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A Comparison of Two Wearable Tactile Interfaces with a Complementary Display in Two Orientations

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Abstract. Research has shown that two popular forms of wearable tactile displays, a back array and a waist belt, can aid pedestrian navigation by indicating direction. Each type has its proponents and each has been reported as successful in experimental trials, however, no direct experimental comparisons of the two approaches have been reported. We have therefore conducted a series of experiments directly comparing them on a range of measures. In this paper, we present results from a study in which we used a directional line drawing task to compare user performance with these two popular forms of wearable tactile display. We also investigated whether user performance was affected by a match between the plane of the tactile interface and the plane in which the users drew the perceived directions. Finally, we investigated the effect of adding a complementary visual display. The touch screen display on which participants drew the perceived directions presented either a blank display or a visual display of a map indicating eight directions from a central roundabout, corresponding to the eight directions indicated by the tactile stimuli. We found that participants performed significantly faster and more accurately with the belt than with the array whether they had a vertical screen or a horizontal screen. We found no difference in performance with the map display compared to the blank display.

Keywords: Evaluation/methodology, haptic i/o, user interfaces, wearable computers, pedestrian navigation.

1 Introduction

As illustrated in Table 1, researchers have proposed various forms of tactile wearable interfaces to convey directional information on different body sites. Some of these systems (e.g. [1], [2], [3]) have been tested and reported as successful in a range of environments. Of the proposed forms in Table 1, we have focused on the wearable systems that use the torso as a display site, specifically belt-type and back torso vest devices, since previous research (e.g. [4], [5]) suggests that their shape, size, and body contact areas support representation of cardinal (i.e. north, east, west and south) and ordinal (i.e. northeast, northwest, southeast, and southwest) directions and other information. We decided not to use the headband because it was reported that users had experienced discomfort wearing the system [6]. For the systems worn on wrists

and feet, the size of body contact areas is too small effectively to afford the display of 8 directions. We also decided not to study the systems worn on fingers because users often require their hands to be free to perform other activities.

Table 1. Tactile wearable interfaces classified by their body contact area and form.

Body contact areas	Forms	Products or Research Projects
Head	Headband	Forehead Retina System [7], Haptic Radar [8]
Shoulders	Shoulder Pad	Active Shoulder Pad [9]
Back Torso	Vest	Tactile Land Navigation [10]
Back Torso	Chair	Haptic Back Display [4]
Back Torso	Backpack	3x3 Tapping Interface Grid [1], Personal Guidance System [11]
Around the waist	Belt	ActiveBelt [5], WaistBelt [3], [12], Tactile Wayfinder [13]
Wrist	Wristband	GentleGuide [14], Personal Guide System [15]
Fingers	Wristwatch with Finger-Braille Interface	Virtual Leading Blocks [16]
Feet	Shoes	CabBoots [2]

The physical interface layout of systems worn on the torso typically follows one of two forms: (1) a back array of vibrators generating straight-line patterns (e.g. [1], [4]); and (2) a waist belt embedded with vibrators generating absolute point vibrations (e.g. [10], [3], [5]). Researchers have reported each of these interfaces as effective.

The back array represents cardinal and ordinal directions by generating stimulation patterns on an array of vibrators to create the sensation of a dotted line, known as the “cutaneous rabbit” phenomenon [17], [4]. The tactile flow patterns, also known as saltatory signals, generated by this approach represent directions of movement [1]. Most of the wearable tactile interfaces using this approach are in the form of a vest and stimulate the user’s back. Tan et al. [4], and Ross and Blasch [1] built their interfaces using a 3x3 motor array. Each direction was generated as a simulated line using three motors, e.g. vibrating motors in the middle vertical row of the array from bottom to top conveyed north. The systems were tested with drawing and street-crossing tasks. The researchers reported that tactile interaction effectively presented spatial information for the drawing tasks [4] and assisted visually impaired pedestrians in street-crossing [1].

