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Head-mounted Sensory Augmentation Device: Designing a Tactile Language

Hamideh Kerdegari, Yeongmi Kim, and Tony J. Prescott

Abstract—Sensory augmentation operates by synthesizing new information then displaying it through an existing sensory channel and can be used to help people with impaired sensing or to assist in tasks where sensory information is limited or sparse, for example, when navigating in a low visibility environment. This paper presents the design of a 2nd generation head-mounted vibrotactile interface as a sensory augmentation prototype designed to present navigation commands that are intuitive, informative and minimize information overload. We describe an experiment in a structured environment in which the user navigates along a virtual wall whilst the position and orientation of the user's head is tracked in real time by a motion capture system. Navigation commands in the form of vibrotactile feedback are presented according to the user's distance from the virtual wall and their head orientation. We test the four possible combinations of two command presentation modes (continuous, discrete) and two command types (recurring, single). We evaluated the effectiveness of this 'tactile language' according to the users' walking speed and the smoothness of their trajectory parallel to the virtual wall. Results showed that recurring continuous commands allowed users to navigate with lowest route deviation and highest walking speed. In addition, subjects preferred recurring continuous commands over other commands.

Index Terms—Sensory augmentation, tactile language, tactile display, vibrotactile feedback

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1 INTRODUCTION

Tactile displays support a variety of applications in sensory substitution [1] and sensory augmentation [2], [3] and may be particularly useful for tasks such as spatial orientation and navigation [4], [5] when other sensory channels, such as vision and hearing, are overloaded or compromised [6]. In this article we consider the design of tactile commands, or what we might call a *tactile language*, for effective communication in a navigation task using a head-mounted display. We compare and contrast different forms of command varying the frequency and nature of the stimulus and exploring the potential of apparent motion as a cue for signaling direction information. The efficacy of different command types is evaluated in an environment containing virtual walls using real-time tracking of user position.

To motivate our study we first summarise prior work on haptic displays for sensory substitution and augmentation, discuss the potential usefulness of body- and head-mounted displays for enhancing spatial awareness, and outline our experimental design and hypotheses.

1.1 Enhanced Awareness through Haptic Displays

Initial investigations with tactile displays explored their potential to compensate for sensory loss or impairment [1]. For example, sensory substitution devices have been developed to assist people with impaired vision [1], [7], hearing [8] or balance sense [9]. Unlike sensory substitution, which translates the form of one modality into the form of another; sensory augmentation adds new synthesized information to an existing sensory channel. The additional senses provided by augmentation can be used to boost the spatial awareness of people with impaired vision [10], [11], or for people operating in environments where visual sensing is compromised such as smoked-filled buildings [2], [3], [12]. Tactile display technologies to enhance spatial awareness and navigation through augmentation have evaluated the use of vibrotactile cueing to various body sites such as the waist, back, wrist and head. Next we consider a number of such systems from the standpoint of tactile language design and position on the body.

1.2 Designing Haptic Signals for Communication

Perhaps the simplest way to signal navigation information through haptics is to activate a single tactor that is positioned on the body close to the intended direction. Nagel et al. [13] and Tan et al. [14] utilized a wearable tactile belt consisting of several tactors, together with a compass, to calculate and display cardinal directions to the user. The tactor that pointed most closely north was always activated allowing users to gain a sense of their global orientation. Karcher et al. [11] showed that this kind of augmentation device can also be used by people with visual impairments to maintain a heading direction over long distances. The 'active belt', developed by Tsukada and Yasumura [15], provided users with directional information via eight tactors distributed around the waist. A target destination was displayed in a discrete fashion by activating the tactor closest to its direction. Van Erp et al. [16] evaluated a similar discrete direction

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- *H. Kerdegari is with Sheffield Robotics, The University of Sheffield, Pam Liversidge Building, S1 3JD, Sheffield, UK .E-mail: h.kerdegari@ sheffield.ac.uk*
- *Y. Kim is with the Department of Mechatronics, MCI, Universitatsstraße 15, 6020, Innsbruck, Austria. E-mail: yeongmi.kim@mci.edu.*
- *T J. Prescott is with Sheffield Robotics, The University of Sheffield, Pam Liversidge Building, S1 3JD, Sheffield, UK .E-mail: t.j.prescott@ sheffiel.ac.uk*

encoding using a vibrotactile waist display where the location of the next waypoint determined the specific tactor that was active at any given time.

Although participants were able to navigate effectively in the above studies the discrete number of displayable directions limits the resolution with which directional information can be conveyed and could lead to sub-optimal routes; this has encouraged the development of more continuous forms of direction display that involve activating multiple tactors. For example, Heuten et al. [17] developed a belt-type display that guided pedestrians by indicating a continuous range of directions and deviations from the path. Similarly, Pielot et al. [18] developed a presentation method that displayed direction by interpolating the intensity of two adjacent tactors in a tactile belt with six tactors. Interpolated presentation was found to be more accurate than discrete presentation and improved the accuracy of perceived directions.

Whilst location of activation is clearly an intuitive way to signal direction, the possibility also exists to communicate navigation instructions through signal timing. For example, Cosgun et al. [19] showed that displaying a rotating pattern of activation on a belt with eight tactors could usefully indicate an intended direction for whole-body rotation.

Different combinations of spatial and temporal signalling are also possible and may be useful for displaying richer instructional cues [20]. For instance, Tan et al. [21] and Ross et al. [22] developed a 3-by-3 haptic back display for directional cueing. Each direction was generated as a simulated line using three tactors, e.g. tactors vibrating in the middle vertical row of the array from bottom to top conveyed North.

The design of tactile display signals for use as navigation commands can benefit from an understanding of how patterns of vibration are perceived by the wearer. For instance, it is well-known that when two nearby positions on the skin are stimulated sequentially people may perceive this as apparent motion—the illusary sensation of a stimulus travelling continuously from the first stimulation site to the second [23], [24]—with the strength of this effect depending on various factors including stimulus timing and the distance between the stimulation positions (see section 2). Roady et al. [25] compared the effectiveness of static (single or multiple tactors activated together), dynamic (tactors activated in sequence but no temporal overlap), and saltatory (overlapping sequential stimuli) vibrotactile patterns in a task in which participants were asked to draw the stimulation pattern using pen and paper. Results showed that saltatory presentation mode, which induced an apparent motion effect, outperformed dynamic display in terms of response time and accuracy, and was easier to interpret than static displays for more complex patterns.

