A Comparative Study of Tactile Representation Techniques for Landmarks on a Wearable Device

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ABSTRACT
Wearable tactile navigation displays may provide an alternative or complement to mobile visual navigation displays. Landmark information may provide a useful complement to directional information for navigation, however, there has been no reported use of landmark information in tactile navigation displays. We report a study that compared two tactile display techniques for landmark representation using one or two actuators respectively. The single-actuator technique generated different vibration patterns on a single actuator to represent different landmarks. The dual-actuator technique generated a single vibration pattern using two simultaneous actuators and different pairs of actuators around the body represented different landmarks. We compared the two techniques on four measures: distinguishability, learnability, short term memorability and user preference. Results showed that users performed equally well when either technique was used to represent landmarks alone. However, when landmark representations were presented together with directional signals, performance with the single-actuator technique was significantly reduced while performance with the dual-actuator technique remained unchanged.

Author Keywords
Tactile interface, tactile feedback, tactile representation of landmarks, tactile representation of direction, pedestrian navigation, wearable interface.

ACM Classification Keywords
H.5.2. User Interfaces: Haptic I/O.

General Terms
Experimentation, Measurement.

INTRODUCTION
Wayfinding can become problematic when one has to find one's way in an unfamiliar environment. Using assistive technologies can help in improving navigation performance [6]. Existing electronic navigation applications deliver information mainly through the visual and audio channels, however, there are many situations where a user's visual and auditory capacities are limited or subject to ambient interference. For example, firemen working in a burning building may have their vision impaired by smoke and their hearing may be overwhelmed by noise. Presenting navigation information via the tactile sense may be an effective alternative or complement to visual and auditory displays in such situations [6].

Research has shown that tactile navigation displays help improve navigation performance, target detection and situation awareness in many operational settings, such as aircraft piloting [4,26], vehicular driving [9,22], boat driving [25,26], pedestrian navigation [6,8,24], situation awareness [4,6], and alerts for command decision making [10].

According to May et al. [15], the two most important pieces of information that navigation guidance systems should provide are directional and landmark information. Direction plays a significant part in navigation completion while landmarks help in building spatial knowledge of the surroundings. In visual- and audio-based pedestrian navigation systems, both types of information are represented, typically as *visual icons* (e.g. arrows and graphic symbols) and as *speech*.

May et al. [15] also suggest that distance information can help provide "approaching" feedback. We did not investigate distance in this study partly because "approaching" feedback does not make sense in the lab setting and, following a more general principle, where there is a large number of factors with potential influence it is often necessary to tease them out in a series of studies, as we have done. Here, we focus on direction and landmark recognition. Distance is a factor in our current field trials but it is worth noting that May et al. [15] concluded that while distance information may play a significant part in vehicular navigation, it is not crucial in pedestrian navigation given the speed of movement.

In tactile-based pedestrian navigation systems, directional information is presented as *tactile icons*, i.e. short vibration signals [22] but there is no reported use of landmark representation in tactile displays. This absence of landmark information in tactile navigation displays may reduce their effectiveness as useful assistive tools that provide data crucial to navigation success [3,15]. This paper reports the evaluation of tactile landmark representation techniques that could work effectively in combination with tactile directional representation techniques that we have previously shown to be effective [19,20].

DESIGN CHALLENGES AND OBJECTIVES

Previous research, e.g. [8,9,19,20,24,25,26], suggests that the waist is an appropriate location for conveying tactile spatial information. In addition, it is large enough to accommodate multiple-location tactile perception compared to other areas such as the wrists, legs and head. In previous studies [19,20], we showed that a wearable device in the form of a waist belt using an point vibration technique to represent directions provided very effective tactile representation of directions for navigation tasks. This paper investigates the effectiveness of combining this technique with complementary tactile landmark representation techniques.

As we aimed to develop a tactile navigation display that can provide directional *and* landmark information, the chosen techniques to represent landmarks must work effectively and be distinguishable from a tactile technique used to represent directions. For this study, we drew on tactile display design frameworks [16] for general guidelines and suggestions; an absolute point vibration technique [22,26] for the design of directional signals; and the heuristic tactile rhythms [11,17,23] for the design of landmark signals. In addition, we assume that the use of tactile displays follows the information processing loop of the Prenav model, consisting of the processes of sensation-perception-decision-action (see [27]).

There are two main approaches to creating informative tactile stimuli: the *abstract* and *symbolic* approaches [14]. Abstract representation focuses on manipulating a stimulus' characteristics, whereas the symbolic approach focuses on the semantic association of stimuli with known metaphors. For example, MacLean et al. [12] designed 36 *abstract* stimuli by systematically varying waveform, amplitude and frequency of vibration signals, while Chan et al. [5] designed a *symbolic* tactile set in which signal patterns were associated with heartbeat and finger-tapping metaphors.

