the body [22]. Although the palmar surface is more sensitive and often used in tactile navigation as well as thermal sensing, trained responders are often taught to use the dorsal surface first, particularly when dealing with potential extreme temperatures. We restricted components to the bony surface of the metacarpals, where movement is limited and real estate is maximized.

3.1 Hardware design

The glove's hardware uses an Arduino Pro Mini microcontroller (Figure 1: A) to process the input of a XL-Maxsonar EZ4 ultrasonic rangefinder (Figure 1: B). The rangefinder's response is calibrated to a distance of 0 to 12 feet (with distances less than 8 inches displaying as 8 inches due to the sensor characteristics), and distances in this range are mapped to a continuous modulation of the pulse width that drives two pancake-style vibrating motors (310-101, Precision Microdrives)(Figure 1: C). Closer distances are mapped to a longer pulse width (which creates a stronger vibration response from the motors.) System hardware is illustrated in Figure 1.

3.2 Glove design

As Figure 1 shows, the system hardware was supported, structured, and protected using layers of EVA foam sheeting. The hardware components were integrated between the shell (cow-hide leather) and lining (Self Extinguishing Fleece Modacrylic thermal lining and Polyurethane moisture barrier) of a structural firefighting glove. The rangefinder was exposed through a puncture in the leather (Figure 2: A). Vibrating motors were positioned closest to the joints, to improve skin contact when the hand is flexed or relaxed (not extended), due to forces between the glove and hand (Figure 2: B). The top motor was positioned close to the middle metacarpo-phalangeal joint (the base of the middle finger) (Figure 2: B), mechanically isolated through a flexible tape joint, and the bottom motor was positioned at the proximal end of this metarpal (close to the wrist). Figure 2 illustrates this positioning.

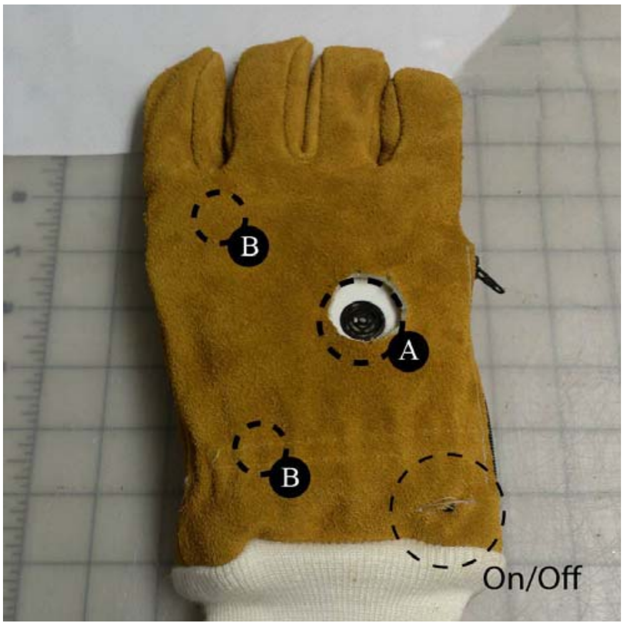

Figure 2. Glove prototype.

4. METHOD

In this first test prototype, the glove is controlled with a simple on/off switch at the medial wrist (farthest from the thumb). Prototypes were created for both right and left gloves, both in size "Small." Design standards for structural firefighting gloves size "small" specify fitting a hand circumference of 7.58", accommodating the range from 6.83"-8.33", and fitting a hand length of 6.99", accommodating the range from 6.80"-7.18" [21]. The glove prototypes were tested in two experiments: a gap-detection test, and a distance perception test. Both gloves were evaluated, but participants were randomly assigned to a glove (not matched to the glove of their dominant hand).

4.1 Participants

15 participants recruited from the university community took part in the experiment (6 female). 2 were left-handed, and 7 tested the glove of their non-dominant hand. Participants were between the ages of 25 and 49 (mean 32.4). All participants tested the same size glove, but their hand circumferences varied from 6.5" to 9.5" (mean 8.22"). Participants were asked if they were aware of any abnormalities in their ability to feel vibration with their hands (haptic stimuli) and were excluded from the study if they did. Participants were not compensated for their involvement.

All participants were oriented to the glove's functionality (including a basic description of the rangefinder's theory of operation) and allowed to experiment with the glove for a short time prior to beginning the evaluation.