The waist belt interface represents a direction by triggering vibration of a motor at the corresponding location around the waist. The tactile representation of absolute positions directly represents directions [3]. Van Erp et al. [3], Duistermaat [10] and Tsukada et al. [5] built prototypes in the form of a waist belt with 8 embedded motors distributed around the belt. Each motor represented one of the eight cardinal and ordinal directions, with each directional signal being generated using one motor. For example, vibrating the motor located at the front in the middle of the waist conveyed north. Evaluation results suggested that tactile interfaces were practical for conveying

directional information in operational environments including pedestrian navigation during daytime [5]) and in low visibility environments such as at night [10]; navigation in visually cluttered environments, e.g. in the cockpit of an aircraft [3]; and in vibrating environments, e.g. in a fast boat [3].

These two interface designs, the back array presenting a saltatory line and the waist belt presenting absolute points, have dominated research on tactile navigation displays on the torso, with each claiming success as a navigation aid. There was, however, no reported research directly comparing performance with these two approaches. Therefore, we directly compared them in a series of experiments, one of which we report here, involving directional pointing [18] and line drawing tasks.

2 Experimental Comparison

We closely followed the designs of both established interfaces, both in the form of the wearable devices and the tactile stimuli patterns used for each. Tan et al. [4] reported that different array sizes could affect performance; specifically, smaller participants performed better with an array with an inter-motor distance of 50 mm while bigger participants performed better with a bigger array (inter-motor distance of 80 mm). Geldard et al. [17] suggests that vibrators in a back array should be spaced at least at 40 mm but no greater than 100 mm to create a saltatory signal “line effect”. With little other evidence, there is no established optimum value for inter-vibrator distance. Therefore, for our initial experiments we built and tested two sizes of back array, 50 mm and 80 mm. Our 50 mm back array consisted of 9 motors mounted into a fabric pad in a 3-by-3 array. The motors had an equal inter-spacing of 50 mm. Our 80 mm back array was similar in shape but had an inter-spacing distance between motors of 80 mm. Our previous experiments [18] found the 50 mm array to be significantly less effective than the 80 mm array; therefore, in this experiment we compared only the 80 mm array and the belt. Our waist belt tactile interface consisted of 8 motors mounted in a belt. Following previous research (e.g. [3], [5]), the motors had an unequal interspacing (from 50 mm to 130 mm) to account for participants’ varying body shape and size. All the interfaces were worn over light clothing such as a T-shirt.

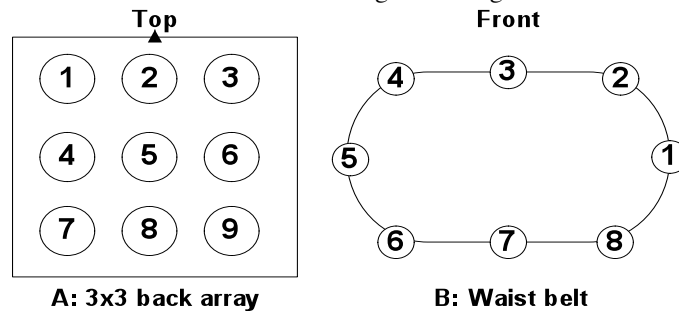


Fig 1. Layouts of the two interfaces.

The design of our tactile stimuli drew on tactile interaction design guidelines [19], the results of previous research [4] and our own pilot studies. We designed two sets

of tactile stimuli: set A (Table 2) for the back array, and set B (Table 3) for the belt. Set A contained eight saltatory signals representing *east, west, south, north, southeast, southwest, northeast, and northwest*. Set B represented the same eight directions based on the location of the motors around the participant's waist, with *north* represented by front centre (i.e. motor number 3).

Table 2. Stimuli set A's signal pattern. Number in signal pattern represents motor number in Figure 1A.

Stimuli code	Signal pattern	Direction
A1	444455556666	East
A2	666655554444	West
A3	222255558888	South
A4	888855552222	North
A5	111155559999	Southeast
A6	333355557777	Southwest
A7	777755553333	Northeast
A8	999955551111	Northwest

Both sets of stimuli had the same constant frequency (200 Hz) and inter-stimulus duration (50 ms). The vibration pattern for stimuli set A involved actuation of 3 motors and consisted of 4 repetitions of signals at 50 ms pulse and inter-pulse on each motor, i.e. 12 pulses in total for each stimulus. The pattern for stimuli set B involved actuation of one motor and consisted of 12 repetitions of signals at 50 ms pulse and inter-pulse duration. Hence, the number of pulses and duration of signal were the same across both stimuli sets.