Previous research in tactile navigation (e.g. [22,26]) proposed *symbolic* mapping for the representation of directional information, involving the mapping of a limited set of cardinal and ordinal directions to their associated vibration signals. These signals have commonly been generated using one of two techniques: (1) simulation of straight-line patterns (i.e. pointing arrows) on an array of actuators, e.g. [22]; and (2) an absolute point vibration for each direction in a distributed placement of actuators around the waist, e.g. [26]. Our previous studies [19,20], investigated the performance of the two techniques and their findings underpin our choice of the symbolic absolute point vibration technique used in this paper. Nevertheless, representing direction using an abstract approach may be useful if the sizes of body contact area or device are limited (e.g. see [12]).

The representation of landmarks is even more challenging. Landmarks can be any objects or places on routes that are stationary, distinct and salient [3]. If we were to map landmarks using a *symbolic* approach, appropriate metaphors would require investigation. For example, it might be possible to draw on a shape metaphor, with each landmark signal represented by a simplified form of its shape. However, such an approach would require a different hardware layout, number of actuators and actuator placement (e.g. [1]) from the waist belt approach adopted here. In addition, the numerous landmarks studied in research projects and used in commercial systems are not systematically classified, are highly diverse and are often poorly differentiated. As a result, signal patterns for landmarks and their meaning associations are effectively arbitrary. All these constraints suggest an abstract approach to extending our tactile directional representation technique to include the tactile representation of landmarks.

The design challenges also include the creation of a usable set of tactile icons to be displayed on a device when rendering size is limited [14] and human tactile perception capacity is restricted [17]. An approach to the tactile representation of landmarks therefore requires two steps: the identification of a limited set of appropriate landmarks and the selection of appropriate representation techniques. The number of unique landmarks that could be represented is very large but both Chan et al. [5] and Gallace et al. [7] have suggested that the optimum number is seven. In a previous study [21], we identified a small set of important and generalisable landmark types based on particular navigational purposes proposed by Sorrow and Hirtle [18]: *commuting* (travelling to a familiar destination), *questing* (travelling to an unknown destination), and *exploring* the area. We use that set here.

To create a distinguishable and learnable set of *abstract* tactile stimuli, researchers [5,12,22,23] have suggested that a technique that manipulates tactile signal duration on a single actuator to create a variety of rhythms provides effective results. In this study, we employed the heuristic tactile rhythms proposed by Ternes and MacLean [23].

Another technique that may help the users of a tactile navigation system distinguish direction from landmark signals is to introduce *discontinuity*. Having motivated our objective of investigating representations of direction and landmark type with the waist belt, a technique to introduce discontinuity had to be localised to the waist area. Since any directional signal is generated on one actuator, discontinuity may be achieved by increasing the number of contact points on the body [17], e.g. using a combination of two or more actuators [11]. Although proposed, this technique has not previously been investigated, therefore, in this study we examined the use of two actuators to create unique tactile stimuli.

To summarise, this study investigated the following tactile landmark representation techniques: (1) manipulating the signal rhythms, and (2) increasing the number of body contact areas (i.e. increasing the number of actuators used to display information). In this paper, we refer to the two techniques as the single-actuator and dual-actuator techniques respectively. Both techniques for tactile representation of landmarks were presented alone and together with tactile directional signals.

EXPERIMENTAL DESIGN

The tactile display took the form of a waist belt with embedded actuators. For the set of landmarks we drew on our previous research [21]. This research suggested that the most suitable small set of landmarks for our prototype tactile landmark representation should be: mall and market, religious place, tourist attraction, public transportation, bridge, monument and memorial, and railway station. These findings corroborated the results of previous research suggesting that there are some generic landmarks that will be appropriate across different environments [2]. To represent directions, we used an established technique, generating an absolute vibration in a corresponding location on the user's body [25]. We evaluated novel tactile representation techniques for the landmarks, both alone and in combination with the directional signals.

Equipment

The main equipment for our experiment consisted of controllers, motors, and an associated switch circuit. The main controller unit was built using two 0/16/16 interface kit controllers, manufactured by Phidgets (www.phidgets.com). Vibrating points, i.e. actuators, were built using VPM2 vibrating disk motors, manufactured by Solarbotics (www.solarbotics.com). The actuators were 1 cm in diameter, which was small enough to be easily embedded in clothing. The motors were connected to the controller's digital output channels. Motor vibration was powered by a 6v battery and controlled by an additional custom-built controller switch.

The prototype was connected to an HP Compaq tablet PC via a USB port. The control software was written using the programming language Java under the Microsoft Windows environment. When the control switch and interface controllers received an input from the tablet PC, corresponding tactile stimuli patterns were generated. The system performed this by turning the output channels of the interface controllers on and off very quickly.