Different parts of the body display differing levels of sensitivity to tactile commands. Jones et al. [26] investigated spatiotemporal vibrotactile pattern recognition on the forearm and back using a 3x3 and 4x4 tactile display respectively. They found that the ability to identify tactile patterns presented on the forearm was lower indicating that the back may be a more effective location for presenting vibrotactile navigation cues.

Wrist-mounted tactile displays have been investigated less than waist and back displays, partly due to the limited skin area and lower tactile sensitivity of the wrist [27]. Nevertheless, if the nature of the information being conveyed is relatively simple wrist displays can still be effective. ‘Gentleguide’, developed by Bosman et al. [28], was a wearable wrist-mounted device for indoor pedestrian guidance consisting of two wrist-mounted devices with a single actuator mounted on each wrist. Results indicated that the device could provide an intuitive means to deliver directional information to guide pedestrians. ‘VibroTac’, created by Weber et al. [29], was a wrist-mounted tactile display developed to provide spatial guidance in a task where participants had to translate and rotate virtual objects. Direction of movement was indicated by discrete activation of specific tactors, whilst a rotation command was conveyed by activating the tactors in sequence (clockwise or anti-clockwise).

1.3 Head-mounted Vibrotactile Displays

An alternative body location that has the potential to provide a reasonably high resolution for tactile discrimination and sensitivity is the forehead. Compared to a hand- or waist-mounted sensory augmentation device, a head-mounted display can also allow faster reactions to unexpected obstacles since tactile response latencies are approximately linear in distance from the brain [30]. A head-mounted display may also be intuitive for navigation since a relative straightforward mapping can be created between sensed objects (such as obstacles) and stimulation of the head in the direction of that object.

Several studies have investigated head-mounted haptic displays for enhancing spatial awareness and navigation. One of the first was the ‘haptic radar’, created by Cassinelli et al. [2], that linked infrared sensors to head-mounted vibrotactile displays allowing users to perceive and respond simultaneously to multiple spatial information sources. In this device, several sense-act modules were mounted together on a band wrapped around the head. Each module measured distance from the user to nearby surfaces, in the direction of the sensor, and transduced this information into a vibrotactile signal presented to the skin directly beneath the module. Users intuitively responded to nearby objects, for example, by tilting away from the direction of an object that was moving close to the head, indicating that the device could be useful for detecting and avoiding collisions. Marsalia [31] has evaluated the effectiveness of a head-mounted display in improving hazard recognition for distracted pedestrians using a driving simulator. Results showed that response hit rates improved and response times were faster when participants had a display present. The ‘Bat Hat’, developed by Buswel et al. [32], was a similar device designed to alert its wearer about obstacles in his or her path through haptic feedback.

The above studies indicate the value of head-mounted haptic display for alerting wearers to possible threats. The close proximity of the display to the brain can allow a fast

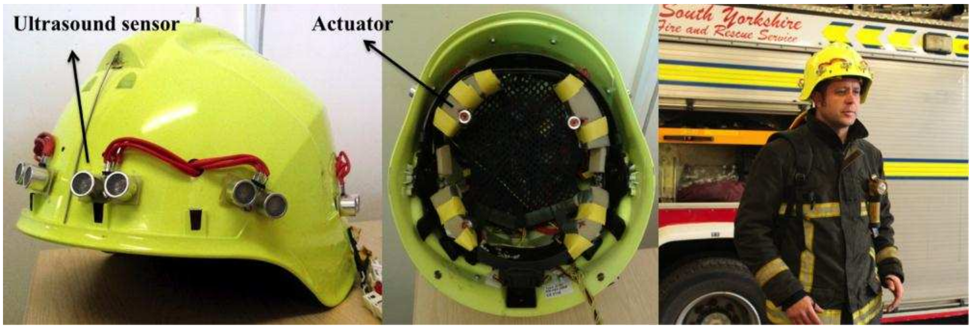


Fig. 1. Our first generation 'Tactile Helmet' [3] was composed of a ring of ultrasound sensors and four actuators inside the helmet and was designed to help firefighter's navigate inside smoked-filled buildings (see Bertram et al. [3] for further details).

response with the direction of the threat displayed in an intuitive way by the position of the activated tactor(s). The 'Tactile Helmet' [3] was a prototype sensory augmentation device developed by the current authors that aimed to be something more than a hazard detector—a device for guiding users within unsafe, low-visibility environments such as burning buildings. We selected a head-mounted tactile display as this facilitates rapid reactions, can easily fit inside a modified fire-fighter helmet, and leaves the hands of the firefighters free for tactile exploration of objects and surfaces. Our first generation device (see Fig. 1) comprised a ring of eight ultrasound sensors on the outside of a firefighter's safety helmet with four voice coil-type vibrotactile actuators fitted to the inside headband. Ultrasound distance signals from the sensors were converted into a pattern of vibrotactile stimulation across all four actuators.

One of the goals of our approach was to have control over the information displayed to the user (relative, for instance to the 'Haptic Radar'), and, in particular, to avoid overloading tactile sensory channels by displaying too much information at once. This is particularly important in the case of head-mounted tactile displays, as vibration against the forehead is also detected as a sound signal (buzzing) in the ears; too much vibrotactile information could therefore be confusing, or irritating, or could mask important auditory stimuli. Despite seeking to provide better control over the signal display, however, field tests with the mark-1 Tactile Helmet, conducted at a training facility for South Yorkshire Fire and Rescue Services, showed that tuning the device to suit the user needs and situation was problematic. Specifically, a design that directly converted local distance information into vibration on multiple actuators generated too much stimulation in confined situations such as a narrow corridor. These tests therefore established the need to better regulate the tactile display of information, to ensure clearer signals and to minimize distracting or uninformative signals. Following on from these field tests, and building on previous investigations of the psychophysics of head-mounted displays [33], [34], we conducted a series of psychophysical studies (e.g. [35]) to investigate how to best optimize haptic display signals to relay effective information to the user. These studies have informed the design of the tactile language as set out below.

1.4 Aims of the Current Study

The research described above has demonstrated (i) the usefulness of haptic displays for guidance in navigation tasks, (ii) that spatial and temporal patterns can separately, or together, provide useful information for conveying haptic commands, and (iii) that spatiotemporal patterns that are perceived as apparent motion may be particularly intuitive. Past work has also shown that location on the body is important when evaluating the effectiveness of haptic displays. In particular, the torso might be a useful location for displaying complex patterns due to the large surface area available, but the head may also be useful, particular where fast reaction time is important. More generally, results obtained for one area of the body may not necessarily transfer elsewhere due to the varying density of mechanoreceptors in the skin, concentration of different tissues (e.g. fat, bone, muscle) that can amplify or mask signals, the ability to move the display area relative to the rest of the body, and speed of transmission to the brain.