Table 3. Stimuli set B's signal pattern. Number in signal pattern represents motor number in Figure 1B.

Stimuli code	Signal pattern	Direction
B1	111111111111	East
B2	222222222222	Northeast
B3	333333333333	North
B4	444444444444	Northwest
B5	555555555555	West
B6	666666666666	Southwest
B7	777777777777	South
B8	888888888888	Southeast

2.1 Experimental Procedure

In this study, we investigated whether performance between the two wearable layouts would differ for a line drawing task. In addition, we investigated if the pointing task in our previous experiment [18] might have favoured the belt layout since the plane of the belt vibrators matched the plane of the wall sensors used for user responses. Hence, in this experiment we also varied the plane in which participants responded.

We used a line drawing task because it requires similar skills to those needed when using a map-based navigation system, e.g. the ability to interpret the understanding of directions into two-dimensional representations [20] and the ability to associate one's current view of the world to its location in the map [21]. The experimental conditions involved drawing arrowed lines, indicating perceived directions, on a touch screen with one of two orientations, vertical and horizontal. We hypothesized that participants would perform better when the plane of the prototype matched the plane of the screen, i.e. they would perform better with the back array when drawing directed lines on a *vertical* screen. On the other hand, they would perform better with the belt when the task involved drawing directed lines on a *horizontal* screen.

As Carter and Fournery [22] suggested that using other senses as cues may support tactile interaction, we introduced a visual display as an experimental factor with two levels. In the first level, the touch screen presented a blank display on which participants drew their directed line (Figure 2A). In the second level, the touch screen presented a visual display of a map indicating eight directions from a central roundabout, corresponding to the eight directions indicated by the tactile stimuli (Figure 2B). We predicted that the visual display of the map would aid the participant in interpreting and responding to the tactile stimuli.

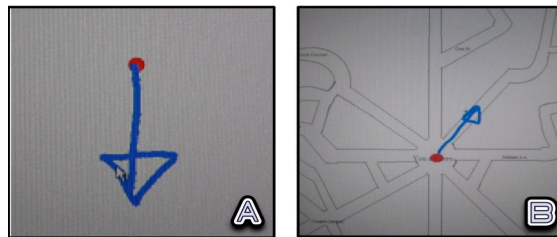


Fig. 2. A: Line drawn by a participant on the blank display. B: Line drawn by a participant on the map display.

In summary, we compared performance with the array and belt tactile interfaces and the effect on performance of (1) the plane of output display and (2) the presence or absence of a visual map display. The experimental hypotheses were as follows.

H1. Performance will be better when the plane of the tactile stimuli matches the plane of the responses, specifically:

H1a. Participants will perform better with the back array when the task involves drawing lines on a vertical screen;

H1b. Participants will perform better with the waist belt when the task involves drawing lines on a horizontal screen;

H2. Participants will perform better with the map display than the blank display.

There were 16 participants, 7 males and 9 females, with an average age of 29. Participants reported no abnormality with tactile perception at the time of experiment. They had no previous experience with tactile interfaces. They understood the concept of “direction” and were able to draw all cardinal and ordinal directions. Participants used both tactile interfaces. They were instructed to stand at a marked point approximately 200 mm away from the screen in the vertical display condition; and 130 mm away from the lower edge of the screen in the horizontal display condition. The height of the screen was adjusted to suit individual participants for the vertical and horizontal conditions. The order of conditions was counterbalanced.

There were 8 conditions, as shown in Table 4. Participants responded to the directions they perceived by drawing arrows with a stylus on the touch screen. Each participant responded to 8 stimuli in each condition. We compared a range of performance measures: time between the end of each stimulus and the response (response time), correctly perceived directions (accuracy), failure to identify any direction for a stimulus (breakdown), and incorrectly identified directions (error).