The wearable device consisted of 8 actuators mounted in a waist belt (Figure 1). It was worn around the participant's waist over light clothing. Following previous research, e.g. [24,26], the actuators were adjusted to account for participants' varying body shape and size, to ensure that each actuator was located in the optimum location and to avoid any bias in direction perception towards the midsagittal plane of the body (see [25]).

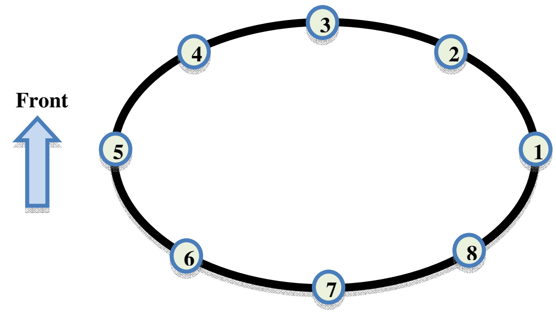

Figure 1. The Waist Belt Prototype (motor number 3 is the front centre actuator.)

Landmark Stimuli Design

The Single-actuator Technique

For the single-actuator technique, we used a set of tactile stimuli proposed by Ternes and McLean [23]. They were designed by using *eliminative heuristics and constraints,* a principled validation methodology based on perceptual optimization [23]. They have been systematically designed, tested and proved to be perceptible and distinguishable. Each signal in a set contains different *note length* and *evenness*. Rhythm is defined as a repeated monotone pattern of variable-length notes, arranged relative to a beat (4/4) and played at a set tempo, manipulated by changing the length, number, or gaps between notes [23]. Essential elements of the heuristics are that signals: (1) are monotone, (2) have a gap between successive notes, (3) have 2 second duration, (4) contain repetitions, and (5) to be perceivable must last at least 1/16 of the 500 ms interval (31.25) plus the same-length break; this signal is called an 'eighth' (1/8) note. The set contains five note lengths: 1/8 (62.5 ms), ¼ (125 ms), ½ (250 ms), ¾ (375 ms) and whole (500 ms). Each note length includes a 62.5 ms gap except the 1/8 note which has a 31.25 ms gap. Positive selection heuristics, i.e. a combination of different note lengths (including gaps between them), allows the generation of distinguishable tactile patterns. For example, a 2-second short stimulus contains a number of repetitions of ¼ notes; a 2-second long stimulus contains repetitions of ¾ notes.

The initial set of Ternes and MacLean's heuristic tactile rhythms contains 21 signals. In the original studies [23], participants experienced vibrations through their hands and a stylus. In order to make sure that these stimuli were still distinguishable when displayed on the waist area, we ran pilot sessions with four participants. Results showed that five out of 21 rhythms were clearly distinguishable (signals S1 to S5 in *Figure 2*). We further followed the positive selection heuristics by testing a combination of two of the five rhythms. As a result, signal S6 is a combination of S2 and S3; Signal S7 is a combination of S5 and S2. The final set of the most distinguishable rhythms is shown in Figure 2.

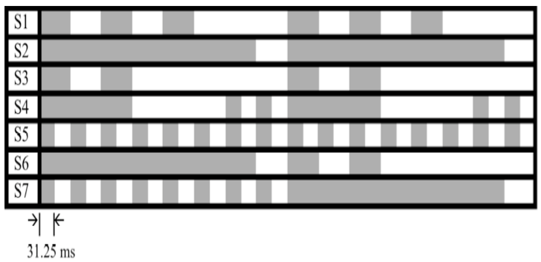

Figure 2. Single-actuator Landmark Signals. Each row represents one bar, to be represented 2 times as a 2-second stimulus. Each note contains vibration on- (grey) and off-time (white) that separates it from the next.

The Dual-actuator Technique

In contrast to the single-actuator technique which used different vibration patterns to represent different landmarks, our dual-actuator technique used the same vibration pattern for all landmarks. The pattern used was the same as that for directional signals: a 1.2 second stimulus consisting of 12 repetitions of a 50-millisecond pulse and inter-pulse. The different landmarks were represented by different combinations of actuators simultaneously providing the signal. Schiffman [17] suggested that increasing the contact area of tactile stimuli would result in better perception and distinguishability among different types of information. Loomis [11] suggested that an effective approach to this would be to use multiple contact points, however, an optimum number was not suggested. Our initial pilot testing found several possible combinations to be indistinguishable from each other. We omitted these from further study and ran pilot studies with 4 participants using the remaining combinations to find the optimum number of simultaneously activated actuators to represent our 7 landmarks. Tested alternatives included (a) pairs of non-adjacent actuators, (b) pairs of adjacent actuators, (c) three non-adjacent actuators, (d) three adjacent actuators, (e) four non-adjacent actuators, and (f) five adjacent actuators. We measured accuracy, mental demand, physical demand, temporal demand, effort, level of frustration, and both distinguishability amongst the landmark signals themselves and distinguishability from directional signals.