The aim of the current study was therefore to explore the design space for display of haptic commands on head-mounted devices, specifically focusing on the potential of signals that can be interpreted quickly and intuitively, and in the context of designing haptic navigation aids for fire-fighters. To deliver these haptic signals to the user, we have also extended our previous work on helmet design [36] by developing a second-generation sensory augmentation device. The new helmet configuration is designed to overcome some of the limitations of the earlier system particularly the low resolution of the tactile display and the size and weight of the on- and off-board electronics. More specifically, based on our psychophysics results [35], the number and positioning of the tactors in the new helmet has been optimized for conveying commands through spatiotemporal patterns that can induce the experience of apparent motion.

As with our first generation device, the mark II 'Tactile Helmet' uses ultrasound sensors to detect distances to nearby surfaces that can be displayed to the user. However, for the current study we decided to bypass the need to sense walls and surfaces in order to focus on development of the tactile language. We achieved this by tracking the participant's position and orientation relative to a layout of virtual walls, from which we then infer the appropriate commands directly. These commands are relayed to the user via the haptic display allowing them to move in a trajectory parallel to the virtual surface. We evaluated the effectiveness of the tactile command language according to both objective measures of the smoothness of the user's trajectory and walking speed, and subjective measures of their utility and comfort as determined using Likert-type rating scales.

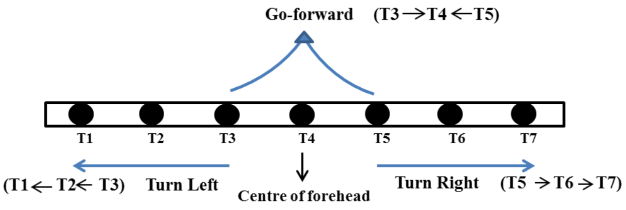


Fig. 2. Vibrotactile patterns for turn-left, turn-right and go-forward commands in the tactile display.

2 EXPERIMENTAL DESIGN

In low visibility environments, firefighters navigate using the existing infrastructure such as walls and doors. These reference points help them to stay oriented and make a mental model of the environment [37]. To facilitate this form of navigation behavior we used a wall-following approach inspired by algorithms developed in mobile robotics that maintain a trajectory close to walls by combining steering-in, steering-out and moving forward commands [38]. Specifically, to navigate the user along the virtual wall, we employed three commands: *turn-left*, *turn-right*, and *go-forward*. The *turn-left/right* commands were intended to induce a rotation around self (left/right rotation) in order to control the orientation of the user; the *go-forward* command was designed to induce forward motion in the current orientation.

Fig. 2 illustrates the positions of tactors in the tactile display and the vibrotactile patterns used to present the different commands. Note that tactor 4 is placed in the center of forehead. Commands are distributed spatially in the tactile display, using multiple tactors, in order to convey rich vibrotactile patterns to the user [20]. The *turn-left* command starts from tactor 3 and ends with tactor 1 while *turn-right* starts from tactor 5 and finish with tactor 7. The *Go-forward* command starts from tactor 3 and tactor 5 simultanously and ends with tactor 4.

We investigated the utility and user experience of these commands using the combination of two command types, *recurring* and *single*, and two command presentation modes— *continuous* and *discrete*.

The continuous presentation mode takes advantage of the phonemena of tactile apparent movement (as discussed in section 1.2 above) [24]. The two main parameters that control the feeling of apparent motion are the *duration of stimulus* (DoS) and the *stimulus onset asynchrony* (SOA) [39]. DoS refers to the amount of activation time of a given tactor per display period, while SOA refers to the interval between the sequential activation of two tactors. In order to induce the perception of tactile apparent movement, the activation period of consecutive tactors should overlap which means that SOA should be shorter than DoS. Previously, we found that a strong impression of movement on the forehead was experienced using a DoS of 400 ms and a SOA of 100 ms. This results in a total rendering time of 600ms for turn right/left commands and 500 ms for go-forward command. To illustrate, a schematic representation of the *turn-left* command is presented in Fig. 3a.

In the *discrete* presentation mode the tactors are activat-

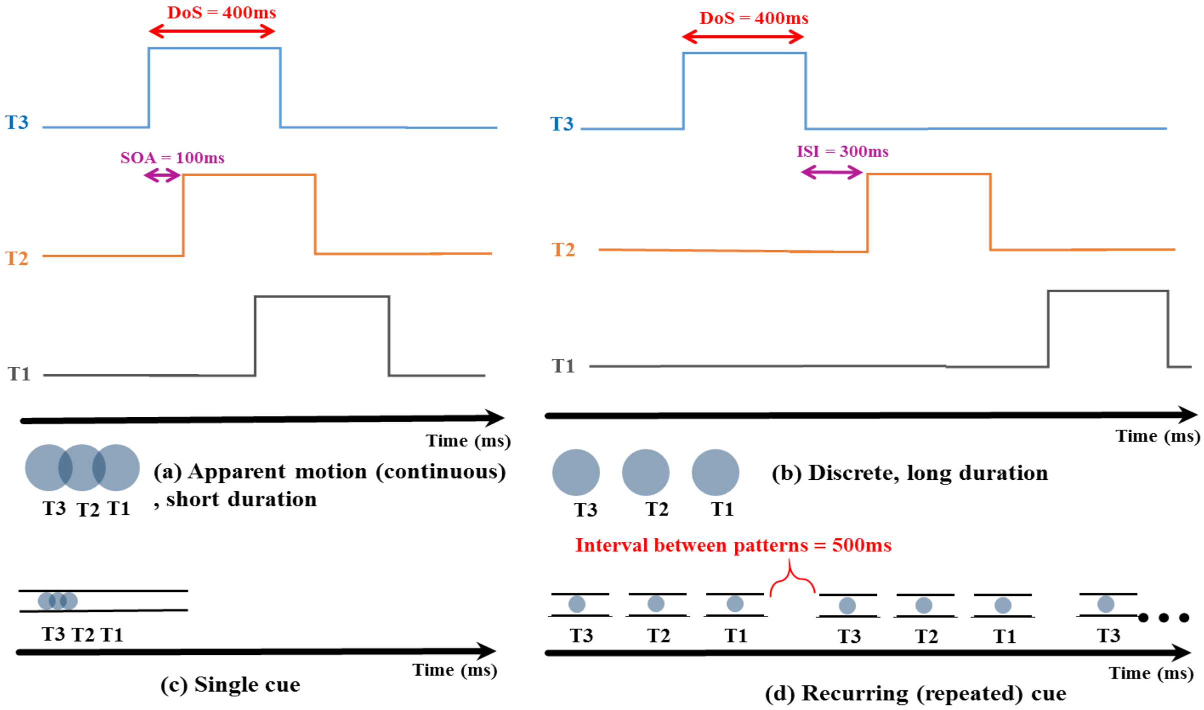


Fig. 3. Schematic representation of the tactile language employed in this study. (a) Continuous presentation. (b) Discrete presentation. (c) Single cue. (d) Recurring cue.