Participants were given a demonstration of how they would receive tactile stimuli via each prototype but were given no other training. We wanted to discover how well they could intuitively (i.e. without extensive training) interpret the meanings of different tactile patterns and to discover how usable the interfaces were without training. A key factor to successfully introducing new technology lies in its usability. Novel consumer technologies typically come with little or no training.

Table 4. Experimental conditions and their codes.

Back Array				Waist Belt			
Vertical screen		Horizontal screen		Vertical screen		Horizontal screen	
Blank (C1)	Map (C2)	Blank (C3)	Map (C4)	Blank (C5)	Map (C6)	Blank (C7)	Map (C8)

2.2 Results

2.2.1 Overall accuracy and response time analysis

The mean accuracy, error, breakdowns and response times for the back array and the belt are shown in Tables 5 and 6. The data were analyzed using a three-way repeated-measures ANOVA with *tactile interface*, *screen orientation* and *visual display* (Table 4 top, second and third rows respectively) as the independent variables. There was no significant interaction effect between *tactile interface* and *screen orientation* on accuracy ($f_{1,15} = 0.54$, n.s.), errors ($f_{1,15} = 0.05$, n.s.), breakdowns ($f_{1,15} = 1$, n.s.) or response time ($f_{1,15} = 1.74$, n.s.). These results tell us that the effects of the different tactile interfaces did not vary depending on the touch screen’s orientation, horizontal or vertical.

Table 5. Mean performance for vertical screen conditions. Scores: *n* of 8, Time: in seconds. SDs in parentheses.

	Back Array <i>Vertical Screen</i>		Waist Belt <i>Vertical Screen</i>	
	Blank (C1)	Map (C2)	Blank (C5)	Map (C6)
Accuracy	5.06 (1.84)	5.25 (1.65)	7.44 (0.63)	7.19 (1.11)
Error	2.81 (0.63)	2.44 (1.59)	0.50 (0.63)	0.75 (1.07)
Breakdown	0 (0.00)	0.31 (0.60)	0 (0.00)	0.06 (0.25)
Time	2.13 (0.50)	2.08 (0.83)	1.40 (0.37)	1.54 (0.67)

Post hoc Bonferroni pairwise comparisons showed that accuracy was significantly better with the belt than with the array in every case ($p < 0.002$); errors were significantly fewer with the belt than with the array in every case ($p < 0.002$); and response time was significantly quicker with the belt than with the array in every case ($p < 0.002$). No significant difference was found for breakdowns.

Table 6. Mean performance for horizontal screen conditions. Scores: *n* of 8, Time: in seconds. SDs in parentheses.

	Back Array <i>Horizontal Screen</i>		Waist Belt <i>Horizontal Screen</i>	
	Blank (C3)	Map (C4)	Blank (C7)	Map (C8)
Accuracy	5.63 (1.75)	5.63 (1.67)	7.5 (0.63)	7.63 (0.89)
Error	2.25 (1.65)	2.31 (1.66)	0.44 (0.63)	0.25 (0.58)
Breakdown	0.12 (0.34)	0.06 (0.25)	0 (0.00)	0.12 (0.50)
Time	2.08 (0.37)	2.21 (0.59)	1.28 (0.35)	1.41 (0.36)

Hypothesis H1 was rejected since participants performed significantly faster and more accurately with the belt than with the array whether they had a vertical screen or a horizontal screen.

A three-way repeated-measures ANOVA was run to compare blank displays and visual map displays on accuracy, response time, breakdowns and errors. No significant effect of display type was found on accuracy ($f_{1,15} = 0.01$, n.s.), response time ($t_{1,14} = 0.06$, n.s.), breakdowns ($t_{1,15} = 2.56$, n.s.), or errors ($t_{1,15} = 0.14$, n.s.). Thus, we rejected hypothesis H2 since display type had no effect on performance.