Results from this pilot study suggested that the best arrangement was two non-adjacent actuators. This alternative received high scores on distinguishability and accuracy performance, and low scores on mental, physical and temporal demand and effort required. It should be noted here that for the waist belt device with 8 actuators, the more actuators that were simultaneously activated, the more confused participants were.

Assuming for ease of referring to the angles that the belt is in the form of a circle, the final list of actuator pairs included: (see Figure 1 for referents of actuator numbers)

- 180° actuator pairs (3-7, 2-6, 1-5 and 4-8);
- 90° actuator pairs (1-3, 2-4, 3-5, 4-6, 5-7, 6-8, 7-1 and 8-2);
- 135° actuator pairs (1-4, 2-5, 3-6, 4-7, 5-8, 6-1, 7-2 and 8-3).

Stimuli code	Vibrated Actuator Number (see Figure 1 for reference)	Direction
B1	1	East
B2	2	Northeast
B3	3	North
B4	4	Northwest
B5	5	West
B6	6	Southwest
B7	7	South
B8	8	Southeast

Table 1. Directional Stimuli: 12 repetitions of signals at 50-millisecond pulse and inter-pulse duration.

Directional Stimuli

Following existing suggestions [22] and guidelines [16], each directional tactile stimulus involved actuation of one motor and consisted of 12 repetitions of signals at 50-millisecond pulse and inter-pulse duration, giving a 1.2 second stimulus (see Figure 3). The eight directions represented included: *east, west, north, south, southeast, southwest, northeast,* and *northwest*. Each actuator represented a direction based on its location around the participant's waist, with *north* represented by the front centre actuator (see Table 1). For details on the design, generation and use of the directional signals see [19,20].

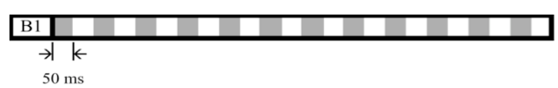

Figure 3. Direction Signals. A row represents one bar, producing a 1.2-second stimulus. Each note contains vibration on- (grey) and off-time (white) that separates it from the next.

Participants

There were 20 participants: 10 males and 10 females with an average age of 29 (SD = 4.94, range 20-40 years). None of the participants reported irregularity with tactile perception around their waist at the time of the study. Participants' average waist size was 78 centimetres (cm) (SD = 9.93, range 62-99 cm). We established from pre-test questionnaires that all participants understood the concept of "direction" and "landmark" and had no difficulties identifying them. Each of them received a 5 British pounds monetary incentive at the end of the experiment.

Experimental Conditions

Our experiment had two independent variables: representation technique (one actuator or two) and the presence or absence of directional signals. The dependent variables were response time (in ms) and accuracy performance. Response time refers to the onset of the stimulus to the onset of the response, including the movement time. The experiments were divided into two stages with five conditions (see Table 2), 2 of the stage 1 conditions being repeated in stage 2. Each participant ran all five conditions. In the first stage, we measured distinguishability, learnability and users' preferences. The first condition was a control condition in which only directional signals were presented. In conditions 2 and 4, only landmark signals were presented. In conditions 3 and 5, we presented directional signals together with landmark signals.

In stage 2, we measured the short term memorability of each type of signal. Approximately 30 minutes after participants finished conditions 2 and 4, we interviewed them and asked them to complete a set of questionnaires. They then repeated conditions 2 and 4. Both response time and accuracy performance were measured and compared with previous results. Since our focus for the study was on landmark representation rather than directional representation, we did not repeat C3 and C5 during stage 2.

Hypotheses

The vibration signals for directions are symbolically straightforward. They involve symbolic mapping of a limited set of cardinal and ordinal directions to their respective vibration signals on corresponding parts of the body. In this and other research (e.g. [26]), there was an absolute point vibration for each designated direction on a distributed placement of actuators around the waist. The representation of landmarks is more challenging. In the navigation design domain, the large set of landmarks studied in research papers and used in commercial systems are not systematically classified and differentiated. As a result, signal patterns for landmarks and their meaning associations are effectively arbitrary. Hence, it was hypothesised that *learning time required for landmark representations will be significantly longer than those for directions* (**H1**) as participants have to learn the association between the signal and what it represents.