ed sequentially with no stimulus overlap. For the current study, the DoS was set at 400 ms for each tactor with an *inter-stimulus interval* (ISI) of 300 ms between consecutive stimuli in a pattern. This result in a total rendering time of 1800 ms for the t*urn left/right* commands and 1100 ms for the *go-forward* command. This mode creates the experience of discrete motion across the forehead for all three commands. Fig. 3b shows an example of discrete presentaion method for the *turn-left* command. Tactor stimulation intensity was the same in both presentation modes (255 Pulse Width Modulation (PWM) intensity at 3V).

Our experiment also used two command types: *recurring* and *single*. In *recurring* conditions the tactile command is presented to the user's forehead repeatedly with an interval between patterns of 500 ms until a new command is received. For the *single* conditions the tactile command is presented just once when there is a change in the command. Fig. 3c and Fig. 3d show a schematic of these two types of commands.

We hypothesized that *recurring* commands would lead to better navigation performance than *single* commands since it avoids the need for the user to remember the current navigation command. We also anticipated that the *continuous* commands would be more effective than *discrete* as apparent motion can provide a strongly intuitive direction signal. For the subjective measures we did not predict an expected preference for either *continuous* or *discrete* commands, but we thought it was possible that users might find the *recurrent* commands more distracting or irritating than the *single* commands.

3 METHODS

3.1 Subjects

Eighteen naive subjects - 9 women and 9 men, average age 24- voluntarily participated in the experiment with no previous experience of navigation using a haptic aid. All subjects were university students or staff. The study was approved by the University of Sheffield Department of Psychology Ethics Committee, and informed consent form was obtained from all participants. None of the participants reported any known abnormalities with haptic perception.

3.2 Apparatus and Materials

3.2.1 Vibrotactile Helmet

The mark II Tactile Helmet (Fig. 4) consists of an array of twelve ultrasound sensors (I2CXL-MaxSonar-EZ2 by MaxBotic) mounted with approximately 30 degrees separation to the outside of a ski helmet (Fig. 4d), and a tactile display composed of seven tactors (Fig. 4b) [35]. The tactile display consists of seven eccentric rotating mass (ERM) vibration motors (Fig. 4a) with 3V operating voltage and 220Hz operating frequency at 3V. These vibration motors are mounted on a neoprene fabric and attached on a plastic sheet (Fig. 4b) with 2.5 cm inter-tactor spacing that can easily be adjusted inside the helmet to increase the comfort and attenuate vibration along the forehead. The helmet also incorporates an inertial measurement unit (IMU), a microcontroller unit and two small lithium polymer batteries (7.4 V) to provide the system power. The ultrasound sensor data and measurements of IMU are sent to the microcontroller through I^2C BUS. The microcontroller in the helmet reads the sensors values and sends them to the PC wirelessly using its built-in WiFi support. The PC receives the sensor values and generates commands for the tactile actuators sending them back to microcontroller wirelessly for onward transmission to the tactile display. For the experiment described below we disabled the direct generation of actuator commands and substitute signals based on information from the motion

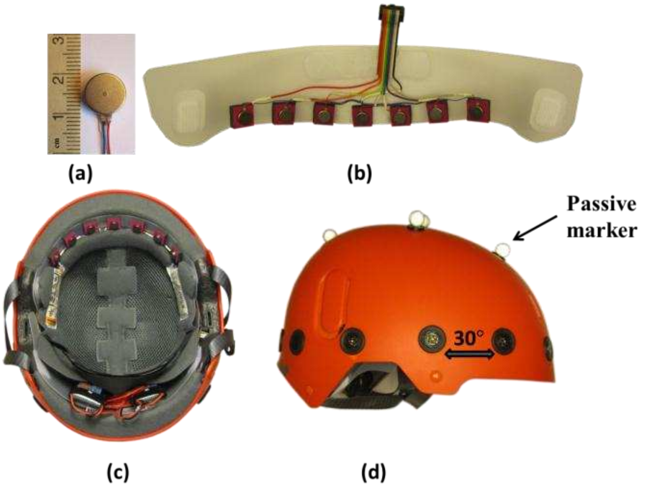
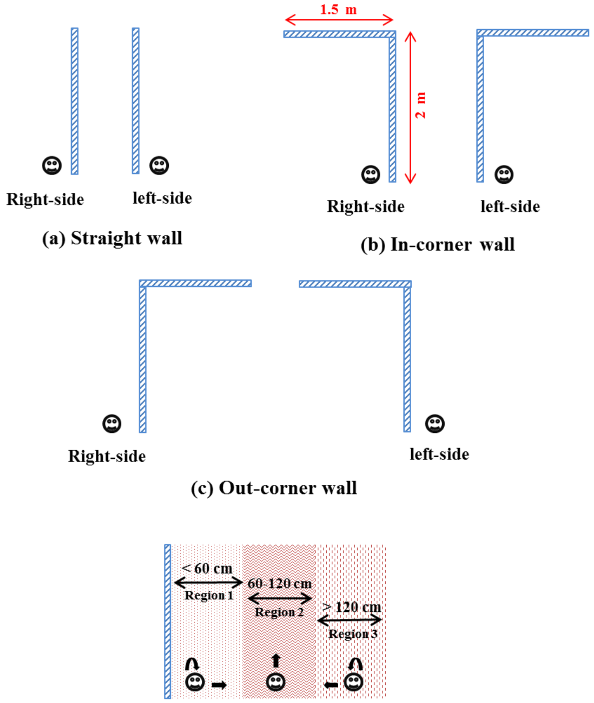


Fig. 4. (a) Eccentric rotating mass vibration motor (Model 310-113 by Precision Microdrives). (b) Tactile display interface. (c) Tactile display position inside the helmet. (d) The Mark II Tactile Helmet.