4.2 Gap detection task

The gap-detection test evaluated the participants' ability to detect the presence or absence of obstacles in a binary fashion, and to detect the presence of a gap in a line of obstacles (such as when looking for a door or a possible collapsed floor). An obstacle course consisting of a row of 6 11" cube obstacles was set up on the surface of a hip-height table, with an 11" gap between two obstacles. (Figure 3 illustrates the experimental setup with example gap at location 2) Participants donned the glove and performed a training session in which they navigated the course fully sighted, to orient to the tactile feedback and to position the glove. Participants stood approximately 3 feet away from the obstacles. Glove position was maintained through a body reference point (e.g. hand on hip) and held consistent throughout the test.

Once the training session was completed, the participant was blindfolded and the gap moved to a pre-determined random position within the array (gaps were never positioned at the beginning or end of the course, always between two obstacles). The participant then navigated the course (using the edge of the table as a guide if needed), stopping or verbally indicating the location where they perceived a gap. Participants were notified when they had reached the beginning or end of the course, but not given feedback on the accuracy of their gap detection. The participant's responses were recorded for each of 5 trials.

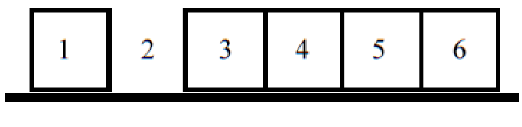

Figure 3. Experimental setup: gap-detection task.

4.3 Distance perception task

The distance perception task evaluated the participants' ability to detect relative and absolute changes in distance of an obstacle, to assess their ability to effectively map the tactile perception to the real-world location of an obstacle during navigation. In this test, the participant was seated at the end of the table, and 4 obstacle positions were marked with paper strips along the length of the table. The first obstacle position was located 18" from the participant's hand, and each successive position was spaced 18" from the previous position. The experimental setup is illustrated in Figure 4.

Again, participants completed a training session in which they were presented one 11" cube obstacle at each position successively, with the obstacle removed between re-positions (to calibrate the "blank" or missing-obstacle condition). Participants were informed that they would be presented with 20 trials in which an obstacle would be presented at one of the four positions, or no obstacle would be presented (missing condition), and that they would be asked to indicate a) whether the obstacle was closer or farther from the previous obstacle, and b) at which of the four positions the obstacle was located. The participant was then blindfolded and their responses recorded for 20 trials. Obstacles were removed between trials, and the participant was notified verbally from a consistent position when each trial's obstacle was in place.

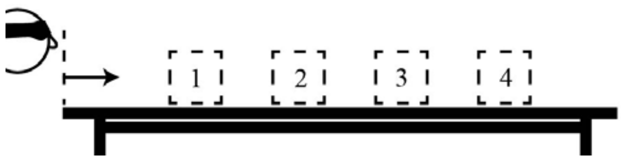

Figure 4. Experimental setup: distance perception task.

4.4 Data analysis

For the gap-detection task, each participant's percentage of correctly-detected gaps was calculated, and the overall correct-detection average calculated for all participants.

For the distance perception task, each participant's percentage of correctly-detected obstacle positions was calculated (and averaged over all participants). This assessment was extended to include the participant's accuracy rate within one increment of the actual position (to control for "off-by-one" errors in which the participant incorrectly identifies one position, then re-calibrates subsequent responses to that relative starting point.) Further, for each participant the average of correct relative distances (e.g. closer, farther, the same, or missing) was calculated, as well as the false-positive and false-negative rate for detecting the presence of obstacles.

5. RESULTS

5.1 Gap detection task

The overall percentage of correctly-identified gaps was 93%. 5 participants mis-identified the position of one gap (no participant missed more than one gap),

5.2 Distance perception task

The distance perception trials had an overall average false positive rate of 18%, and false negative rate of 3%. It should be noted, however, that there were far more trials in which the obstacle was actually present than trials in which the obstacle was missing (N=242 obstacle present, N=58 obstacle missing), and therefore false-positive errors had a disproportionate impact on the overall rate (in a trial where there was only one missing-obstacle trial, an error on that trial resulted in a rate of 100%. This instance occurred for two participants). The mean, standard deviation, and