Previous research, e.g. [13,22], has suggested that humans can recognize 4-7 abstract tactile patterns and associate them with predefined meanings. We hypothesized that *participants will be able to recognize 7 landmarks with at least 80% accuracy in at least 1 non-control condition, either in condition 2 or 4* (**H2**). Based on the same previous research, we predicted that *participants will be able to distinguish landmark from directional signals in conditions 3 and 5* (**H3**).

However, in conditions 3 and 5 where we present directional signals together with landmark signals, we hypothesised that *the presence of direction signals will reduce participants' performance in recognizing landmark patterns* (**H4**). This is due to the constraints on human memory and attention capacity [17]. In both conditions, participants had to attend to directional signals then to landmarks and then provide responses.

Condition	Description	Stage
C1	Direction only	1
C2	Landmark (single-actuator)	1
C3	Direction + Landmark	1
C4	Landmark (dual-actuator)	1
C5	Direction + Landmark	1
C2r	Landmark (single-actuator)	2
C4r	Landmark (dual-actuator)	2

Table 2. Experimental Conditions

While many researchers (e.g. [22,23]) have concluded that using different signal rhythms will effectively make stimuli distinguishable, the combination of two simultaneous actuator vibrations may make the iconic stimuli for landmarks unique [11,17] and clearly distinguishable from directional stimuli. With the single-actuator technique, signal patterns could be generated on an actuator that has just generated a direction signal, so participants might suffer from tactile adaptation, i.e. continued pressure stimulation that may result in a decrease of sensory experience [17]. As a result, they might fail to distinguish between different signal types. Using two actuators to represent landmarks introduces 'discontinuity' [17] that could help to make landmark signals perceptibly different from direction signals. Hence, we predicted that *the dual-actuator technique will produce better performance than the single-actuator technique when representing landmarks in a waist-belt tactile display that provides both directional and landmark information* (**H5**).

Experimental Procedures

Participants were given training to learn the signal patterns and their associations. In phase 1, each vibration stimulus was presented twice with its associated meaning, direction or landmark. Phase 2 allowed participants to memorise the signals for 4 minutes. By clicking with a stylus on direction and landmark icons on a tablet PC screen, the participant generated the associated vibration signals. In phase 3, vibration signals were generated randomly and participants had to select the associated direction or landmark icon. They received feedback for every selection that they made. Signals were repeated until the correct selection was made. In the final phase, participants were presented with vibration signals and again they selected the associated direction or landmark. In this phase, participants were given a performance score only at the end of each set. Training stopped when participants scored over 71% or had been through 4 repetitions of the entire 4-stage process.

Each participant then completed all five conditions in stage 1 and repeated conditions 2 and 4 in stage 2.

Stage 1 – Measuring learnability and distinguishability

In stage 1, we investigated whether performance with the two tactile representation techniques for landmarks differed in terms of learnability and distinguishability. The system generated tactile stimuli and participants identified perceived directions or landmarks by selecting corresponding icons on a touch screen tablet PC. We measured: perceived directions, perceived landmarks and response time.

All participants started with C1. The order of experimental conditions C2-C5 was counterbalanced. Vibration signals in all conditions were generated in a pseudo-random order. In addition, landmark associations with vibration signals were systematically shuffled. Vibration signals and meaning associations were counterbalanced amongst participants.

In the control condition C1 (direction only), participants experienced 3 repetitions of 8 directions. In C2, C3, C4, and C5, participants experienced 21 signals (i.e. 7 landmarks x 3 repetitions) for each condition. Repetitions were introduced to mitigate the possibility that participants might make correct responses by chance.

In C2 and C3, the tactile single-actuator technique was used to generate landmark signals. In C2, only landmark stimuli were generated. In C3, the system generated a random directional signal, paused for 2 seconds, and then generated a landmark signal on the same actuator.

In conditions C4 and C5, the dual-actuator technique was used to generate landmark signals. In C4, landmark stimuli were generated on pairs of actuators. Of the seven landmark signals, four were generated using the 180° distance pairs. The other three pairs were a mix of pseudo-random 90°, and 135° pairs, counterbalanced on the left and the right sides and front and back of the body. We randomized the non-adjacent pairs and sought the optimum distance that provided the best performance. In C5, the system generated a random directional signal, paused for 2 seconds, and then generated a landmark signal on a pair of actuators.

Each stimulus was presented only once. When each tactile stimulus had been generated, participants were required to indicate (as “quickly and accurately” as they could) to which direction or landmark they thought it corresponded, by selecting one of the associated icons on the tablet PC. The computer logged response time. Each session was followed by a short questionnaire capturing subjective data on distinguishability and learnability. When participants had finished all 5 conditions, they were asked to answer questions comparing the one- and dual-actuator techniques. They were also asked to reflect on their experiences with tactile communication. The final questionnaire took around 5-10 minutes to complete.