(a) Straight wall

(b) In-corner wall

(c) Out-corner wall

(d) User's distance from virtual wall: Region 1: <60cm, Region 2: 60-120cm, Region 3: >120cm

Fig. 5. Schematic of the virtual walls and the user in the right and left side of them.

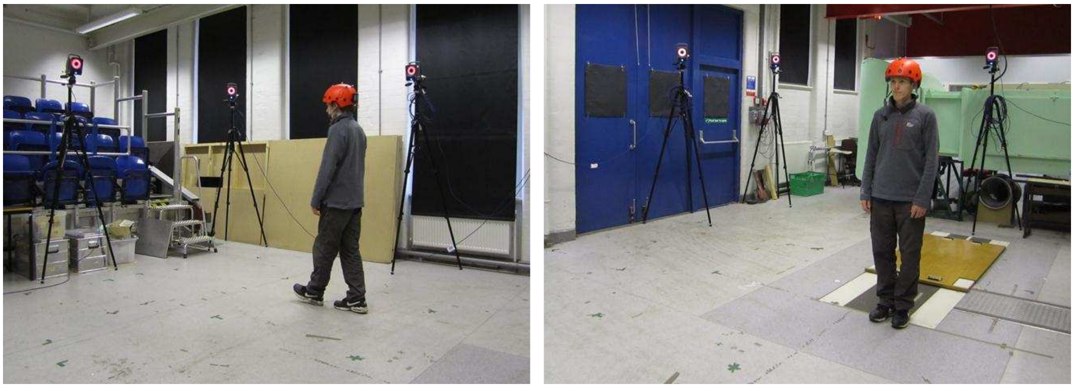


Fig. 6. Experimental environment: 3x5 m^2 free space. A volunteer is walking along a virtual wall in the capture room.

capture system.

3.2.2 Experimental Set-up

To create an environment in which to explore a tactile language relevant to such settings, we used virtual walls to simulate the challenge faced by a firefighter seeking to follow walls within a building. Users navigated in a space of 3x5m^2 relative to three different virtual walls on either their left or right hand side as illustrated in Fig. 5. The length of vertical wall was 2 meters and the length of horizontal wall was 1.5 meters. The experiment was performed in a motion capture room at the Sheffield Robotics laboratory in the UK. A picture of this experimental set-up is show in Fig. 6.

3.2.3 Tracking System

We used a motion capture system (Vicon) consisting of ten cameras and reflective markers, as a precise optical marker tracking system to instantaneously measure the user's position and orientation. The cameras are connected to the controlling hardware module which is simultaneously connected to the host PC through a Gigabyte Ethernet interface. The Vicon Tracker as the software on host PC enables us to view and track global position values and the global rotation values of the object within the capture room. Furthermore, the Vicon DataStream created by the Vicon Tracker software streams in real time to third-party software such as MATLAB on the host PC. Finally, the tactile command is generated and sent wirelessly to the helmet to navigate the user in the capture room. The vibrotactile helmet, whose motion is to be captured by cameras, has five reflective passive markers attached to its surface (Fig. 4d). Fig. 7 shows the 3D perspective of the capture room from the Tracker software and a screen shot of the 3D perspective of the helmet as an object in the Tracker software.

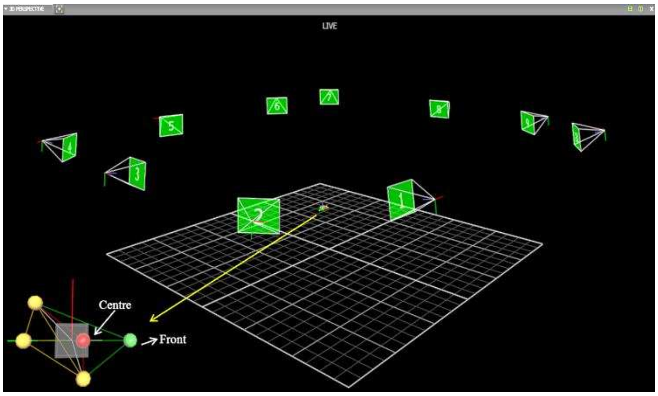


Fig. 7. 3D perspective of the capture room from the perspective of the Vicon tracker software [40] and representation of the helmet as an object within the capture room (bottom left). Ten cameras (green boxes) cover the experimental environment with the size of 3x5 m^2.

3.3 Procedure

3.3.1 Design

We employed a within-subjects repeated measures design in which we tested all four possible combinations of the two presentation modes and command types, giving the following four conditions: *recurring continuous* (RC), *recurring discrete* (RD), *single continuous* (SC), and *single discrete* (SD) commands.

3.3.2 General Procedure

At the beginning of the experiment, each participant was invited into the motion capture room and asked to put on the Tactile Helmet. Participants were told that they would be using vibrotactile commands, relayed through the helmet, to follow a path at a fixed distance relative to a virtual wall. It was explained that the vibrotactile commands would help them to stay on course either by turning to the left or right or by maintaining a forward path. The participants were instructed to follow the commands as closely as possible. A short training session was then provided to familiarize the participants with the tactile language, and with the experimental set-up. At this stage, each of the vibrotactile commands was presented sequentially and the experimenter explained the required response to each command. Finally, the participants were asked to keep their heads oriented in the direction of travel while walking and to avoid making unnecessary sideways head movements.

Before the experiment, the participants performed five practice trials. During the experiment, subjects were asked to wear headphones playing white noise to mask the sound created by the tactors. In each trial, the participant started from a fixed position in the motion capture room and navigated with respect to a virtual wall either to the left or right hand side. Since the walls were virtual, they were permitted to move with their eyes open. Subjects were allowed to rest after each trial and started the next trial whenever they were ready.

In total, each participant performed 72 trials (3 different virtual walls x 2 for left & right hand wall-following x 4 types of haptic command x 3 repeats) in a pseudo-random order. After completing all trials, subjects were given a questionnaire consisting of fifteen Likert-type [41] scales, where for each question then provided a rating of between 1 (“strongly disagree”) and 7 (“strongly agree”). As shown in Table 1, responses assessed the extent to which partipants considered the helmet to be comfortable and easy to use and vibration motors to be irritating, and, for each of the four conditions whether the commands were considered to be (i) easy to distinguish, (ii) effective for navigation along the virtual wall, and (iii) provided a comfortable and tolerable experience. The maximum duration of the experiment was approximately one hour.