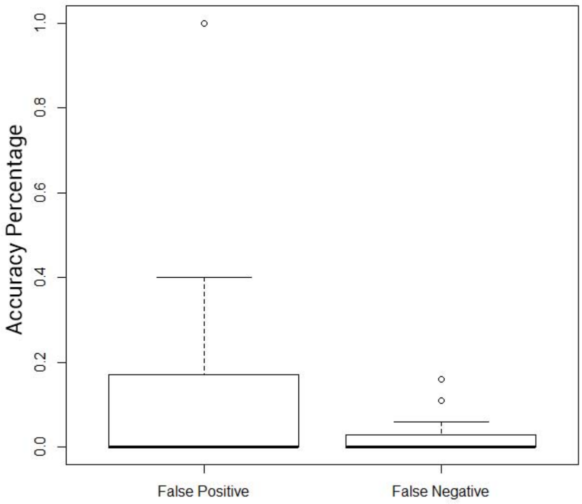

Figure 5. False-positive and false-negative rates for distance perception task.

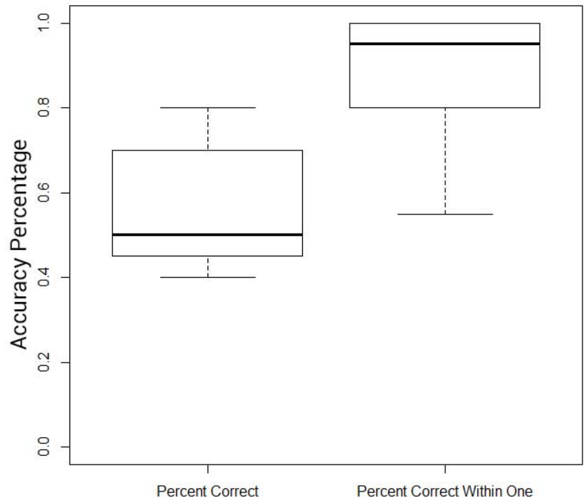

Figure 6. Absolute position perception for distance perception task.

range of percentage false positive and false negative rates are shown in Figure 5.

Relative position of the obstacle (direction of movement from previous obstacle) was accurately perceived 74% of the time, averaged over all participants. Absolute position was more difficult to determine, and had an overall average accuracy rate of 57%. However, many participants "re-calibrated" their understanding of distance after an error, resulting in a continuation of "off-by-one" perceptions following the error. When accuracy of perceived position was relaxed to include positions that were one increment off of the actual position, accuracy rates improved to 89%. Percentage of correctly-perceived absolute position for these two metrics is illustrated in Figure 6.

As only one size glove prototype was developed for evaluation, hand circumference (a variable influencing proper fit) is a possible confounding variable. Hand circumference in our participants ranged from 6.5" to 9.5", while design guidelines for a "small" sized structural firefighting glove specify fitting a hand circumference of 7.58" and accommodating the range from 6.83"-8.33" [21]. Correlations between hand circumference measures and each of the error metrics previously discussed (percentage of correct gap detections, false-positive and false-negative rate in distance perception, percentage of correctly-identified relative positions, percentage of correctly-identified absolute positions, and percentage of correctly-identified absolute positions within one unit of the actual position) were computed in order to assess the influence of this possible confounding variable on perception accuracy, and the r-squared value for each correlation is presented in Table 1.

Table 1. Correlations (r-squared) between hand circumference and error measures

	Gap Detection	False Neg.	False Pos.	Rel. Pos.	Abs. Pos.	Abs. Pos. +1
r-sq	0.04	0.01	0.02	0.00	0.08	0.15

6. DISCUSSION

In general, our participants found the glove intuitive and required little training prior to beginning test trials. Training sessions were not limited in length, but generally required less than a minute before the participant felt comfortable with the glove (consistent with the requirement that tactile displays be self-explanatory, due to the low likelihood that users will be familiar with interfaces in this modality [30]). The only explicit explanations that participants were given with regards to glove operation were 1) the general theory of operation, with closer obstacles represented by "louder" or stronger vibrations; 2) the location and "column" nature of the sensor signal; and 3) the calibration of the sensor feedback response ("max" within 6 inches, "zero" outside of 12 feet).