Stage 2 – Measuring memorability

In stage 2, we aimed to compare the two tactile representation techniques for their short term memorability. Stage 2 took place after participants completed distraction tasks, i.e. answering a questionnaire and discussing their experience of the experiment, approximately 30 minutes after they had been exposed to each type of landmark vibration stimulus.

Participants were asked to repeat conditions 2 and 4 in the same order that they had carried them out in stage 1. In each condition, each stimulus was presented only once. When each tactile stimulus had been generated, participants were required to indicate (1) the associated landmark by selecting an icon on the tablet PC and (2) their level of confidence in their answer on a 1 to 5 likert scale (1 being very unconfident and 5 being very confident). The computer logged response time.

RESULTS

Learnability

During training, participants learned the vibration signals and their associated meanings. Tables 3, 4 and 5 present quantitative results on learnability in terms of average number of rounds, average number of signal trials, and average training duration in each training phase.

Training phase	Direction	Single-actuator	Dual-actuator
Phase 1	1.2	1.65	1.65
Phase 2	1.05	2.40	2.05
Phase 3	1	1	1
Phase 4	1.05	2.55	2.15
Total	4.3	7.6	6.85

Table 3. Training Requirements: Average Number of Rounds.

Training phase	Direction	Single-actuator	Dual-actuator
Phase 1	10	12	12
Phase 2	15	54	61
Phase 3	8	7	7
Phase 4	8	18	15
Total	41	91	95

Table 4. Training Requirements: Average Number of Signals.

A repeated-measures ANOVA (sphericity assumed) indicated that overall training requirements for all representation techniques were significantly different: number of training rounds $F(2, 38) = 16.93$, $p < .01$, training duration $F(2, 38) = 26.07$, $p < .01$ and number of signal trials $F(2, 38) = 20.91$, $p < .01$. Statistical data for each training phase can be found in Table 6.

Training phase	Direction	Single-actuator	Dual-actuator
Phase 1	00:45	00:56	01:01
Phase 2	00:36	01:26	01:38
Phase 3	00:39	01:09	00:55
Phase 4	00:39	00:45	00:39
Total	02:40	04:17	04:14

Table 5. Training Requirements: Average Duration (min:sec).

Training phase	Duration	No of Rounds	No of Signals
Phase 1	7.03*	7.03*	2.47
Phase 2	26.49*	11.07*	19.91*
Phase 3	6.11*	*n/a*	*n/a*
Phase 4	11.89*	12.78*	10.06*

Table 6. Repeated-measures ANOVA Results for Training Requirements: * indicates that the result is significantly affected by representation technique $F(2, 38)$, p < .01.

Post-hoc pairwise comparisons (Bonferroni adjustment) indicated that training requirements for both landmark representation techniques were significantly greater than those for the directional technique in number of training rounds (both $p < .01$), training duration (both $p < .01$), and number of training signals (both $p < .01$). No significant difference was found in training duration, rounds and number of signal trials between the one- and dual-actuator techniques (all three $p > .05$). These results were congruent with our expectation that learning to associate landmark signals with their meanings should require more effort than learning directions since meaning associations for landmarks are completely arbitrary. Hence, we accept *H1*.

Performance and Distinguishability

The repeated-measures ANOVA (sphericity assumed) showed that the time to complete each condition was not significantly affected by the type of representation technique, $F(2, 38) = 1.60$, $p > .05$. However, different techniques significantly affected accuracy performance, $F(2, 38) = 3.82$, $p < .05$. Post-hoc pairwise comparison (Bonferroni adjustment) revealed that participants performed significantly better with directional identification than with both landmark techniques, (both $p < .05$). There was no difference in accuracy performance between the landmark one- and dual-actuator techniques ($p > .05$).

Prior to the study, we predicted that participants would spend more time and effort in learning landmarks with the single-actuator technique (according to *H5*). However, our results indicated that participants spent as much time and effort on either technique. Performance scores for all techniques at the end of training showed no significant difference $F(2, 38) = 2.82$, $p > .05$.

We predicted that participants would exceed 70% accuracy performance with either landmark technique. Results in Table 7 (1st row) show that participants were able to recognize landmark signals with over 80% accuracy rate for both landmark techniques. Therefore, *H2* is accepted.

We predicted that the performance of landmark signal perception would be affected by the presence of directional signals. We ran a dependent *t*-test that compared accuracy performance of C2-C3 (single-actuator technique) with C4-C5 (dual-actuator technique). With the single-actuator technique, landmark identification performance was significantly lower when directional information was present than when it was absent, $t(19) = 2.65$, $p < .05$. In contrast, with the dual-actuator technique participants were able to identify landmarks equally well whether or not directional signals were presented $t(19) = 0.32$, $p > .05$. Therefore, we reject *H4* since the presence of directional signals affected only the landmark single-actuator but not the landmark dual-actuator technique.