3.3.3 Procedure within a Trial

Throughout each trial the user’s position and orientation was obtained from the motion capture system and mapped into one of three regions relative to the nearest virtual wall (Fig. 5d) in order to calculate the haptic commands that were relayed to the helmet.

Region 1, less than 60 cm. In this region the user was too close to the wall and needed to turn away from it. In this case, the user's head orientation was checked and then the turn left/right command activated to encourage the user to rotate around his/her self (left/right) until the go-forward command was received. By following these instructions the user should enter region 2.

Region 2, between 60 and 120 cm. In this region the user was within a “good” range of values, and could go straight. In this case, the go-forward command was activated if the user’s orientation value was within the range of a predetermined threshold, otherwise the turn left/right command was activated to rotate the user toward that threshold.

Region 3, greater than 120 cm. In this region the user was too far from the wall and needed to turn towards it. As in region 1, the turn left/right command was activated and the user encouraged to rotate around his/her self until the go-forward command was received. By following these instructions the user should enter region 2.

As an illustration, Fig. 8 shows tracked positions (black dash line) and orientation (red arrow) of one participant while walking along an out-corner wall. This experiment started from region 2 (between 60 and 120 cm) and the user therefore initially received the go-forward command. When the user passed the vertical wall, the turn left command was activated and the user rotated until the go-forward command was triggered. By following this command, the user reached the area of the horizontal wall. Here, the user was too close to the wall and needed to turn away from it, so the turn-right command was activated. The user continued to navigate following the different commands until the finish point was reached where all of the vibration motors were activated simulatenously to indicate the end of the experiment.

3.3.4 Dependent Variables

The following objective measures of the effectiveness of the haptic commands were calculated:

- **Recognition accuracy (%)** defined as the percentage of correct recognition of tactile commands. We classified a head orientation of greater than or equal to 15 degrees (relative to the motion capture origin) as constituting a turn to the left or right and an orientation of less than 15 degrees as constituting forward motion.
- **Reaction time (s)** defined as elapsed time be-

TABLE 1
USERS’ EXPERIENCE EVALUATION

Questions		Median	SD
Q1	The helmet was comfortable.	5	1.1
Q2	It was easy to move while wearing the helmet.	6	1
Q3	The vibration motors were noisy and irritating.	4	0.9
Q4	RC command was easy to distinguish.	6	0.7
Q5	RD command was easy to distinguish.	5	0.9
Q6	SC command was easy to distinguish.	5	1.2
Q7	SD command was easy to distinguish.	5	1.3
Q8	RC command was effective to navigate you along the virtual wall.	6	0.5
Q9	RD command was effective to navigate you along the virtual wall.	5	1
Q10	SC command was effective to navigate you along the virtual wall.	5	1.1
Q11	SD command was effective to navigate you along the virtual wall.	5	1.1
Q12	RC command was comfortable.	5	1.2
Q13	RD command was comfortable.	5	0.9
Q14	SC command was comfortable.	4	1.1
Q15	SD command was comfortable.	4	1.2

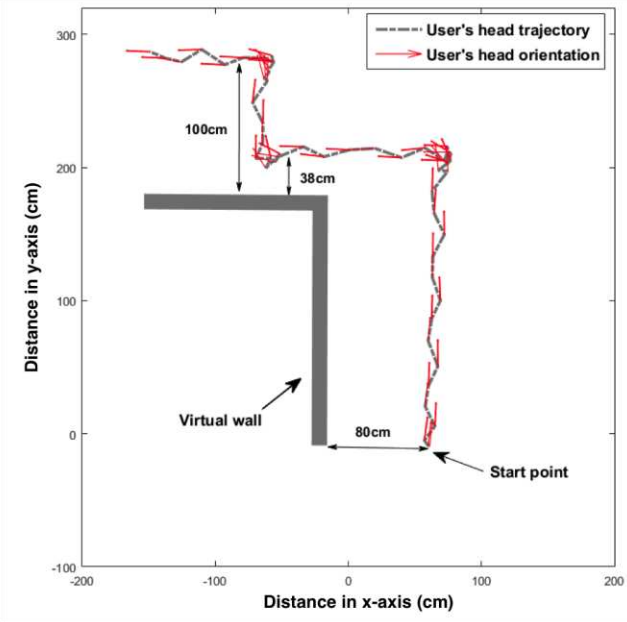


Fig. 8. An example of left out-corner wall following of one subject. Dash lines show the user's head trajectory and arrows show the user's head orientation while receiving the related command.

tween finishing the display of the vibrotactile command and the moment that subject has turned left /right for turning commands and has walked toward forward direction in go-forward command.

- **Average walking speed (ms^{-1})** defined as the total distance travelled along the virtual walls (m) divided by the elapsed time (s).
- **Smoothness of the user's trajectory (cm)** defined as the mean absolute deviation (MAD) of the path followed by the user compared to an ideal path following parallel to the virtual walls at a fixed distance.

4 RESULTS

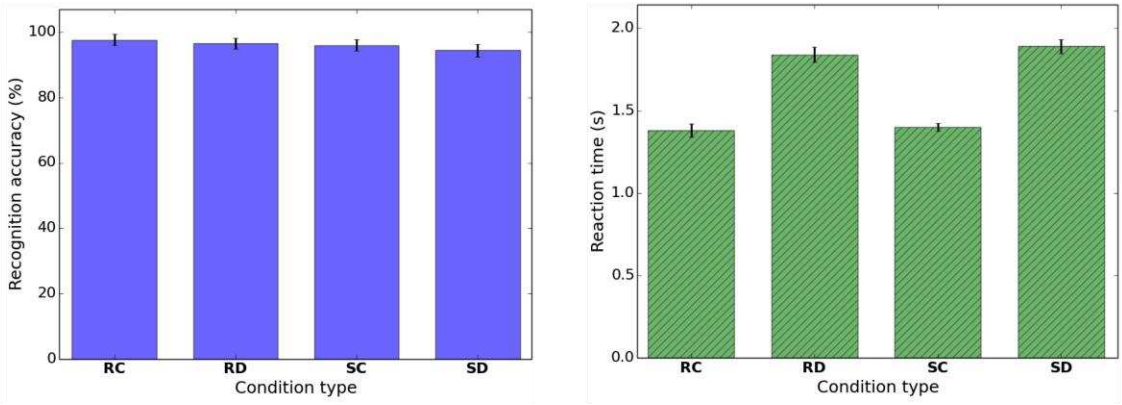
An alpha value of 0.05 was chosen as the threshold for statistical significance, all reported p-values are two-tailed. A Shapiro-Wilk test showed that data were normally distributed. We employed a two-way repeated measure Multivariate analysis of variance (MANOVA) to teast our objective measures. Box's Test indicated that assumption of equality of covariance matrices was met (p = 0.15). Levene's test showed that the assumption of equality of error variance was met (p > .05 for all the dependent variables). Measures of command recognition accuracy, reaction time to the tactile command, smoothness of the user trajectory, and walking speed are shown in Fig. 9 and 10 repectively for each of the four conditions. We next summarise results for each of these quantitative measures in turn followed by the subjective reports (Likert-type scales).