As can be seen from the results presented here, the prototype glove was most effective in binary sensing contexts (presence/absence of an obstacle), but also effective at communicating relative distance (closer/farther/same). For the most challenging task, absolute distance perception, participant responses were almost 3 times as accurate as chance (58% correct), and improved to an extremely high level of accuracy (92%) when adjusted for "within-1" accuracy. Many participants exhibited a re-calibration behavior in which a mis-identification of one trial adjusted subsequent trials by the same increment. However, this result is more indicative of the success of the glove in a relative-position detection scenario than in an absolute-position identification scenario. In a field context, it is likely that firefighters would have the advantage of some amount of visual or other sensory "calibration" information (at the very least, the position of the floor relative to their hand). Therefore, our blindfolded context, temporally separated from the training (tactile + vision context) session represents something close to a worst-case scenario, in that generally, there is at least some ambient light, rather than total darkness as simulated with a blindfold.

However, several variables emerged in the assessment sessions that may not be fully captured by the quantitative results. Firstly, the ultrasonic sensing mechanism resulted in a few perception challenges. Most importantly, although the rangefinder we implemented has the narrowest beam of the supplier's options, its approximately two-foot wide beam at times caught other objects (e.g. the table on which obstacles were displayed), providing a vibrotactile response corresponding to the closer obstacle. In practice, this may result in inaccurate information presented to the wearer. However, error on the side of the closer obstacle may promote safety in navigation. In addition, although the ultrasonic rangefinder measures every 49ms, in practice participants experienced a several-second delay in accurate feedback on the proximity of an obstacle. The gap-detection task, for example, was often performed by participants at a slow, shuffling pace – sufficient for laboratory experimentation, but perhaps prohibitively slow for field deployment. Further investigation of speed of tactile response and its effect on time to complete the task is necessary.

About half of our participants were questioned anecdotally (outside of the experimental procedure) about their perception of the arrangement of tactile feedback. All of these participants detected a single locus of vibration, indicating that the glove structure and internal hardware may have resulted in significant mechanical coupling of the independent vibrating motors. Recent investigation of gestalt principles applied to haptic feedback suggests that perceptual grouping by proximity does not occur, while grouping of similarity does occur [23]. It is possible that this explains some participant's reports of a single locus of vibration; the inability to overcome perceptual grouping of identical vibration even though vibration originates in different locations seems to support those findings.

6.1 Limitations

A potentially complicating limitation of our study was the availability of only one size of glove for testing. As previously described, this was a "small" in the NFPA 1971 sizing system, with a specified average 7.58" hand circumference to fit a range of hand circumferences from 6.83-8.33" (compared to the mean 8.21" and range 6.5"-9.5" measurements of our participants). In practice, several participants had trouble donning the glove. Closer fit due to a too-small glove can be hypothesized to improve the perceptibility of a vibration response, while looser fit (due to an oversized glove) can be hypothesized to potentially reduce perceptibility of the vibration response, depending on hand position. However, as seen in Table 1, we found no significant correlations between hand circumference and any of the measured error metrics. This would suggest that, for an implementation with the bulk and mechanical coupling of this prototype, that accuracy of fit does not play a significant part in perception of the vibrotactile response. Another influencing factor which could contribute to isolating the impact of fit on perception is the unified response of the tactors in this glove. Previous work has indicated that fit may play an important role in body contact for 3D body shapes, limiting the ability to detect individual tactors within an array [24].

7. CONCLUSION

In general, the glove prototype displayed promising results for distance perception in a completely sightless scenario. The results presented and discussed here support the further development of vibrotactile distance feedback for sensory augmentation. The initial prototype evaluated here was reliably capable of displaying position of openings, and binary and relative distance information across genders and even within hand sizes. Absolute distance information proved more difficult to detect using this prototype, but was nevertheless better than chance in communicating distance.

Variables for further investigation and design development for this application include response time for sensor feedback, absolute judgment, effects of sizing and fit, and influence of field variables such as cognitive load and temperature. Further development is needed to effectively investigate the potential of this application for field deployment, especially with regard to glove interface and the activation mechanism for this feedback response. The directed, selectively-activated paradigm for augmentation of sensory perception identified as an area of high potential in this kind of system is crucial for less-structured or field evaluation of this prototype, and therefore the method by which the response is activated and deactivated must be addressed with similar attention to human factors of interaction in order to produce a field-usable device.

8. ACKNOWLEDGMENTS

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