Description	Direction	Single-actuator	Dual-actuator
Accuracy (C1, C2 and C4)	93.75	80	82.14
Accuracy after adding direction (n/a, C3 and C5)	n/a	68.1	81.43
Accuracy after distraction (n/a, repeating C2 and C4)	n/a	77.14	83.57
Average completion time (C1, C2 and C4)	01:22	01:40	01:37
Average completion time (n/a, C3 and C5)	n/a	03:08	02:33
Average completion time (n/a, repeating C2 and C4)	n/a	00:55	01:00

Table 7. Performance Measures: Accuracy in %, Time in mm:ss.

Memorability

In order to measure the landmark signals memorability, we distracted participants with interviews and questionnaire sessions before asking them to repeat conditions 2 and 4. Raw results are presented in Table 7, 3rd row.

Paired-samples *t*-tests showed no significant difference in forgetting rates between the two landmark representation techniques. There was no significant difference in accuracy performance between repeated C2 and repeated C4, $t(19) = -0.95$, $p > .05$; no significant difference in performance between C2 and repeated C2, $t(19) = 0.64$, $p > .05$, and no significant difference between C4 and repeated C4, $t(19) = -0.51$, $p > .05$.

Subjective Measurements	Single-actuator	Dual-actuator
Distinguishable among themselves	3.55	3.55
Memorable	2.75	3.2
Associable with landmarks	2.6	2.65
Distinguishable from directions	4.25	4.5
Interference with directions	2.55	2.3

Table 8. Average Scores of Subjective Measures: n of 5 on a 1-5 likert scale, 1 being low and 5 being high.

Subjective Data and Preferences

Post-questionnaires were used at the end of each experimental condition. We gathered user's subjective data on the two landmark representation techniques on several measures. They included: distinguishability from direction signals, distinguishability amongst landmarks themselves, memorability, ease of meaning association, and the level of directional signals' interference. Participants gave ratings on a 1-5 likert scale, 1 being low and 5 being high.

The single-actuator representation technique scored lower than the dual-actuator technique in all subjective measures except for distinguishability amongst landmark signals, in which it scored equal with the dual-actuator technique (see Table 8).

Paired-samples *t*-tests showed no significant difference in all subjective measures. Specifically, there were no significant differences between the two landmark representation techniques in: distinguishability amongst landmark signals, $t(19) = 0.00$, $p > .05$; memorability, $t(19) = -1.76$, $p > .05$; association with landmarks, $t(19) = -0.15$, $p > .05$; distinguishability from direction signals, $t(19) = -1.10$, $p > .05$; and level of interference with direction signals, $t(19) = 0.84$, $p > .05$.

Based on landmark accuracy performance and the subjective measurement scores on distinguishability, we conclude that all participants were able to distinguish landmarks from directional signals in both conditions 3 and 5. Therefore, we accept *H3*.

As for subjective preference between the two landmark representation techniques, while 12 participants (60%) preferred the dual-actuator to the single-actuator technique, paired-samples *t*-tests showed no significant difference in preference, $t(19) = -0.89$, $p > .05$. Whichever technique a participant preferred, their comments and reasons were very similar and included "easy to remember and interpret", "more natural", and "easy to associate with landmarks".

If we look carefully at accuracy performance, each participant performed better with his or her preferred technique in C2 and C4. However, in C3 and C5 (when directional information was presented), performance of participants who preferred the dual-actuator technique dropped drastically when they carried out the single-actuator condition, while that of participants who favoured the single-actuator technique remained similar in both conditions. As a result, we found a significantly low overall accuracy performance score in condition 3.

Overall

Results showed that the one- and dual-actuator techniques offered almost equal support for landmark representation. To be precise, they required equal amounts of training and users performed equally well in experimental conditions in which only landmark signals were presented.

However, both direction and landmark information are crucial for navigation completion and should be provided in an operational tactile pedestrian navigation system. According to the accuracy performance results of C3 and C5 (Table 7, 3rd row), participants were able to perform significantly better with the dual-actuator technique than with the single-actuator technique when landmark signals were presented together with directional signals $t(19) = -2.63$, $p < .05$. Therefore, *H5* is accepted.

For the dual-actuator representation technique, we varied the pairs of actuators used. All the 180° actuator pairs were used by all participants. Other pairs were distributed evenly across all participants. Detailed results on the accuracy of each actuator pair are presented in Table 9.