A two-way repeated measure MANOVA showed no significant interaction effect between command type and command presentation on the combined dependent variables, F (4, 14) = 1.622 , p = 0.224 ; Wilks' Λ = 0.683.

Overall recognition accuracy rate from a total of 1296 trials was 96% with a standard deviation of 8%. A two-way repeated measure MANOVA revealed no significant main effect on recognition accuracy of command presentation mode (F (1, 17) = 1.735, p = 0.205) or command type (F (1, 17) = 3.476, p = 0.08).

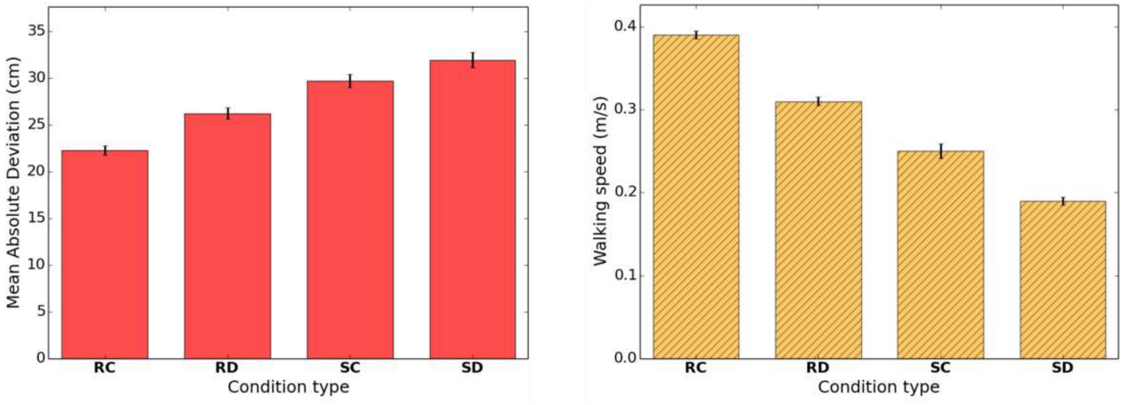
Mean reaction time from a total of 1296 trials was 1.63 s (standard deviation: 0.31s). Two-way repeated measure MANOVA showed a significant main effect on reaction time for command presentation mode (F (1, 17) = 122.56, p < 0.001) but no main effect for command type (F (1, 17) = 0.812, p = 0.325). As can be seen in Fig. 9b, reaction times were fastest when commands were presented continuously compared to when they were presented discretely. Additionaly, we found that reaction time differed significantly between *turn-left, turn-right*, and *go-forward* commands (F (1.949, 33.140) = 159.957, P < 0.0005). Post hoc tests using the Bonferroni correction revealed that there was a significant difference in reaction time between the *go-forward* and *turn-left* commands (p = 0.0005), and between the *go-forward* and *turn-right* commands (p = 0.0005), but no significant differences between *turn-left* and *turn-right* (p = 0.217).

We next evaluated the effectiveness of the commands according to the smoothness of the user's trajectory as measured by the Mean Absolute Deviation (MAD) from the ideal path. A two-way repeated measure MANOVA found a significant main effect on MAD score for both



(a) (b)

Fig. 9. (a) Recognition accuracy (%) for each condition. (b) Reaction time (s) for each condition. Error bars indicate standard error.



(a) **(b)**

Fig. 10. (a) Smoothness of user's trajectory measured by Mean Absolute Deviation (MAD). (b) Walking speed for each condition. Error bars indicate standard error.

command presentation mode F (1, 17) = 22.362, p < 0.001 and for command type F (1, 17) = 80.012, p < 0.001). Fig. 10a shows the MAD for each condition, indicating that MAD increases from RC to SD command, that is, participants navigated with the lowest route deviation using RC (Recurrent Continuous) command. This same pattern is evident in Fig. 11 that shows the trajectory of the users along the out-corner virtual walls for each of the four conditions.

Average walking speed was also calculated for each condition. A two-way repeated measures MANOVA found a significant main effect on speed for command presentation mode (F (1, 17) = 75.177, p < 0.001) and for command type (F (1, 17) = 128.402, p < 0.001). As shown in Fig. 10b, users had maximum walking speed with the RC command (0.39 m/s) suggesting that subjects were more confident in responding to tactile commands in this condition.

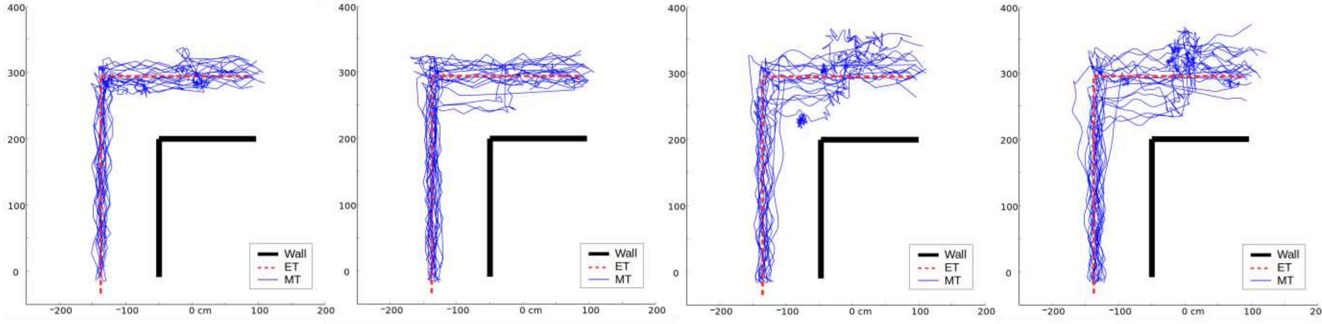
In the Likert-scale data, participants reported that helmet was comfortable, that it was easy to move while wearing the helmet, and that the vibration motors were not irritating. A Friedman test revealed that there was a significant difference between the four conditions (RC, RD, SC and SD) for ease of distinguishability, χ^2 (3) = 19.075, p < 0.001 and effectiveness for navigation χ^2 (3) = 32.813, p < 0.001, while no significant differences were found for comfort (χ^2 (3) = 6.025, p = 0.17). Post hoc analysis with Wilcoxon signed-rank test was conducted with a Bonferroni correction, resulting in an adjusted significance level (p = 0.0083, calculated by utilizing Sidak Correction [42]). As it is shown in Table 2, for ease of distinguishability, there was a significant difference between RC and RD, RC and SC, and between RC and SD, while no significant difference was found between RD and SC, RD and SD, and SC and SD. In terms of effectiveness for navigation, there was a significant difference between RC and RD, RC and SC, and RC and SD, while no significant difference was found between RD and SC, RD and SD, and SC and SD.