2.2.2 Accuracy and response time by stimulus

We performed further analysis on accuracy and response times with respect to the stimuli. Using the array, participants performed worst in accuracy (C1 and C2 in Figure 3, and C3 and C4 in Figure 4) with vertical (*north* and *south*) and horizontal saltatory signals (*east* and *west*). The inaccuracy ranged widely from 45 to 180 degrees (both to the left and to the right of intended directions). Figure 5 also shows

that participants responded much more slowly with the array than with the belt in all directions. They were slowest with the *north* signal. Using the belt, there was no significant difference in participants' accuracy and response times with different stimuli. Almost all incorrect answers were 45-degree errors.

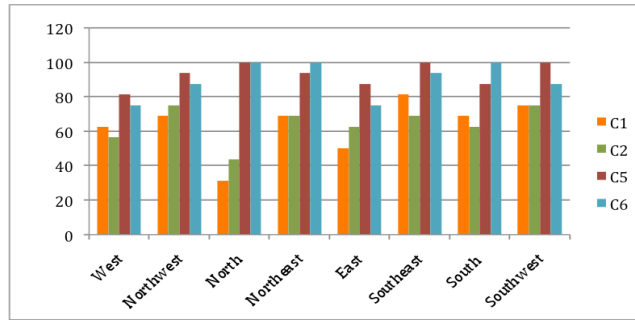


Fig. 3. Accuracy of responses (%) for all directions with the vertical screen conditions.

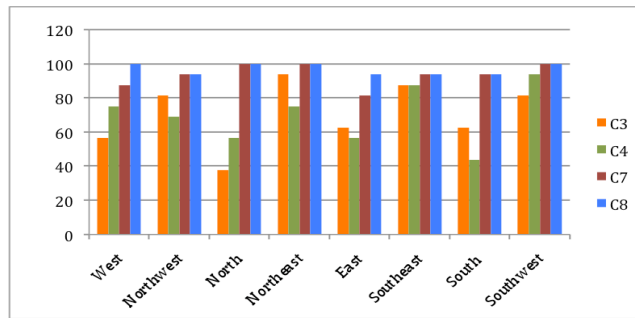


Fig. 4. Accuracy of responses (%) for all directions with the horizontal screen conditions.

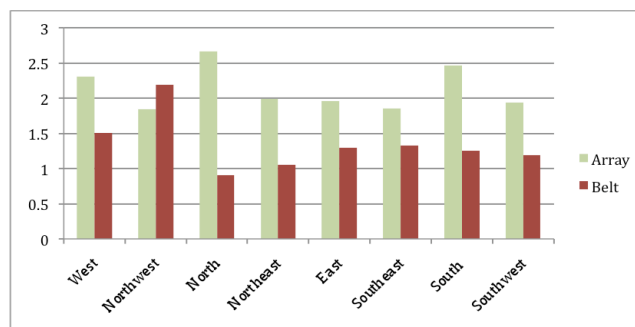


Fig. 5. Average response time (in second) for array conditions (C1 – C4) and belt conditions (C5 – C8).

3 Conclusion

Two types of wearable tactile displays, back array and waist belt, have been reported as successfully representing direction in experimental trials, however, previous research has not directly compared their performance. Our experiments reported here and in [18] show the belt to be significantly better than the array across a wide range of conditions, in this study regardless of screen orientation or visual display.

The experiment reported here also suggests that the visual display of the directions (in the map condition) did not aid the perception of and response to the tactile stimuli. This offers support to the notion that a unimodal tactile system, such as the tactile navigation aids presented by Tan et al. [4] and Van Erp et al. [3], is feasible without support from other modalities such as visual displays. It does not, however, rule out the possibility that other complementary displays might provide such aid.

Overall, our results suggest that the belt is a better choice for wearable tactile direction indication than the back array, however, our experiments did not seek to tease out which particular features of these two established approaches led to the observed differences. The two approaches actually vary on at least three potentially significant features: physical layout of vibrators, stimuli patterns (tactile flow *vs* absolute point), and body contact areas. We have found no published research that attempts to systematically vary these three features. In the experiment reported here, we have shown that the belt is more effective than the array in the form in which each of these designs has most commonly been realized. We did not examine the effects of more extensive training or long-term use. Other studies will be required to investigate these effects, which might help to improve the performance of the back array.

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