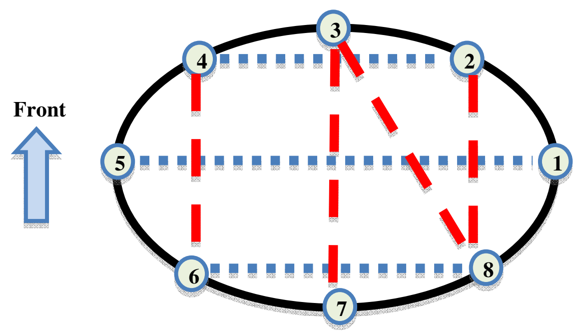

Figure 4. Best Actuator Pairs (motor number 3 is the front centre actuator). Horizontal lines show the three best pairs: 2-4, 1-5, 6-8; vertical lines demonstrate the next best three pairs: 2-8, 3-7, 4-6. The diagonal line shows the next best pair: 3-8.

Participants performed well with the actuator pairs that were vertically or horizontally aligned with their body. These pairs included the 2-4, 1-5, 6-8, 2-8, 3-7 and 4-6 pairs. The next best pair was the 3-8 pair. The actuator pairs which afforded highest performance, are shown in Figure 4. We recommend choosing these 7 pairs to represent our set of 7 landmarks in a tactile navigation aid.

We expected participants to have performed better with the other two 180° actuator pairs (i.e. the diagonal 4-8 and 2-6). However, results revealed that asymmetric or diagonal pairs did not support good performance.

Actuator Pairs	Condition 3	Condition 5	Repeated Condition 3
3-7	90.00	98.33	95.00
2-6	80.00	75.00	80.00
1-5	96.67	95.00	90.00
4-8	71.67	68.33	75.00
1-3	100.00	100.00	66.67
1-7	100.00	66.67	100.00
2-4	100.00	100.00	100.00
2-8	88.89	72.22	100.00
3-5	88.89	66.67	66.67
4-6	85.71	80.95	85.71
5-7	86.67	73.33	100.00
6-8	100.00	100.00	83.33
1-4	41.67	75.00	75.00
1-6	66.67	66.67	50.00
2-5	83.33	83.33	100.00
2-7	55.56	66.67	100.00
3-6	33.33	44.44	33.33
3-8	88.89	100.00	100.00
4-7	66.67	83.33	100.00
5-8	58.33	66.67	50.00

Table 9. Accuracy Performance (%) by Actuator Pairs (See Actuator Number Reference in *Figure 4*.

CONCLUSION

In this paper, we report an empirical study which compared two techniques to represent landmark information via the tactile channel. Our results have shown that the mapping symbology chosen to represent landmarks achieved acceptable performance. Through a device capable of presenting the information with a number of actuators, users perceived the vibration signals quite well and they were able to recognize the signals' meanings.

Compared with directional signals, participants took a significantly longer time to learn landmark signals and their associations. In the presence of directional signals, performance of landmark identification significantly dropped for the single-actuator technique and remained the same with the dual-actuator technique. With training, participants were able to distinguish landmark signals from directional signals and recognized over 80% of learned landmarks. With respect to both techniques' forgetting rates, it appeared that they were equal.

Results from our study suggest that the dual-actuator technique was better than the single-actuator technique in various ways, especially as it afforded better performance when presented together with directional signals. This is crucial to the development of a tactile pedestrian navigation system that provides both directional and landmark information.

Participants had an average response time of 4 seconds per signal across all conditions. This value is probably just about satisfactory for the intended use. Nevertheless, if these signals were to be used in outdoor urban environments, performance levels might drop since there are several other factors such as different levels of users' cognitive load and levels of noise in those environments. We anticipate that further training might help decrease response time in the lab setting, which might in turn reduce response time in applied environments. Further study is necessary to investigate whether extensive training can better the performance and the extent to which external factors such as noise might affect the results and system robustness, especially in the field.

The wearability and aesthetics of such systems will be crucial to user acceptance. Clearly our prototype, involving a notebook computer and protruding wires, allows for little meaningful evaluation of these issues. It is also worth noting that the tactile signal is brief and skin perception adapts through time so continued stimulation may lead to a decrease or even elimination of the sensory experience [17]. This may cause some missed signals in use. And as with all vibration-based systems, it is susceptible to not being perceived in high vibration environments.

Our experimental study assessed learnability and short-term memorability and we have obtained some promising results. However, based on these results, it is not possible to determine the effects of longer term use. A longitudinal study is required to address such issues.

Our next steps are to refine the tactile navigation prototype for use in field trials in an urban area. We will build on the insights from the lab-based work reported here to investigate specific applications' utility and acceptability with various users and in particular settings, for example in situations of high cognitive and visual load. Through these investigations, we will evaluate and improve the design and address user acceptability, and the performance-related benefits and challenges of a wearable tactile pedestrian navigation system.

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