In sum, subjects reported that recurring continuous commands (RC) were the easiest to distinguish and the most effective for navigation. This agrees with the quantitative measures, which showed that RC command led to faster and more accurate navigation compared to the other commands.

6 DISCUSSION AND CONCLUSION

This research builds on our previous work [3] by developing a simplified 'tactile language' for communicating navigation commands to a head-mounted vibrotactile sensory augmentation prototype. Our results provide new evidence that head-mounted haptic displays have promise as an intuitive means of displaying navigation signals and can improve spatial awareness in low visibility environments.

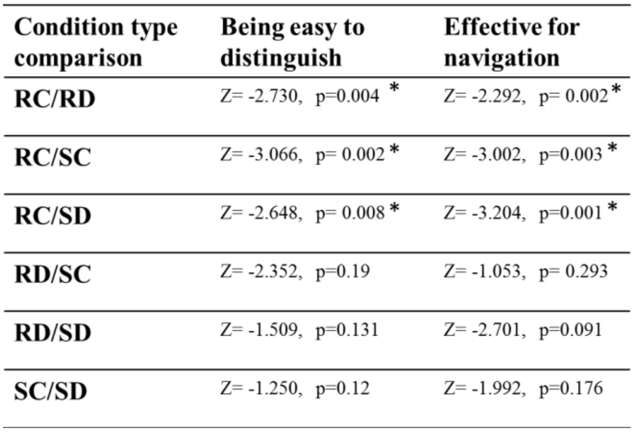
In our experiment, overall recognition accuracy for all commands was high, and did not distinguish between different modes and types of tactile command. However, consistent with our hypothesis, we found that tactile commands that exploit continuous signals creating an apparent motion effect were more effective in indicating desired movement



(a) **(b)** **(c)** **(d)**

Fig. 11. User's trajectory with: (a) Recurring Continuous (RC), (b) Recurring Discrete (RD), (c) Single Contiuous (SC), and (d) Single Discrete (SD) command. Blue lines show user's Motion Trajectory (MT) and red dash lines show user's Expected Trajectory (ET).

TABLE 2
POST HOC TEST FOR CONDITION TYPES COMPARION IN TERMS OF BEING EASY TO DISTINGUISH AND EFFECTIVE FOR NAVIGATION



Condition type comparison	Being easy to distinguish	Effective for navigation
RC/RD	Z= -2.730, p=0.004 *	Z= -2.292, p= 0.002*
RC/SC	Z= -3.066, p= 0.002*	Z= -3.002, p=0.003 *
RC/SD	Z= -2.648, p= 0.008*	Z= -3.204, p=0.001 *
RD/SC	Z= -2.352, p=0.19	Z= -1.053, p= 0.293
RD/SD	Z= -1.509, p=0.131	Z= -2.701, p=0.091
SC/SD	Z= -1.250, p=0.12	Z= -1.992, p=0.176

direction than discrete patterns of stimulation. This was shown in the measured reaction times to command signals, in the smoothness of the user trajectory and in walking speed. We also found that navigation was more effective when commands are presented repeatedly, rather than only when a change of movement direction was needed. We found that the helmet was well tolerated by users, and interestingly, that users did not specifically report the recurring stimuli as being particularly irritating or burdensome.

These results were obtained in a lab setting for a specific structured environment and should be viewed with caution in considering their application to everyday enviroments. For instance, in an environment with many distractions, such as a busy street or building, repeated commands could be more distracting as previously suggested by [43]. Nevertheless, we hope that these results will be useful in formulating the design of tactile languages for future haptic augmentation devices for use in real-world settings. One outstanding issue, which should be addressed in future studies, is the potential for separate movement of the head and body. In the current study, subjects were instructed to keep their head aligned with their body direction, however, in general navigation behavior, head movement may be partially decoupled from the movement of the torso (for instance, looking around to explore a room) and this could reduce the utility of the specific tactile command set tested here. In ongoing work we are examining how our tactile language can be used to convey navigational signals calculated directly from the ultrasound sensors of the Tactile Helmet in response to real-world surfaces and obstacles. We believe that this research can build on the progress made here in identifying language tokens that are informative, minimize information overload, and that are intuitive to understand and use.

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Hamideh Kerdegari received her MSc degree in Computer and Communication System Engineering from the University Putra Malaysia (UPM) in 2012. She is currently working toward the PhD degree at the University of Sheffield, UK on sensory augmentation system for navigation in low visibility environments. Her research interests are in wearable computing, human-computer interaction and haptic interfaces.

Yeongmi Kim received her MSc and Ph.D. degree in the Mechatronics department Gwangju Institute of Science and Technology (GIST), Republic of Korea in 2006 and 2010, respectively. She worked as a postdoctoral fellow at the Rehabilitation Engineering Laboratory, ETH Zurich, in Switzerland and at the Interactive Graphics and Simulation Group, the University of Innsbruck in Austria. Currently she is a lecturer at the department of Mechatronics, Management Center Innsbruck, the University of Applied Sciences in Austria. Her research interests are in assistive technology, human-computer interaction, psychophysics, and haptic interfaces.

Tony J. Prescott received a BSc in Psychology from the University of Edinburgh, an MSc in Applied Artificial Intelligence from the University of Aberdeen, and PhD in Machine Learning from the University of Sheffield. He is currently Professor of Cognitive Neuroscience at the University of Sheffield and Director of Sheffield Robotics, an inter-disciplinary research institute with over 100 active researchers. He has broad research interests in the field of human-machine interaction, and natural and artificial haptics.